博士論文

Study on geometric and control design of at-grade crossing facilities for vehicle-pedestrian urban network

(都市部車両・歩行者ネットワークにおける平面交差施設の幾何構造と交通制御設計に関する研究)

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Abstract

Pedestrian crossing facilities, whether located at intersections or at midblock locations, are an important factor for better pedestrian walkability. They improve connectivity, accessibility and continuity of the pedestrian network. Existing design manuals, however, generally provide guidelines about locating crosswalks from safety viewpoint only. Moreover, traditionally crosswalks are usually taken as exogenous inputs and the network performance is maximized subsequently.

Aside from their impact on pedestrian efficiency and safety, crosswalks can affect vehicle efficiency too. For example, crosswalks converge pedestrians to a particular location and reduce crossing time which in turn increases the vehicular capacity of the road. Presence of multiple crosswalks distributes the pedestrian demand and reduces the delay. Midblock crosswalks may impact the vehicular progression and queues may reach a crosswalk if it is located too close to an intersection. Pedestrians crossing at intersection crosswalks may impede the turning vehicle flow especially when either the pedestrian or turning vehicle volumes are high. Therefore, it is important to optimize the placement, quantity and signal settings of crosswalks in a network so as to maximize the network performance for both vehicles and pedestrians.

The primary objective of this research was to maximize the performance of networks for both vehicles and pedestrians by incorporating pedestrian crossing facilities into the optimization framework. The secondary objective is to explore pedestrian risk taking behavior at midblock locations in order to determine whether or not it is necessary to optimize the pedestrian crossing facilities from unobservable factors viewpoint. Another secondary objective is to evaluate the performance of a particular scenario where

crosswalks are removed from critical intersections and placed at midblock locations.

A self-reported survey was conducted in order to explore the pedestrian crossing behavior at unmarked midblock locations. The results showed that pedestrians undertake risk taking behavior at midblock locations especially at urban and local roads and may cross at unmarked midblock locations when marked crosswalk is far. Hence, the study indicated that it is important to optimize the location of pedestrian crossing facilities in order to prevent pedestrian risk taking behavior. In order to achieve the primary objective, a total travel time minimization problem for a network was formulated so as to optimize the crosswalk existence, quantity, location and signal settings. The optimization model followed system optimum principle and could be used for planning purposes.

The results indicated that intersections can be operated at shorter cycle lengths signal settings are simultaneously optimized with crossing facilities design. The pedestrian demand distribution across the network reduced the concentration of pedestrians at few crosswalks only. The impact of pedestrians on saturation flow rates of turning vehicles also reduced. Further, an integrated approach involving pedestrian route choice behavior was developed. The solutions obtained under system optimum principle provided the lower bound to the system performance and could work as a reference to compare other optimization models which take pedestrian route choice behavior into account. The optimization formulations proposed in this study are an improvement on the traditional approaches where vehicle and pedestrian efficiency is maximized by keeping the crosswalk related design parameters as fixed inputs.

The proposed optimization models often resulted in solutions where crosswalks were not needed at intersections and were instead placed at nearby midblock locations. Such kind of crosswalk design for critical intersections was termed as alternative crossing design and its performance was evaluated separately using a simulation and optimization package. The relative applicability of this alternative crossing design and the traditional crossing designs for critical intersections was also determined. Alternative crossing design outperformed traditional crossing design for busy intersections and stayed undersaturated even for higher vehicle and pedestrian demands. Alternative crossing scenario with half cycle lengths at midblock crosswalks performed better especially at higher pedestrian volumes and unbalanced vehicle demand scenarios. Traditional phasing scheme where pedestrians can cross with parallel through traffic performed better at balanced demand scenarios, however, its performance deteriorated at unbalanced scenarios. Alternative crossing design with similar cycle lengths at the intersection and midblock crosswalks outperformed the traditional phasing scheme at unbalanced vehicle demand scenarios.

Contents

List of Figures

List of Tables

Chapter 1

Introduction

This dissertation attempts to optimize the vehicle-pedestrian network performance for both vehicles and pedestrians by incorporating pedestrian crossing facilities. The proposed optimization models attempt to maximize the network efficiency from both vehicle and pedestrian viewpoint. As it is important to study the pedestrian behavior in order to design crossing facilities, therefore, pedestrian crossing behavior at unmarked midblock locations is also explored.

At-grade pedestrian crossing facilities are the locations at the ground level where vehicles and pedestrians interact with each other in a traffic network. These crossing facilities, whether located at intersections or at midblock locations, are an important factor for better pedestrian walkability (McNally, 2010; Dannenberg et al., 2005). They improve connectivity, accessibility and continuity of the pedestrian network which in turn affect the walkability (Ellis, 2016). Existing design manuals generally provide guidelines about locating crosswalks from the safety viewpoint. However, installing a crosswalk may affect the efficiency of the network for both vehicles as well as pedestrians.

Crosswalks can affect the traffic network in multiple ways. For example, capacity of a road link decreases by the square of the pedestrian crossing time. In the absence of crosswalks, pedestrians may cross diagonally along the links taking more crossing time (Zhuang and Wu, 2011) and thereby reducing capacity. Whereas crosswalks converge pedestrians at specific locations to reduce crossing times and increase link capacity. Similarly, quantity of crosswalks is important because queueing models suggest that distributing pedestrian demand across several crosswalks can increase the capacity of the road and reduce delays. In addition, crosswalk signal settings may affect vehicle progression, therefore, it is important to optimize individual crosswalk signal settings as well as its coordination with adjacent intersections. Crosswalk location along a link should also be properly decided so as to reduce pedestrian detour times and to prevent the downstream queues from reaching the upstream crosswalks. Finally, the above-mentioned crosswalk design related factors, for example, crosswalk existence, quantity, location and signal settings may impact the vehicle route choice (Meneguzzer, 1997) and pedestrian route choice. Hence, resulting vehicular and pedestrian route choice should also be taken into account while designing vehicle and pedestrian networks. Traditionally, crosswalk design is taken as an exogenous input and the efficiency of the network is maximized subsequently (Ishaque, 2007). However, keeping the above factors in view, crosswalk design should be incorporated into the network optimization process so as to maximize the efficiency of the network for both vehicles and pedestrians.

The premise of this research is to design vehicle-pedestrian networks so as to maximize the performance for both vehicles and pedestrians by incorporating the crosswalk design. The process involves the determination of crosswalks' quantity, location and signal parameters in order to maximize the performance of the whole network. This approach is an improvement on the traditional approaches where vehicle and pedestrian efficiency is maximized by keeping the crosswalks' parameters as fixed inputs.

1.1. Research Objectives and Significance

The main objective of this research is to design the traffic networks by incorporating pedestrian crossing facilities. A secondary objective is to evaluate the performance of an alternative crossing design for critical intersections to show how crossing design can impact the efficiency.

Firstly, this research aims to review pedestrian behavior for various crossing scenarios for example, intersection crosswalks, midblock crosswalks and unmarked midblock locations etc. It is also an aim to identify missing link, if there is any, in the pedestrian crossing behavior studies and fill this gap by conducting appropriate study. Conclusions are drawn from this behavioral study and used in the subsequent optimization formulations.

Secondly, this research aims to formulate an optimization model for maximizing efficiency for under-saturated networks, which incorporates crosswalk design factors into the network design. The optimization model is formulated under system optimal principle for pedestrians.

Further, it aims to formulate an integrated optimization model to account for more detailed factors such as pedestrian route choice etc.. A numerical example is also to be shown. Then sensitivity analyses needs to be conducted to determine how the solution behaves as various input parameters are changed.

Finally, it aims to evaluate the performance of critical intersections by changing the crosswalk design. The crosswalks are removed from busy intersections and placed at midblock locations. Its applicability and limitations are determined.

1.2. Scope and Limitations

This study focused on urban vehicle-pedestrian networks only. Therefore, only signalized crosswalks are considered in the network design process. Only pedestrian street network is considered for pedestrians. Pre-timed signal control system is assumed. Steady state traffic conditions are assumed throughout the dissertation.

1.3. Research Contributions

The main contributions of this research study are:

1. A detailed review of pedestrian crossing behavior at various locations for example, signalized crosswalks and unmarked midblock locations. A self-reported survey for exploring pedestrian behavior at unmarked midblock locations in order to fill the gap in the existing research about pedestrian crossing behavior.
2. Dealing with the problem of optimizing the network performance considering pedestrian crossing facilities. To the author's knowledge, no major studies exist which analyzed such kind of problem except few which primarily focused on a single link or a small corridor.
3. Initially an optimization model is formulated to optimize the crosswalks' existence, location and signal parameters in small to medium sized networks by ignoring the vehicle route choice behavior. Tradeoff between vehicle and pedestrian traffic and sensitivity analyses is conducted to gain further insight.
4. A framework consisting of integrated optimization and a traffic flow model, which also incorporates pedestrian route choice, is developed to optimize the network performance for both vehicles and pedestrians. Although such frameworks have been developed for other applications, this study developed the framework specifically for optimizing the network performance considering the crossing facilities. The analysis of the output and further detailed sensitivity analyses provides more insight into designing the network considering the pedestrian crossing facilities.
5. Applicability of a particular crosswalk design scenario is analyzed and discussed where crosswalks can be removed from busy intersections and installed at midblock locations. By testing for various vehicle and pedestrian demand levels, it was found that this design outperformed traditional crossing

design at busy intersections. It remained undersaturated for higher vehicle and pedestrian demand levels where traditional intersection design becomes oversaturated.

6. Finally, the implications of the results are discussed for designing traffic networks.

1.4. Organization of the Dissertation

Figure 1.1 shows the research flow. Chapter 2 presents a review of the traditional guidelines on designing and locating pedestrian crosswalks, signal settings and optimization models incorporating pedestrians and crossing facilities etc. Chapter 3 delves into more details about pedestrian crossing behavior at various crossing locations and determines the information and constraints needed to formulate the optimization problems in the subsequent chapters. It also addresses a gap identified in the existing literature on pedestrian crossing behavior at unmarked midblock locations. Chapter 4 presents an optimization formulation to optimize crossing design by maximizing network performance. Chapter 5 proposes an integrated approach to design vehicle-pedestrian networks considering crossing facilities. It also takes pedestrian route choice behavior into account. Chapter 6 specifically focusses on a special scenario where crosswalk are removed from busy intersections and located at midblock locations. The applicability of this kind of design with respect to traditional crossing design is also shown. Chapter 7 summarizes the findings of the dissertation and provides recommendations and suggests future works.

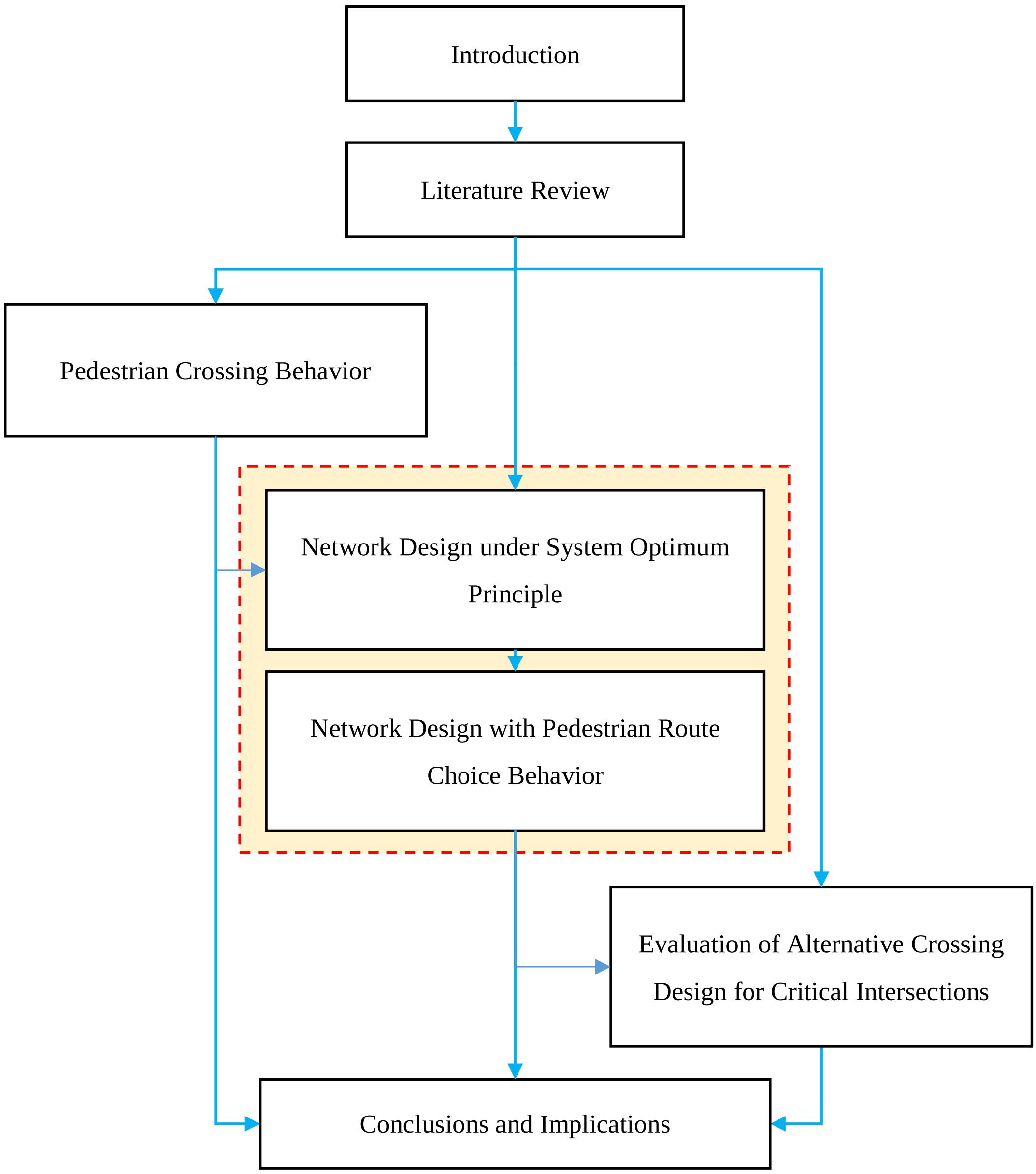


Figure 1.1: Organization of the Dissertation and Research Flow

Chapter 2

Literature Review

This chapter provides a review of existing crosswalk design guidelines, signal optimization and the recent researches incorporating crosswalk design into the network design.

2.1. Existing Crosswalk Design Guidelines

Generally marked crosswalks are provided at intersections. Crosswalks at midblock locations are generally recommended from safety viewpoint. There are certain criteria in design manuals about when, where and how to locate a crosswalk. This section reviews existing design guidelines on how to design and locate crosswalks.

Federal Highway Administration (2009) presents qualitative criteria for crosswalk design and placement in Manual on Uniform Traffic Control Devices (MUTCD). It recommends placing a crosswalk where there are substantial pedestrian and vehicle conflicts. A proper engineering study should be conducted if the crosswalk is located at a location other than intersection (such as a midblock location). A crosswalk should be located where pedestrian demand is concentrated.

Institute of Transportation Engineers recommends that marked crosswalks are generally installed where pedestrians can be merged at a single location, where it is confusing for the pedestrians, near schools, and where there are significant conflicts between vehicles and crossing pedestrians. Further, adequate sight distance should be ensured for vehicles and pedestrians and crosswalk be marked so as to minimize the crossing time for pedestrians (Traffic Engineering Council, 1998).

New Zealand Transport Agency provides guidelines for selection of pedestrian crossing facilities. Four main reasons are listed which dictate the selection of the most suitable pedestrian facility: level of service, safety, specific access provisions and integration (New Zealand Transport Agency, 2019).

Washington DOT (2019) states that crosswalks should generally not be located within 300 feet of a traffic signal, a bus stop or another crossing facility. A midblock crosswalk should not be located on a street with speed limits over 72 kph.

Illinois Department of Transportation warrants installation of crosswalk where there are more than 300 vehicles per hour for any 8 hour of day or where pedestrian volume exceeds 75 pedestrians per hour for same 8 hours and at urban signalized intersections (Smith & Knoblauch, 1987).

Toronto recommends not installing a crosswalk where turning movements are excessive. A crosswalk installation is warranted where pedestrian volumes exceeds 100 pedestrians per hour in each of 8 hours in which 10 or more pedestrians have to wait (Smith & Knoblauch, 1987).

Smith & Knoblauch (1987) provided guidelines for installation of marked crosswalk with respect to average daily traffic volume and hourly pedestrian volume. Pedestrian warrants for traffic signals also exist (Federal Highway

Administration, 1978; Zageer et al. 1983).

2.2. Crossing Facilities: A Wider Perspective

The guidelines mentioned above generally consider local conditions while installing a crossing facility. The impact of installing a crosswalk on the surroundings or the impact of the surroundings on a crosswalk is usually discussed qualitatively.

Crosswalks can impact an arterial or a network in several ways. If there is no crosswalk, pedestrians will cross diagonally ending up taking more crossing time (Zhuang and Wu, 2011) and reducing the capacity of the road by the square of the pedestrian crossing time. Whereas, placement of a crosswalk, where needed, will merge pedestrian trajectories at a specific location thereby increasing the road capacity.

Concentration of pedestrian demand at a single intersection will result in less road capacity and higher delays. Therefore, according to queueing models, distributing the pedestrian to multiple locations can increase the road capacity and reduce delays.

A midblock crosswalk can impact the progression of vehicles along a road, therefore, it is important to coordinate the signalized midblock crosswalks with adjacent intersection so as to ensure smooth progression of vehicles.

The location of a midblock crosswalk should be decided in such a way so that pedestrian detour times are reduced. Otherwise pedestrians may not use the crosswalk at all and cause safety hazards. Also, the location be decided such that the queues at downstream intersection do not reach the upstream crosswalk.

Location and quantity of crosswalks provide opportunities for pedestrians to cross. Hence, pedestrian route choice may be impacted if these are changed. Drivers may also alter their route choices depending on several factors including location of crosswalks, quantity of crosswalks and delays at such crosswalks etc.

2.3. Pedestrian Crossing Behavior

Pedestrian behavior should be considered while designing traffic networks because pedestrians may behave differently to different crossing designs. A traffic network with pedestrian crossing facilities can provide better walking environment if pedestrian behavior is taken into account properly. Therefore, it is important to study how pedestrians are going to react to a certain crossing design in the network. This chapter summarizes the existing knowledge on pedestrian behavior at crossing facilities and determines the implications of this knowledge which will be used in developing the models in the subsequent chapters. The scope of this chapter includes only signalized crosswalks at intersections and midblock and unmarked midblock locations. There are observable factors (such as road and traffic factors) and unobservable factors (human-related factors) which affect pedestrian crossing behavior (Avineri et al., 2012; Figliozzi et al., 2016; Van and Hugo, 1982; Rosenbloom et al., 2009; Zeedyk et al., 2003). Most of the existing research focused on non-human related factors. The ones which focused on human related factors mostly paid attention to the pedestrian crossing behavior at intersection crosswalks. Hence, a secondary objective of this chapter is to address this gap by studying the effect of unobservable factors on pedestrian crossing behavior at midblock locations.

2.3.1. Pedestrian behavior at signalized crosswalks

There are various factors which affect pedestrian crossing behavior at signalized intersection crosswalks. However, some of the factors are outside the scope of this study and are, therefore, not studied in detail in this dissertation. The factors which are needed for the model formulation in the subsequent chapters are waiting duration and clearance time etc.

Duration of signal intervals plays an important role in determining the pedestrian behavior. Longer red intervals impose longer waiting times on pedestrians. A study conducted in Montreal concluded that longer maximum waiting times (red interval) led to higher proportion of violations (Brosseau et al., 2013). A hazard-based duration model was developed to study pedestrian crossing behavior at signalized crossings in Beijing, China. Results indicated that the longer the time has passed since the start of the waiting duration, the more likely the risk of pedestrian violation (Guo et al., 2011). Similar behavior was observed in India, where the percentage of unsafe crossings increases with the increase in pedestrian delay (Tiwari et al., 2007). A study in China indicated that the longer the red interval is, the more likely are pedestrians to cross during red interval. Longer red intervals are the biggest reason for red-time crossing in China. It was recommended to reduce pedestrian waiting time at intersections especially where crossing distance is short (Yang & Sun, 2013). An experiment conducted in Chicago, USA created two scenarios for the pedestrians who wanted to cross two intersection legs. Those pedestrians who faced only few seconds until the onset of the green interval after crossing the first leg committed significantly few violations whereas many of those pedestrians who had to wait for 30 seconds until the onset of the green interval after crossing the first leg, jaywalked just to avoid a waiting time of about 30 seconds (Jason & Liotta, 1982).

An improper signal timing may urge pedestrians to commit violations. Such signalized intersections where vehicular volume is low and pedestrians are still forced to wait, give rise to more violations. Akin & Sisiopiku (2007) captured such behavior in Michigan State University. The study showed that the pedestrian compliance with Walk signal was only 50.63% which could be attributed to the fact that vehicular volume was low, therefore, pedestrians found relatively longer gaps to safely cross the road even during red interval. An observational study in Australia also concluded that showing red indication to pedestrians, when it is safe to cross, will lead to disrespect of the signal in a way that pedestrians will start ignoring the signal (Daff & Cramphorn, 2006). More red light violations by pedestrian were observed at an intersection in Lund, Sweden than an intersection in Hasselt and Leuven given the fact that average waiting time at the intersection in Lund was much smaller than that in Hasselt and Leuven. However, the traffic volume was low at the intersection in Lund which could be stimulating factor in red light violations by pedestrians (Langbroek et al., 2012). 450 persons were interviewed in Stockholm, Malmoe, and Lund. The pedestrians more or less always walking against red were asked to rank some countermeasures to reduce red-walking. The responses indicated that "more supervision by the police" and "shorter waiting time for green" were considered to be the most effective countermeasures to reduce red-walking (Gårder, 1989).

Besides above mentioned observable factors, there are unobservable factors that affect pedestrian behavior at signalized intersection crosswalks.

2.3.2. Pedestrian behavior at unmarked midblock locations

This section summarizes the researches on pedestrian behavior at unmarked midblock locations. Then it determines the important findings that need to be incorporated into the optimization formulations proposed in the following chapters. There is plenty of research about effect of observable factors, however, there is little research on unobservable factors affecting pedestrian behavior at midblock locations. This gap is address in this section by conducting a study on unobservable factors affecting pedestrian behavior at unmarked midblock locations.

A mid-block is a location away from intersections where there is no crosswalk. Pedestrians often cross at mid-block locations putting themselves at risk. The chances of getting involved in a crash at mid-block locations are higher as compared to the intersections owing to the fact that vehicle speeds are higher and drivers do not normally expect pedestrians at mid-block locations. Al-Masaeid et al. (1997) investigated the impact of road, traffic and environmental factors on the frequency of pedestrian accidents on urban arterial mid-blocks in Irbid, Jordan. The results indicated that 74% of arterial pedestrian accidents occurred at mid-block locations. Furthermore, crossing at a mid-block location is found to be particularly more dangerous (Tarko et al., 2011). Chu (2006) developed multiple regression model to assess the role of crossing locations and lighting conditions in pedestrian injury severity in Florida. The results showed that the probability of a pedestrian dying when struck by a vehicle is higher at mid-block locations than at intersections under any light conditions. Therefore, it is important to explore the factors affecting pedestrian crossing behavior at mid-block.

2.4. Self-reported Pedestrian Behavior Surveys

As it is difficult to measure unobservable factors, Self-reported questionnaire surveys consisting of travel and crossing practices are typically used to explore underlying/unobservable factors affecting pedestrian behavior (Evans et al., 1998; Yagil, 2000). A review of some of such researches is given below.

Evans et al. (1998) applied theory of planned behavior to predict pedestrians' road crossing intentions. The respondents answered the questionnaires consisting of three potentially dangerous road crossing behaviors, followed by social psychological variables. The results showed that the social psychological variables explained about 39 to 52% of the variance in intentions to cross the road in the manner portrayed in the scenarios. Yagil (2000) studied self-reported road crossing behavior of pedestrians in relation to beliefs regarding the consequences of the behavior, instrumental and normative motives for compliance with safety rules and situational factors.

Diaz (2002) developed a pedestrian behavior questionnaire based on a driver behavior questionnaire which consisted of 16 five-point Likert type items. The questionnaire was used to measure risky pedestrian behavior especially at mid-block locations in Chile. It was found that younger pedestrians are more likely to commit violations, errors and lapses. The results also showed gender differences in beliefs, instrumental motives and normative motives.

Elliot and Baughan (2003) developed the adolescent road user behaviour questionnaire (ARBQ) in England. Three factors were found: unsafe road crossing, dangerous playing the road and planned protective behaviour. Granie et al. (2013) developed and validated a self-reporting scale to measure pedestrian injury risk behaviors. The scale included 47 items about pedestrian behaviors. Factor analysis was carried out to extract four underlying factors namely “transgression”, “lapses”, “aggressive behavior” and “positive behavior”.

Papadimitriou et al. (2013) conducted principal component analysis on the data obtained through a questionnaire survey consisting of 33 items. Eight component were revealed, of which six were associated with pedestrian attitudes and the remaining two with pedestrian behaviour. The effect of different countries, age groups and gender was also analyzed. Papadimitriou et al. (2017) designed a questionnaire to capture underlying human factors affecting pedestrian walking and crossing behavior in urban areas. Likert type questions about attitudes, perceptions, motivations, behavior and habits were asked in the questionnaire. Categorical principal components analysis (CATPCA) was carried out on the data which yielded three dimensions of human factors of pedestrian behavior namely “risk taking and optimization”, “conservative and public transport user” and “pedestrian for pleasure”. However, sample size was rather small.

Qu et al. (2013) developed Chinese version of the Pedestrian Behaviors Scale (PBS) by combining features of the Granie et al. (2013) and Turkish pedestrian behavior questionnaires (Nordfjærn et al., 2013). Factor analysis on the data produced four factors: transgressions, lapses, positive and aggressive behaviors with strong internal reliability. PBS has also been validated in Serbia (Antić, 2016).

Deb et al. (2017) developed and validated a self-reporting pedestrian behavior questionnaire to measure frequency of pedestrian risky behavior in the United States. Confirmatory factor analysis (CFA) yielded five factors namely “violations”, “errors”, “lapses”, “aggressive behaviors” and “positive behaviors”. In addition, the effects of gender and age on the pedestrian behavior were also explored.

2.5. Pedestrian Route Choice

Under deterministic user equilibrium, it is assumed that users have perfect knowledge of route costs based on which they choose the best route so as to minimize their travel costs. However, this assumption of having perfect knowledge is not realistic. Hence, probabilistic route choice models have been developed which takes the uncertainty into account. According to these models, a pedestrian chooses a route to minimize his/her perceived costs.

Discrete choice models are generally used to model route choice behavior. These models are normally derived from utility theory which consist of a deterministic and a random component. The random component accounts for the uncertainties involved in the real world scenarios. Users try to maximize the utility if choosing a certain route from a set of routes. Several factors which affect user route choice are included in a generalized cost function which forms the utility function.

The route choice models normally differ depending on the assumptions about the probability distribution of the random component. Two most common models known as Multinomial Logit (MNL) (Hausman and Wise, 1976) and

Multinomial Probit (MNP) (Daganzo and Sheffi, 1977) assume Gumbel and Normal distribution for the random component, respectively. Although MNL has its own limitations, it has been implemented for assignment problems because of its simple analytical form.

2.6. Traffic Signal Optimization

2.6.1. Isolated signal optimization

There are two basic classes of isolated signal optimization; off-line and on-line. Off-line techniques utilize historic data to design the traffic signals whereas on-line techniques utilize the real-time information of traffic through detectors to optimize the signal settings. As this study deals with off-line signal optimization, therefore a review of off-line optimization methods is presented here.

Webster (1958) conducted one of the earliest studies on traffic signal design. The optimal cycle lengths can be determined by minimizing the overall intersection delay. The delay function consisted of a uniform component, a random component and a correction term. Allsop (1971a) formulated a convex optimization model to minimize the delay for isolated signalized intersections which was implemented as a program called SIGSET (1971b).

Allsop (1972) formulated a linear optimization program for maximizing the capacity by introducing common flow multiplier in to the optimization problem. Yagar (1974) also formulated a capacity maximization problem.

Traditionally, all the methods required stages and stage sequences as exogenous inputs. Several researchers attempted to incorporate the stages and stage sequences into the optimization problems (Tully, 1976; Heydecker, 1992).

Improta and Cantarella (1984) formulated an isolated signal optimization problem as binary mixed integer linear program which eliminated the need to provide stages and stage sequences as exogenous inputs. Webster's delay formula was linearized and a brand and bound technique was used to solve the problem.

Although stage structure and stage sequences were integrated into the optimization formulations, lane-use was still an exogenous input. Lam et al. (1997) attempted to deal with this problem by formulating a binary mixed integer program. Lane-use and stage plans were optimized so as to maximize the junction capacity. Pedestrian signal timings and changes in the stage sequences were optimized later. Lane-based methods were proposed which integrated lane-use into the group-based signal optimization problem. Cycle lengths minimization and capacity maximization were formulated as binary mixed integer linear program while delay minimization problem was formulated as a binary mixed integer nonlinear program (Wong et al., 2000; Wong and Wong, 2003; Wong et al., 2002)

2.6.2. Signalized arterial and network optimization

Linking the traffic signal on an arterial or within a network can provide additional benefits to traffic. The idea is to determine offsets between traffic signals in order to maximize the efficiency for the traffic.

One of the earliest studies on coordinating traffic signal along an arterial was conducted by Little (1966) who attempted to maximize the bandwidth along an arterial. Improta and Sfroza (1982) formulated a binary integer program to optimize offsets in signalized networks. Hillier (1996) proposed an algorithm to optimize the offsets by minimizing delay.

2.7. Combined signal control and assignment problem

There are two basic principles of traffic assignment: user equilibrium and system optimal Wardrop (1952).

Changes in signal timings can lead to changes in flow pattern in a network. Changes in flow pattern then require changes in signal settings. Allsop (1974) was one of the very first researchers to address this problem.

Allsop and Charlesworth (1977) proposed an iterative procedure to reach a mutually consistent point where further changes in signal settings and the equilibrium assignment are negligible. Cantarella et al., (1991) proposed a procedure called ENETS for iterative signal control and equilibrium assignment.

Till date, several researches have attempted to deal with the problem of combined signal control and traffic assignment (Yang and Yagar, 1995; Wong and Yang, 1999; Chiou, 1999; Wong and Wong, 2002; Ziyou and Yifan, 2002; Ukkusuri et al., 2013).

2.8. Pedestrians Integration in Optimization Formulations

The section reviews researches which attempted to incorporate crosswalk designs into optimization formulations.

Traditionally, signal optimization problems included pedestrian requirements merely as constraints, however, increasing pedestrian activities urged researchers and practitioners to not only maximize vehicle efficiency but also pedestrian efficiency. Ma and Yang (2009) attempted to formulate an optimization model to coordinate midblock crosswalks with adjacent signalized intersections. The objective function consisted of bandwidth for vehicles in both directions. There was a noticeable decrease in vehicular delays, however, the impact was limited on pedestrian delay. Chang and Sun (2012) proposed an optimization model for the design of crosswalk between coordinated intersections by taking pedestrian tolerance limit into account. Zhang and Zhang (2012) also attempted to deal with the problem of coordinating midblock crosswalk with adjacent intersections and proposed to use distance-flow rate-time graph. Zhao, Ma and Li (2016) presented a multi-objective optimization model to optimize the design of midblock crosswalk in order to achieve trade-off between vehicular and pedestrian traffic. Two conflicting objectives consisted of weighed average bandwidth for vehicles and weighted average bandwidth for pedestrians in both directions. The results indicated that the crosswalk performance decreases as the crosswalk is moved away from the optimal location. Two-stage crosswalk always performed better than one-stage crosswalk. They also concluded that the crosswalk performance decreases with the length of the crosswalk because of the longer clearance time required for pedestrians.

Ishaque (2006) formulated an optimization model for minimizing aggregated vehicle and pedestrian delay in a network, however, number and location of midblock crosswalks were not considered as decision variables in the optimization. The objective function consisted of mean excess travel cost per person. It was concluded that generally shorter cycle lengths benefit pedestrians. Also, policies which are advantageous from vehicles viewpoint may not be beneficial for pedestrians. Yu and Ma (2015) presented an integrated model for an arterial optimizing the quantity, locations and signal settings of midblock crosswalks by bandwidth maximization and pedestrian delay minimization. It was concluded that noticeable improvements can be achieved by optimizing crosswalk related parameters. Also, adding excess midblock crosswalks may not improve the performance and two-stage crosswalk performed better for both vehicles and pedestrians. However, the problem was formulated for an arterial only and its application to a network level problem is not straightforward. Moreover, bandwidth maximization does not necessarily minimize vehicular delays.

2.9. Solution Techniques

Numerous solution techniques have been proposed depending on the type of the optimization problem. There are exact and deterministic methods which generally require analytical information such as information about continuity and derivatives etc. There are other methods which do not require such information and termed as derivative free methods. They are generally stochastic methods and search through the solution space to reach the global optimum. In this study, two optimization techniques for mixed integer nonlinear programs will be used.

1. Brand and Bound Method

2. Genetic Algorithm

2.10. Gaps in the Literature

Based on the literature review presented in the previous sections, the following major research gaps were identified in the literature:

1. Pedestrian crossings are generally taken as exogenous inputs
2. Lack of adequate research on optimum crossing design at network level

The subsequent chapters attempt to address these gaps.

Chapter 3

Pedestrian Crossing Behavior

Pedestrian behavior should be considered while desgining traffic networks because pedestrians may behave differently to different crossing designs. A traffic network with pedestrian crossing facilities can provide better walking environment if pedestrian behavior is taken into account properly. Therefore, it is important to study how pedestrians are going to react to a certain crossing facility in the network. The previous chapter summarized the existing knowledge on pedestrian behavior at crosswalks located at intersections and midblock locations and discussed the implications of such behavior. There are observable factors (such as road and traffic factors) and unobservable factors (human-related factors) which affect pedestrian crossing behavior (Avineri et al., 2012; Figliozzi et al., 2016; Van and Hugo, 1982; Rosenbloom et al., 2009; Zeedyk et al., 2003). Most of the existing research focused on non-human related factors as they are easier to observe and analyze as compared to unobservable factors. The researches which focused on human related factors mostly paid attention to the pedestrian crossing behavior at intersection crosswalks. The scope of this chapter includes exploration of pedestrian crossing behavior at unmarked midblock locations. For this purpose, a self reported survey is conducted about pedestrian crossing behavior at unmarked midblock locations. Although the reported behavior may differ from the observed behavior, reported surveys have their own advantages. For example, unobservable factors (human-related factors such as crossing intentions, preferences etc.) can be accommodated in self-reported surveys. Moreover, hypothetical scenarios can be included in the suvery. Pedestrian risk-taking behavior is explored which will help in determining whether pedestrian risk-taking behavior can be reduced by providing pedestrian crossing facilities at midblock locations.

3.1. Pedestrian Behavior at Unmarked Midblock Locations

3.1.1. Research hypotheses

Based on the published literature and common understanding, the hypotheses to be tested were formulated as follows:

- The younger pedestrians are more risk-taking
- Male pedestrians are more risk-taking
- Pedestrians from developing countries are more risk-taking
- Pedestrians violating traffic signals at mid-block locations are more likely to undertake risk-taking behavior at mid-block locations

3.1.2. Method

Survey instrument

A questionnaire was developed by modifiying previously developed questionnaires (Papadimitriou, 2017) and is shown in Table 3.1. The items, irrelevant to mid-block crossing, were removed and a few relevant items were added based on the literature review. The questionnaire consisted of various sections: A: demographics, B: mobility, C: travel motivations, D: behavior and risk taking, E: perceptions and preferences and F: violations. The respondents were asked to answer the questions using a 5-point Likert scale. The last section (Section F) included items related to violations at signal controlled mid-block crosswalks and was included in the quesionnaire to test the hypotheses whether crossings at mid-block are associated with signal violations.

Survey administration

The questionnaire was created online using Survey Monkey. The questionnaire was administered online to the students, researchers and alumni of several Japanese universities who belonged to various countries. The respondents were then asked to further distribute the survey in their respective countries and so on. The responses were totally anonymous and any identifying details were kept confidential.

Table 3.1: Questionnaire design

A	**Demographics**
A_1	Gender (male/female)
A_2	Age (18-29, 30-39, 40-49, 50-59)
A_3	Car ownership (yes/no)
A_4	Region (developing country, developed country)
B	**How many times per week do you travel to your destination by each one of the following modes?***
B_1	Walk + Public Transport
B_2	Passenger Car
B_3	Walk to destination
C	**As a pedestrian, how much would you agree with each one of the following statements? ****
C_1	I walk because I enjoy walking
C_2	I walk because it is healthy
C_3	In short trips, I prefer to walk
C_4	I walk because I have no other choice
D	**As a pedestrian, how often do you adopt each one of the following behaviors? *******
D_1	I cross at mid-block at major urban arterials
D_2	I cross at mid-block at urban roads
D_3	I cross at mid-block at local/residential roads
D_4	I cross at mid-block when intersection crosswalk is far
D_5	I cross at mid-block when my destination is on the opposite side
D_6	I cross at mid-block when I am in a hurry
D_7	I pay extra attention when I cross at mid-block
D_8	I run when I cross at mid-block
D_9	I cross at mid-block when I see other people crossing
E	**As a pedestrian, how much would you agree with each one of the following statements? ****
E_1	Crossing at mid-block is safer than crossing at intersection crosswalk
E_2	Vehicles are more respectful to pedestrians at mid-block than at intersection crosswalk
E_3	Crossing at mid-block saves time
E_4	Crossing at mid-block increases the risk of accident

E_5	Crossing at mid-block is wrong
E_6	Crossing at mid-block is acceptable because other people do it
E_7	I am willing to take potential accident risk at mid-block to save time
E_8	I prefer crossing at mid-block than crossing at intersection crosswalk
F	**As a pedestrian, how often do you adopt each one of the following behaviors at signalized mid-block crosswalks? *** **
F_1	Crossing with a DON'T WALK/Red indication
F_2	Crossing with a Flashing Don't Walk/Flashing Green indication
F_3	Crossing outside of the crosswalk boundary

* (1: never, 2: less than once a week, 3: once a week, 4: more than once a week, 5: everyday)

** (1: strongly disagree, 2: disagree, 3: neither agree nor disagree, 4: agree, 5: strongly agree)

*** (1: never, 2: rarely, 3: sometimes, 4: often, 5: always)

Participants

The sample comprised 220 participants (139 men and 81 women) between 18 and 59 years of age; 55% were in the 18-29 age group, 39% were in the 30-39 age group; 5% were in the 40-49 age group and merely 1% were in the 50-59 age group. About half of the participants (47.3%) owned a car. 62.2% were from developing countries and 37.8% were from developed countries.

3.1.3. Results and Discussion

The main objective of this study was to explore the unobservable factors affecting pedestrian mid-block crossing behavior. A 24 item (excluding section A and F in Table 3.1) questionnaire was designed based on the research hypotheses and literature review. The questionnaire consisted of several sections which required respondents to answer items about demographics, mobility, travel motivations, travel behavior, risk-taking behavior, perceptions and preferences in the context of mid-block locations; and signal violations in the context of signalized mid-block crosswalks.

Descriptive analysis

Descriptive analysis was carried out on the collected data. Means, standard deviations and distribution of responses are shown in Table 3.2.

Table 3.2: Questionnaire items: means, standard deviations and distribution of responses

Item	Mean	SD	Distribution of responses (%)				
			1	2	3	4	5
B. How many times per week do you travel to your destination by each one of the following modes?							
Walk + Public Transport	3.28	1.44	16.4	18.2	12.3	27.3	25.9
Passenger Car	2.76	1.59	35.5	13.6	10.9	19.1	20.9
I walk to my destination	2.83	1.58	32.3	16.4	9.1	20.9	21.4
C. As a pedestrian, how much would you agree with each one of the following statements?							
I walk because I enjoy walking	3.50	1.07	5.0	11.8	29.1	36.8	17.3
I walk because it is healthy	3.92	0.95	1.8	7.3	16.8	45.5	28.6
In short trips, I prefer to walk	4.21	0.85	1.4	3.6	8.6	45.0	41.4
I walk because I have no other choice	2.90	1.25	12.7	30.9	23.2	19.5	13.6
D. As a pedestrian, how often do you adopt each one of the following behaviors?							
I cross at mid-block at major urban arterials	1.97	1.02	40.0	33.6	17.3	7.3	1.8
I cross at mid-block at urban roads	2.46	1.04	22.3	27.3	33.6	15.9	0.9
I cross at mid-block at local/residential roads	3.46	1.10	4.1	16.8	26.8	33.2	19.1
I cross at mid-block when intersection crosswalk is far	3.02	1.06	11.4	15.5	38.6	29.1	5.5
I cross at mid-block when my destination is on the opposite side	3.01	1.06	9.5	20.0	36.8	27.3	6.4
I cross at mid-block when I am in a hurry	3.09	1.11	8.6	21.4	31.8	28.6	9.5
I pay extra attention when I cross at mid-block	4.35	1.01	2.7	4.1	10.9	20.5	61.8
I run when I cross at mid-block	3.27	1.18	10.0	14.5	28.6	31.8	15.0
I cross at mid-block when I see other people crossing	2.95	1.05	10.5	20.5	38.2	25.5	5.5
E. As a pedestrian, how much would you agree with each one of the following statements?							
Crossing at mid-block is safer than crossing at intersection crosswalk	2.30	1.10	28.6	32.3	22.3	14.5	2.3

Vehicles are more respectful to pedestrians at mid-block than at intersection crosswalk	2.28	1.07	25.9	39.5	17.7	14.5	2.3
Crossing at mid-block saves time	3.65	0.81	1.4	6.8	27.7	53.6	10.5
Crossing at mid-block increases the risk of accident	3.98	0.93	3.2	4.5	11.4	52.7	28.2
Crossing at mid-block is wrong	3.72	0.95	1.8	8.6	26.4	42.3	20.9
Crossing at mid-block is acceptable because other people do it	2.24	0.98	23.2	42.7	23.2	8.6	2.3
I am willing to take potential accident risk at mid-block to save time	2.57	1.16	21.8	28.6	23.6	22.3	3.6
I prefer crossing at mid-block than crossing at intersection crosswalk	2.55	1.09	17.7	36.4	21.8	21.8	2.3
F. As a pedestrian, how often do you adopt each one of the following behaviors?							
Crossing with a DON'T WALK/Red indication	1.89	1.04	48.6	24.1	17.7	8.6	0.9
Crossing with a Flashing Don't Walk/Flashing Green indication	2.65	1.06	15.9	26.8	37.7	15.0	4.5
Crossing outside of the crosswalk boundary	2.32	0.94	22.3	33.6	34.5	9.1	0.5

51.4% of the participants walked to their destination at least once a week to everyday. Most of the respondents (74.1%) walk because it is healthy and a majority of the respondents (86.4%) prefer to walk in short trips.

Respondents declared that they mostly cross at mid-block at local/residential roads as compared to urban roads or major urban arterials. About 26%, 50%, and 79% of the respondents declared that they cross at mid-block locations sometimes to always at major urban arterials, urban roads and local/residential roads, respectively. A majority of the respondents (82.3%) said that they are extra attentive when they cross at mid-block. An overwhelming majority of the respondents (80.9%) believed that crossing at mid-block increases the risk of accident and 63.2% believed that crossing at mid-block is wrong.

Exploratory factor analysis

In order to explore the underlying factorial structure, exploratory factor analysis (principal axis factoring with orthogonal Varimax rotation) was carried out on the items in section B, C, D and E in questionnaire. Negatively worded items (i.e. B_2, C_4, D_7, E_4 and E_5) were reverse coded before conducting exploratory factor analysis (EFA).

Initially, the EFA conducted on all the items produced 8 factors based on the eigenvalues criteria (i.e. eigenvalues > 1) which accounted for 48.96% of the total variance. However, not all the factors were interpretable and some did not have adequate internal consistency.

Therefore, a four factor solution was selected which explained about 42.54% of the total variance. The Kaiser-Meyer-Olkin measure of sampling adequacy was satisfactory (0.757), Barlett's test of sphericity was significant (0.000) and the determinant of the matrix was 0.003. A cut-off value of 0.35 was used for item loadings. All results are presented in Table 3.3.

The first axis explained 17.31% of the variance. It was defined by 7 items. All the items loading on this axis represented risky mid-block crossing behavior. This axis could be referred to as "risk-taking". The second axis explained 9.88% of the variance. It was explained by 5 items. Items loading on this axis predominantly expressed risk perception of pedestrians. For example, vehicles are respectful to pedestrians, it is wrong to cross at mid-block. Hence, this axis could be referred to "wrong perception". As mentioned earlier, negatively worded items were reverse coded before the analysis, therefore, a higher value for this factor means the pedestrians perceive crossing at a mid-block to be safe and a right thing to do. The third axis explained 8.84% of the variance and was explained by 4 items. Items loading on this axis represented walking motivations which expressed positive attitudes towards walking. Hence, this factor is referred to as "pedestrian for pleasure" as defined in (Papadimitriou, 2017). The fourth axis explained 6.51% of the variance. It was explained by 3 items which showed respondents' tendency towards walking. This axis could be referred to "walking pattern".

Table 3.3: Principal axis factor analysis of the questionnaire items (Varimax rotation)

Items	Factor 1	Factor 2	Factor 3	Factor 4
I cross at mid-block at major urban arterials	.507			
I cross at mid-block at urban roads	.663			
I cross at mid-block at local/residential roads	.550			
I cross at mid-block when intersection crosswalk is far	.834			
I cross at mid-block when my destination is on the opposite side	.821			
I cross at mid-block when I am in a hurry	.751			
I cross at mid-block when I see other people crossing	.450			
Crossing at mid-block is safer than crossing at intersection crosswalk		.687		
Vehicles are more respectful to pedestrians at mid-block than at intersection crosswalk		.691		
Crossing at mid-block increases the risk of accident		.408		
Crossing at mid-block is wrong		.535		
I prefer crossing at mid-block than crossing at intersection crosswalk		.599		
I walk because I enjoy walking			.739	
I walk because it is healthy			.737	
In short trips, I prefer to walk			.454	
I walk because I have no other choice			.486	
Walk + Public Transport				.686
Passenger Car				.686
I walk to my destination				.396
% of variance explained	**17.31**	**9.88**	**8.84**	**6.51**
Cronbach's alpha	**0.838**	**0.726**	**0.682**	**0.596**

Cronbach's alphas for "risk-taking" (0.838), "wrong perception" (0.726), "pedestrian for pleasure" (0.682) and "walking pedestrians" (0.596) indicated that "risk-taking" and "wrong perception" had good internal reliability. However, Cronbach's alpha was low for "walking for pleasure" and "walking pattern". Hence, additional items for these factors may be added to increase internal consistency.

Raw scores were summed and averaged for all the items loading above the cut off value for each individual to estimate the factor scores and were used for further analyses (DiStefano et al., 2009).

Effects of gender and age

Two-way ANOVAs were conducted on the effects of gender and age (A_1 and A_2 in Table 1) on factors scores for all four factors. Sample size for age 40+ was very limited, therefore, only first two age groups (18-29 and 30-39) were considered in the analysis. Gender consisted of two groups (male and female). The means and standard deviations are shown in Table 3.4.

The results of two-way ANOVAs on the effects of gender and age on the factor scores are shown in Table 3.5. The main effects for both gender and age indicated a significant difference in risk-taking behavior (factor 1) between gender and age groups. Male respondents declared a significantly higher risk-taking behavior than female respondents. This is consistent with previously published literature (Diaz, 2002). Pedestrians in the age group 18-29 reported more risk-taking behavior at mid-block than those in the age group 30-39. This finding is in line with previously published literature (Papadimitriou, 2017).

The main effect for age showed a significant difference in wrong perception between the two age groups. Pedestrians in the age group 30-39 perceive mid-block crossing wrongly. It is interesting to note that although 30-39 years old pedestrians are less risk-taking, they still believe that vehicles are respectful to pedestrians at mid-block and it is safe and right to cross at mid-block. No significant effects of gender and age were observed on "walking for pleasure" (factor 3).

Table 3.4: Means (standard deviations) of factor scores for each gender, the two age groups and the total sample

Gender	Age (N)	Mean (Standard Deviation)				
		Factor 1	Factor 2	Factor 3	Factor 4	Violations
Male	18-29 (76)	3.53 (1.04)	3.55 (0.77)	2.84 (0.74)	2.28 (0.76)	2.43 (0.85)
	30-39 (54)	3.00 (1.03)	3.83 (0.62)	2.93 (0.78)	2.07 (0.67)	2.31 (0.80)
	Overall Male (130)	3.00 (1.03)	3.83 (0.62)	2.93 (0.78)	2.07 (0.67)	2.31 (0.80)
Female	18-29 (45)	3.13 (1.16)	3.54 (0.83)	2.89 (0.77)	2.4 (0.69)	2.27 (0.79)
	30-39 (32)	2.69 (1.17)	3.73 (0.73)	2.68 (0.69)	2.44 (0.68)	2 (0.70)
	Overall Female (77)	2.94 (1.18)	3.62 (0.79)	2.80 (0.74)	2.42 (0.68)	2.16 (0.76)
Overall	18-29 (121)	3.38 (1.10)	3.55 (0.79)	2.86 (0.75)	2.32 (0.74)	2.37 (0.83)
	30-39 (86)	2.88 (1.09)	3.79 (0.66)	2.83 (0.75)	2.21 (0.69)	2.20 (0.77)
	All respondents (207)	3.17 (1.12)	3.65 (0.75)	2.85 (0.75)	2.28 (0.72)	2.30 (0.81)

A significant gender effect was observed on “walking pattern” (factor 4). Females declared more weekly walk as compared to males. Similar results indicating women making more trips than men were found in a study conducted in Chennai, India (Srinivasan, 2005). The more trips by women are likely because they perform most of the household related tasks.

The interaction effects were nonsignificant on all four factors.

Table 3.5: Two-way ANOVA results on the effects of gender and age

Demographics	F statistics from ANOVA (p-value, η^2)			
	Factor 1	Factor 2	Factor 3	Factor 4
Gender (df: 1, 203)	5.118 (0.025*, 0.025)	0.282 (0.596, 0.001)	0.827 (0.364, 0.004)	5.503 (0.020*, 0.026)
Age (df: 1, 203)	9.344 (0.003*, 0.044)	4.570 (0.034*, 0.022)	0.360 (0.549, 0.002)	0.571 (0.451, 0.003)
Interaction (1, 203)	0.085 (0.771, 0.000)	0.207 (0.649, 0.001)	1.818 (0.179, 0.009)	1.490 (0.224, 0.007)

*p<0.05

Effect of region

Mean factor scores and corresponding standard deviations for developing and developed countries against each of the four factors are shown in Table 3.6. Independent samples t-tests were performed to test whether region had any significant impact on pedestrian mid-block crossing behavior. The results of t-tests are shown in Table 3.7.

The results indicated no significant effects of region on first three factors. However, region had a significant effect on walking pattern (factor 4). Pedestrians in the developing countries declared more weekly walk which is consistent with published literature (Downing, 1991).

Table 3.6: Means (standard deviations) of factor scores for developing and developed countries

	Developing (N = 137)		Developed (N = 83)	
	M	SD	M	SD
Factor 1	3.12	1.12	3.11	1.19
Factor 2	3.63	0.75	3.76	0.73
Factor 3	2.85	0.72	2.85	0.81
Factor 4	2.39	0.71	2.10	0.68

Note: M = Mean, SD = Standard Deviation

It is interesting to note that region was found to have no significant impact on risk-taking behavior (factor 1). This finding could be attributed to the fact that pedestrians reported behavior could differ from their actual behavior. Therefore, pedestrians from different countries may respond to the survey in the same way but may behave in a totally different way when in the field. Nonetheless, a future study with improved classification of developing and developed countries may provide further insight.

Table 3.7: t-test results for the effect of region

	t-test (p-value)			
	Factor 1	Factor 2	Factor 3	Factor 4
Region (df = 218)	0.027 (0.978)	-1.312 (0.191)	-0.027 (0.979)	3.010 (0.003**)

**p<0.01

Relation between mid-block crossing behavior and mid-block signal violations

Exploratory factor analysis (principal axis factoring with orthogonal Varimax rotation) was carried out on the items in the section F of the questionnaire in order to extract the factor underlying violation behavior at signalized mid-block crosswalks. EFA yielded a single factor which explained about 46.95% of the total variance. The Kaiser-Meyer-Olkin measure of sampling adequacy was satisfactory (0.665), Barlett's test of sphericity was significant (0.000) and the determinant of the matrix was 0.547. All the items loading on the factor represented violations committed at mid-block traffic signals. This axis could be referred to as "signal violations". The Cronbach's alpha (0.719) showed that the scale was internally consistent. The results are shown in Table 3.8.

Table 3.8: Principal axis factor analysis of section F (Varimax rotation)

Items	**Factor**
Crossing with a DON'T WALK/Red indication	.784
Crossing with a Flashing Don't Walk/Flashing Green indication	.668
Crossing outside of the crosswalk boundary	.589
% of variance explained	**46.95**
Chronbach's alpha	**0.719**

To test the hypothesis that mid-block signal violations were associated with mid-block crossing behavior, Spearman correlation analysis was performed on "Signal Violation" and the four factors previously extracted. Mean factor scores and corresponding standard deviations are shown in Table 3.9.

Table 3.9: Means (standard deviations) of the factor scores for Spearman correlation analysis

	M	SD
Factor 1	3.11	1.14
Factor 2	3.68	0.74
Factor 3	2.85	0.76
Factor 4	2.28	0.71
Signal Violations	2.29	0.81

N = 220 (Sample size)

Note: M = Mean, SD = Standard Deviation

Spearman correlation analysis on Factor 1 and "Signal Violations" revealed a weak correlation ($r_s = .23$, $n = 220$, $p < .000$) implying that pedestrians violating traffic signals at mid-block might also undertake a risky crossing at mid-block locations where no crosswalks exist. However, the correlation is too weak to clearly support this proposition.

The Spearman correlation analysis on Factor 2 and "Signal Violations" revealed a very weak negative correlation ($r_s = -.19$, $n = 220$, $p = .006$). Although the correlation is very weak, it implies that pedestrians who commit violations believe that it is not appropriate to cross at mid-block. Although it seems counterintuitive, the reason could be the fact that pedestrians at signalized crosswalks know that drivers are aware of their presence, therefore, they tend to commit more violations. While on the other hand, pedestrians are aware that crossing at mid-block may not be safe owing to the fact that drivers may not be expecting pedestrians at such locations.

A moderate correlation was found between Factor 3 and mid-block signal violations ($r_s = .41$, $n = 220$, $p < .000$). The pedestrians who violate traffic signals are probably the ones who walk for pleasure and health reasons. This could be attributed to the fact that the pedestrians frequently walking for pleasure reasons are familiar with the infrastructure and may undertake such behavior. A very weak correlation ($r_s = .11$, $n = 220$, $p = .091$) was revealed between Factor 4 and "Signal Violations".

This study had some methodological limitations. The sample size was not large enough because of the difficulty of administering the survey in various countries and a limited sample size may not be adequate to generalize the results, however, the results provided a strong statistical foundation for future studies on this topic. The questionnaire distribution was not completey random, therefore, the results may include some bias. Nonetheless, the results of the items, which had been previously studied, were consistent with the published literature. The representation of older pedestrians in the survey was not adequate. Further, respondents were asked to answer whether they come from a developing country or a developed country. This item may be improved by providing an appropriate classification of developed and developing countries to the respondents. The factor scores (and the distribution of residuals), in general, were not normally distributed. However, ANOVA and t-tests are highly robust to non-normality (Norman, 2010). Spearman's correlation was used, instead of Pearson correlation, to evaluate the correlation between "signal violations" and the four factors. The results of this study may be validated at a later stage by conducting a larger-scale study with a more representative sample size. On the other hand, self-reported behavior alone cannot explain the pedestrian behavior accurately. The observed behavior also needs to be taken into consideration.

3.2. Implications for Network Design

The results of the analysis on the questionnaire survey indicated that pedestrians are more likely to undertake risk-taking behavior at midblock locations at urban and local roads as compared to major urban arterials. Also, no significant difference was found between respondents from developing and developed countries.

Pedestrians reported that they are likely to cross at midblock locations if marked crosswalks are far.

Hence, it is important from unobservable factors viewpoint that crossing facilities needs to be optimized in vehicle-pedestrian networks to prevent pedestrians from undertaking risk-taking behavior. The optimization model to be formulated in the subsequent chapter should take these findings into account.

Chapter 4

Network Design under System Optimum Principle

Pedestrian crossing facilities need to be optimized in vehicle-pedestrian network in order to provide maximum benefits to both vehicles and pedestrians. This chapter deals with the problem of designing a network by optimizing crossing facilities and signal settings. An optimization model is formulated for optimum number and location of crosswalks and the signal settings by minimizing aggregated vehicle and pedestrian travel times. Pedestrians are assigned under system optimal principle. In case of vehicles, system optimal solutions are generally realized by route guidance systems so that vehicles choose those paths that will lead to system optimum. However, it might not be straightforward in case of pedestrians as pedestrians' route choice sets and their route choice process is pretty complex. Nonetheless, system optimal solution provides the best possible solution which can be obtained from system viewpoint and it provides a good reference for comparison purposes. Therefore, the problem formulated in this chapter optimizes the network performance by assigning pedestrians to various paths under the system optimal principle.

The following are the assumptions made in this study:

- All possible pedestrian paths are enumerated beforehand by considering a possible existence of a midblock crosswalk at each link.
- Vehicle route choice is not taken into account
- Progression factors are applied to account for the effect of platooned arrivals as no

progression model is employed

- Pedestrian demand is assumed to be discretely distributed across the network
- Off-street pedestrian network is not considered
- Concurrent signal phasing is assumed for pedestrians at the intersections (however, any phasing scheme can be considered.)

4.1. Network Description

A typical grid network is shown in Figure 4.1. The blue rectangles represent the pedestrians' origins and destinations (ODs). Pedestrian ODs could be entrances or exits to subway stations, bus stops or maybe shopping centers etc. It is assumed that every link in the network contains possible intersection crosswalks and a single mid-block crosswalk. The exact number and location of crosswalks is determined after solving the optimization problem.

4.2. Model Formulation

The development of the model involves four steps: pedestrian delay model, pedestrian walk time model, vehicle delay model and signal settings. Based on these, the optimization model is formulated. The formulated problem is a mixed-integer-nonlinear-program (MINLP).

4.2.1. Pedestrian delay model

Pedestrian volume on a crosswalk c is given as follows:

$$v_c^p = \sum_{(r,s)\in RS} \sum_{k_{rs}\in K_{rs}} \left(x_{rsk_{rs}} a_{ck_{rs}} v_{rs}^p\right) \qquad \forall c \in C \tag{1}$$

where, r and s are origin and destination nodes, respectively (Figure 1); RS

is the set of all OD pairs. v_{rs}^{p} is the pedestrian demand between OD pair rs. k_{rs} is a path connecting origin r and s and K_{rs} is the set of all paths connecting OD pair rs.

$x_{rsk_{rs}}$ is a decision variable indicating the existence of a path between an OD pair:

$$x_{rsk_{rs}} = \begin{cases} 1, & if\ path\ k_{rs}\ exists\ between\ OD\ pair\ rs \\ 0, & otherwise \end{cases}$$

$a_{ck_{rs}}$ is a known binary parameter indicating whether a crosswalk belongs to a path:

$$a_{ck_{rs}} = \begin{cases} 1, & if\ crosswalk\ c\ belongs\ to\ path\ k_{rs} \\ 0, & otherwise \end{cases}$$

Total pedestrian volume along all the paths between an OD pair should be equal to the total pedestrian volume between that OD pair (v_p^{rs}):

$$\sum_{k_{rs} \in K_{rs}} v_p^{krs} = v_p^{rs} \qquad \forall (r,s) \in RS \tag{2}$$

The number of used paths between an OD pair cannot exceed the maximum existing paths between that OD:

$$\sum_{k_{rs} \in K_{rs}} x_{rsk_{rs}} \leq \sum_{k_{rs} \in K_{rs}} k_{rs} \qquad \forall (r,s) \in RS \tag{2}$$

The following pedestrian delay model was adopted which takes pedestrian noncompliance into account (Virkler, 1998):

$$d_c^p = [C - (g + 0.69A)]^2 / 2C \tag{3}$$

Therefore, the following model is used to compute the delay for those pedestrians who undertaking diagonal crossing:

$$d_{diag} = \frac{(C - g_i)(g_i - {}^{L}/_{v_s}) + 0.5(g_i - {}^{L}/_{v_s})}{C} \tag{4}$$

Demand weighted pedestrian delay in the network is given as follows:

$$D_p = \sum_{c=1}^{C} d_c^p v_c^p \Big/ \sum_{c=1}^{C} v_c^p \tag{5}$$

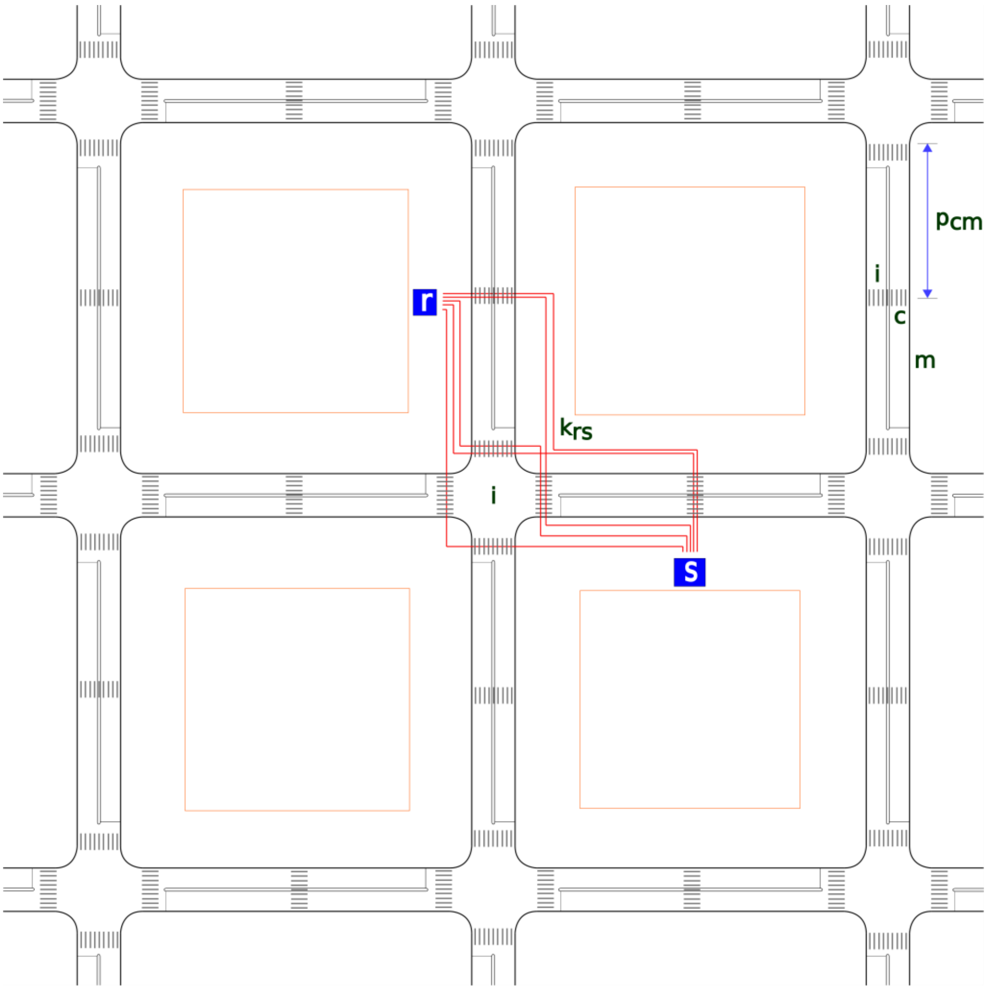


Figure 4.1: A typical grid network layout with possible paths between an OD

4.2.2. Pedestrian walk time model

The position of a midblock crosswalk along a link may change the walking time for pedestrians along a certain path.

The walk time along a path ($w_{k_{rs}}$) is computed as a function of the location (p_{cm}) of the midblock crosswalk along the link (m) (Figure 4.1) along that path (Figure 4.2) and is simply the length of the sidewalk divided by the pedestrian walking speed.

$$w_{k_{rs}} = f(p_{cm}) \quad for\ all\ c\ on\ K_{rs} \tag{6}$$

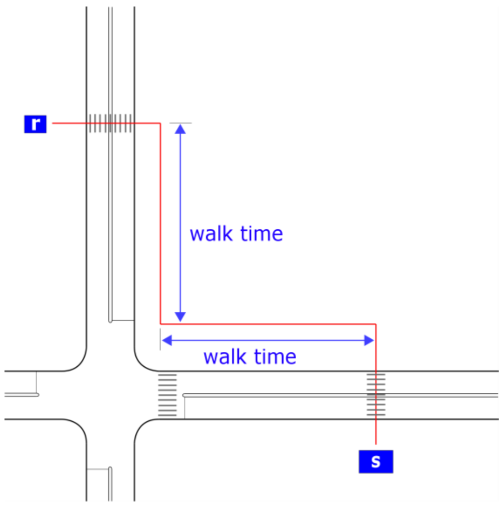


Figure 4.1: Pedestrian walk time illustration

Demand weighted pedestrian walk time in the network can be computed as:

$$W_p = \sum_{(r,s)\in RS} \sum_{k_{rs}\in K_{rs}} \left(x_{rsk_{rs}} w_{k_{rs}} v^p_{k_{rs}}\right) / \sum_{k_{rs}\in K_{rs}} \left(v^p_{k_{rs}}\right) \tag{7}$$

Pedestrian travel time is simply the summation of pedestrian delay and pedestrian walk time.

$$T_p = D_p + W_p \tag{8}$$

4.2.3. Vehicle delay model

Intersections in the network are divided into two classes: Main-intersections and midblock-intersections. Main-intersection is the intersection where two roads intersect, whereas midblock-intersection is the intersection where a crosswalk and a road intersect at a midblock location. Average vehicle delay at an intersection is calculated as follows:
For main-intersections:

$$d = (PF)d_1 + d_2 \tag{9}$$

For midblock-intersections:

$$d = \delta_i[(PF)d_1 + d_2] \qquad \forall i \in I \tag{10}$$

where, d is the average vehicle delay. PF is the progression factor which accounts for the effect of platooned arrivals on uniform delay component (Transportation Research Board, 2015). d_1 is the uniform delay component and d_2 is the random delay component. These are calculated using Webster's uniform and random delay model (Webster, 1958) as follows:

$$d_1 = \left[\frac{C(1 - {}^{g}/_{C})^2}{2\left[1 - \left(\frac{g}{C}\right)x\right]}\right] \tag{11}$$

$$d_2 = \left[\frac{x^2}{2q(1-x)}\right] \tag{12}$$

Webster further applied a correction term to the above model which accounted for about 10% reduction in the delay computed by above formulae (Cheng, 2016). Delay to turning vehicles during permissive phasing is indirectly determined by applying adjustment factors to saturation flow rates. δ_i is a binary variable which indicates whether midblock-intersection i exists or not.

$$M^2\delta_i \geq M\left(\sum_{(r,s)\in RS}\sum_{k_{rs}\in K_{rs}} x_{rsk_{rs}} a_{ck_{rs}} b_{ci}\right) \geq \delta_i \qquad \forall i \in I, \forall c \in C \tag{13}$$

where, M is a sufficiently large number and b_{ci} is a known binary parameter indicating whether crosswalk c belongs to intersection i or not.

Although only undersaturated situation is considered in this study which means queues clear during the green indication, constraints can be set on the queue lengths so that they do not reach the upstream intersection. This optimization model does not consider spatial queuing of vehicles, therefore, queue length is estimated as follows (Mystkowski, C., & Khan, S., 1999):

$$Q = \frac{A}{\left[\left(1-\frac{A}{D}\right)3600\right]}R \tag{14}$$

where, Q is the back of queue size, A is the arrival flow rate, R is the effective red time and D is the departure rate. The spatial length of the queue can be calculated by multiplying the back of queue size by average vehicle spacing. Then a constraint can be set to keep the length of the queue under certain threshold so that it does not reach the upstream intersection.

Demand weighted vehicle delay in the network is computed as follows:

$$D_v = \sum_{i=1}^{I}\sum_{j=1}^{J} d_{ij}v_{ij}^{v} \Big/ \sum_{i=1}^{I}\sum_{j=1}^{J} v_{ij}^{v} \tag{15}$$

where, d_{ij} is the average vehicle delay for approach j at intersection i.

Demand weighted vehicle running time is computed by summing the product of individual link's running time and link's volume and dividing it by the total vehicle volume in the network. Vehicle delay combined with the vehicle running time gives the vehicle travel time.

$$T_v = D_v + R_v \tag{16}$$

Where, T_v is the demand weighted vehicle travel time and R_v is the demand weighted vehicle running time.

4.2.4. Signal settings

Cycle length for each intersection (not explicitly indicated) is given as:

$$C = \sum g + Y + AR \tag{17}$$

where, C is the cycle length, g is the green time for a phase, Y is the total yellow time and AR is the total all-red time.

Cycle time should be constrained between a minimum and maximum value.

Green splits should satisfy the minimum green requirement.

Pedestrian walking time can computed using the HCM approach. The clearance time for pedestrians is calculated as follows:

$$I = l/v_s^p + t_s \tag{18}$$

where, l is the crossing distance, v_s^p is the pedestrian speed and t_s is additional safe time.

The capacity factor for an approach should be greater than 1:

$$\frac{(s_j \cdot g_j)}{(C \cdot q_j)} \geq 1 \qquad j = 1, \ldots, J \tag{19}$$

where, s_j and q_j are the saturation flow rate and demand flow at approach j.

4.2.5. Objective function

Based on the formulations presented above, an objective function is proposed to obtain optimum number and location of midblock crosswalk and signal settings by minimizing total vehicle and pedestrian travel time.

$$\min(\alpha \times \gamma \times T_v + \beta \times T_p) \tag{20}$$

where, α and β are weight factors which can be determined by time values for vehicles and pedestrians and γ is the average vehicle occupancy.

4.2.6. Decision variables

Binary variable for existence of paths between each OD pair($x_{rsk_{rs}}$)

Continuous variable for position of midblock crosswalks(p_{cm})

Continuous variable for pedestrian volumes along paths (v_{krs}^p)

Greens times for all intersections(g)

4.3. Solution Approaches

The optimization model formulated in this chapter is a mixed-integer-nonlinear program (MINLP). MINLPs are inherently nonconvex because of the presence of discrete variables. Multiple algorithms exist for solving MINLPs (Duran and Grossmann, 1986; Fletcher and Leyffer, 1994; Grossmann, 2002). However, solution to the combinatorial problems are usually difficult to find in finite time especially when path sets (in this particular case) get large. Improta and Cantarella (1984) carried out a piece-wise linearization of Webster's delay model which makes the first term of the objective function linear. The problem can be converted into a mixed-integer-linear program given that the nonlinear constraints are also linearized simplifying the problem. In addition, Gallivan (1982) showed that Webster's two term delay formula is convex in g and g/C which means the local solution of the relaxed problem is also the global solution. Hence, a local MINLP solver can then be used to solve the convex MINLP. Branch and bound method searches for the optimum solution by solving sub-problems consisting of relaxed MINLP problems. The convergence to the global optimum is guaranteed if the relaxed problem is convex (Adjiman et al., 1998). The solvers for convex MINLPs can also be used for nonconvex problems, as they may provide a feasible solution (Belotti et al., 2009). Next section presents a numerical example for a small network with few paths for pedestrians and is solved using Gekko optimization suite with APOPT solver which uses branch and bound method to solve mixed integer programs (Beal et al. 2018; Hedengren et al., 2012). Such exact algorithms are usually computationally expensive as they iterate through all solutions to reach the optimum solution (Grefenstette et al., 1985). Moreover, these deterministic algorithms use the convexity of the problem to reach the global optimum and may not be able to converge to global optimum solution if the relaxed problem is nonconvex. On the other hand, stochastic optimization algorithms are global search algorithms which explore the solution space in such a way so as to avoid getting trapped in local extrema. Simulated annealing (Cardoso et al., 1997), genetic algorithm (Costa and Oliveira, 2001) and particle swarm optimization (Yiqing et al., 2007) are some examples of stochastic optimization algorithms which have been used to solve MINLPs. Section 4.5 solves the optimization model by using a stochastic global search algorithm i.e. genetic algorithm implementation in global optimization toolbox in MATLAB (Mathworks, 2019). Genetic algorithm provides a faster solution for this formulation as compared to the exact algorithm, however, it has its own pros and cons which are discussed in the subsequent sections.

4.4. Local Optimization Algorithm – Brand and Bound

A numerical example is presented in this section. A hypothetical network with pedestrian origins and destinations is shown in Figure 4.3. Figure 4.4 and Figure 4.5 show phasing scheme for all main intersections and midblock intersections in the network. A two phase scheme is adopted at all the main intersections and a concurrent phase is assumed for pedestrians as this happens to be the most common phasing scheme for pedestrians in the real world. Total travel time was minimized instead of average travel time. In order to avoid some technical difficulties, the average delays to right and left turning vehicles were computed using the Adams' delay model (Adams, 1936) instead of adjustment to saturation flow rates:

$$d_{L/R} = \frac{e^{-Nt}}{N} - \frac{1}{N} - t \qquad (21)$$

Where, N is the pedestrian volume in vehicles per hour, t is the minimum gap required to cross through the opposing traffic and $d_{L/R}$ is the average delay to find an adequate gap in the opposing traffic. It is to be noted that minimum required gap is different for right and left turning vehicles as right turning vehicles have to find a gap between opposing vehicular as well as pedestrian traffic. A minimum required gap of 11 seconds was used for right turning vehicles (Banerjee et al., 2004) and 7 seconds for left turning vehicles (Polus, 1983).

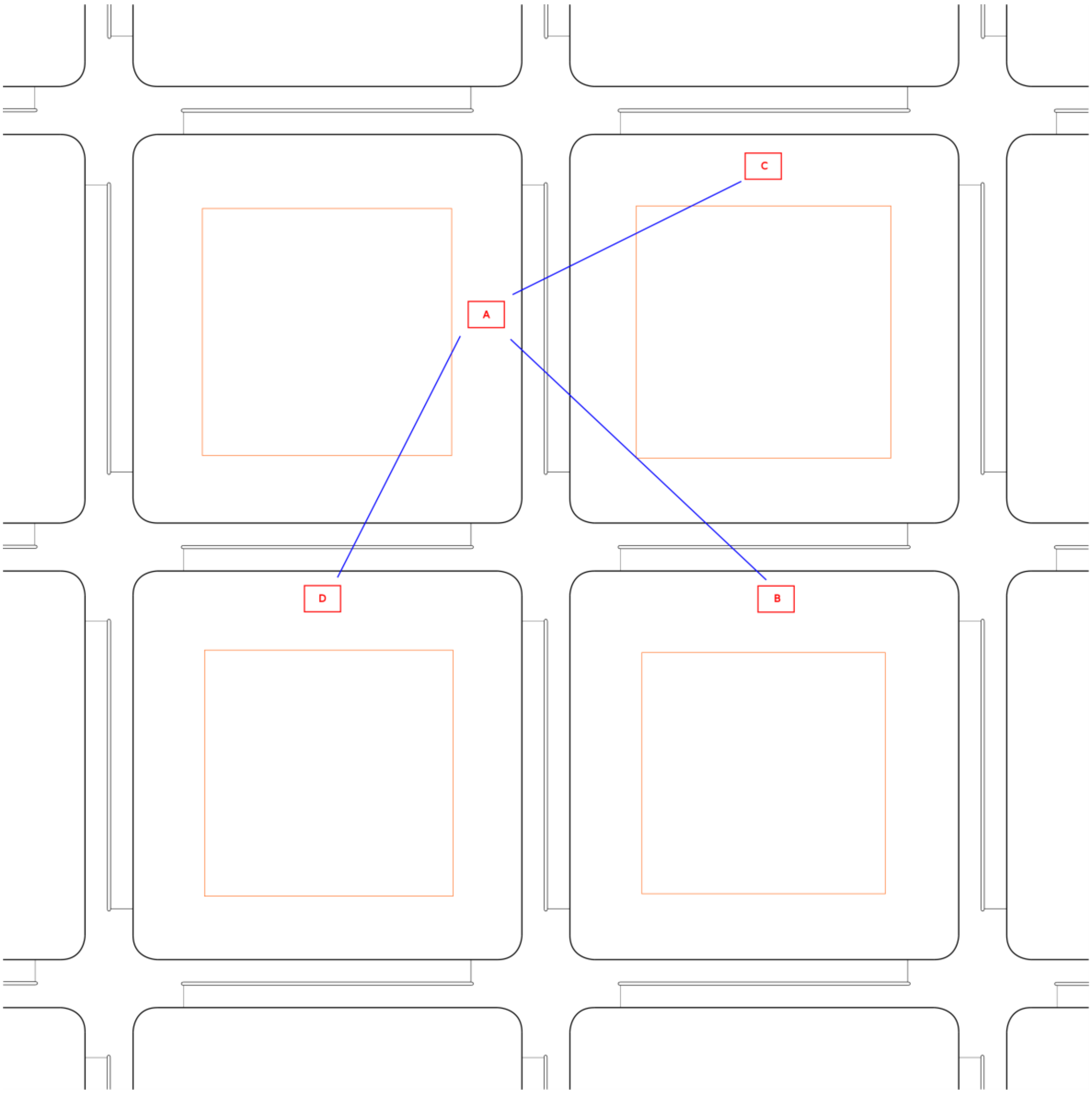


Figure 4.2: Hypothetical network layout for numerical example

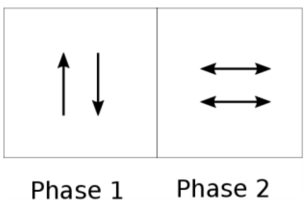


Figure 4.3: Phasing scheme for main intersections

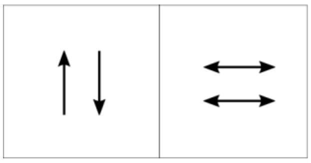


Figure 4.4: Phasing scheme for midblock intersections

Figure 4.6 shows a particular scenario with fixed bi-directional pedestrian demand of 900 pedestrians per hour between each origin and destination. Figure 4.7 shows how cycle length varies for various vehicle demand levels. The cycle length at lower vehicle volumes may be constrained by the minimum cycle length constraints. Whereas, maximum cycle length in the network decreased with increasing vehicular volume and then increased again at very high vehicle volumes. It is interesting to note that cycle length reduction can be achieved if pedestrian demand is properly distributed across the network.

Figure 4.8 and 4.9 show the solutions corresponding to vehicle demand of 700 vehicles per hour and 900 vehicles per hour at all approaches in the network. It can be seen that only one phase contains pedestrian crosswalk at the middle intersection at higher vehicular demand while crosswalks exist during both phases at the middle intersection at lower vehicular demand level.

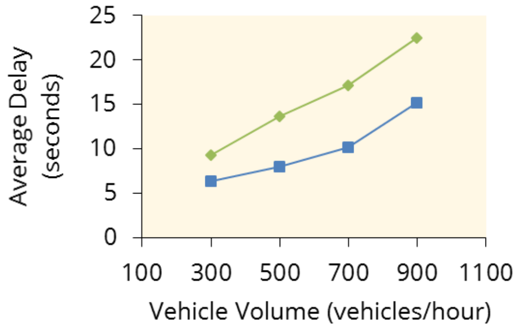


Figure 4.5: Average pedestrian and vehicle delay

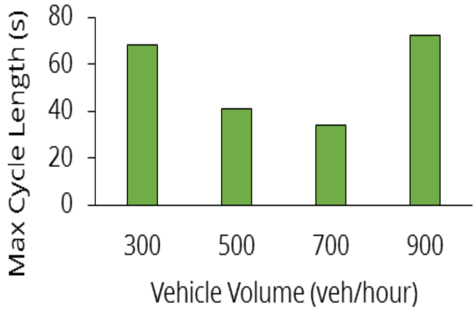


Figure 4.6: Maximum cycle lengths

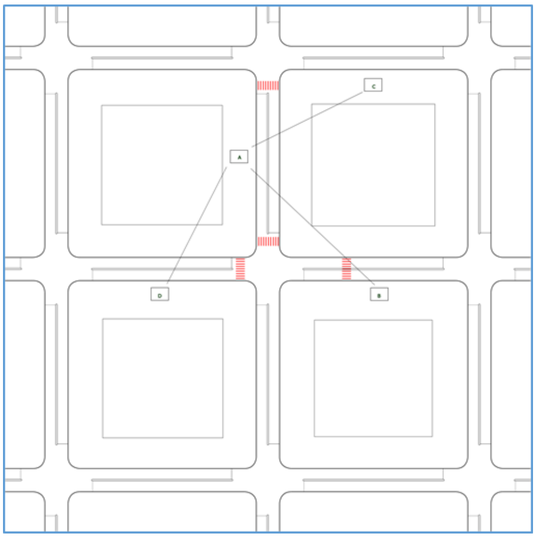


Figure 4.7: Optimized number and location of crosswalks for vehicle demand = 700 vehicles per hour at all approaches

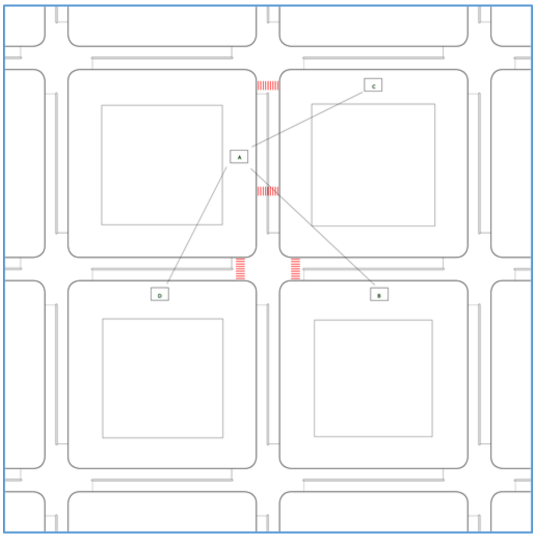


Figure 4.8: Optimized number and location of crosswalks for vehicle demand = 900 vehicles per hour at all approaches

In order to determine the general trend, the problem is solved for various vehicle and pedestrian demand as shown in Table 4.1. Signal and geometry related parameters are shown in Table 4.2.

Table 4.1: Vehicle and pedestrian demand scenarios

	Vehicle demand (vehs/hour/approach)	Pedestrian demand (peds/hour/crosswalk)
Levels	Total demand	Bidirectional Demand
1	300	100
2	500	300
3	700	600
4	900	900
5		1200
Turning Ratios		
Right	10%	
Left	10%	

Table 4.2: Signal and geometry related input parameters

Parameter	Value	Unit
Yellow time	3	seconds
All red time	1	seconds
Lanes on each approach	3	number
Lane width	3.5	meters
Walk time	4	seconds
Veh occupancy	1.7	
Progression adjustment factor	0.4	

Figure 4.10 shows how average vehicle travel time changes with change in vehicle and pedestrian demand. As expected, average vehicle delay increases with increase in vehicle demand. However, average vehicle travel time does not increase much with increase in pedestrian demand. It can be attributed to the fact that pedestrian demand is distributed to different locations so as to minimize the travel time for both vehicles and pedestrians.

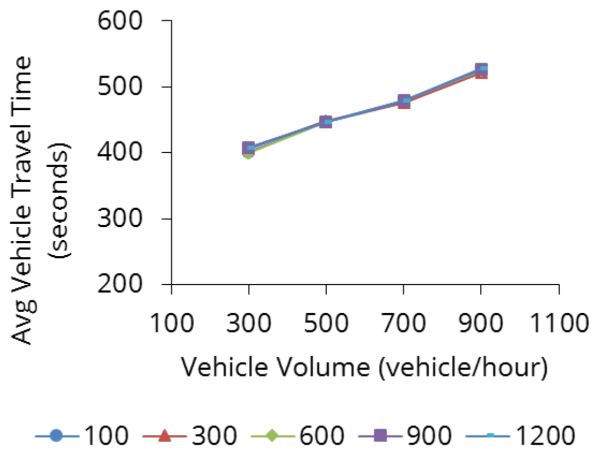


Figure 4.9: Average vehicle travel time vs vehicle and pedestrian volumes

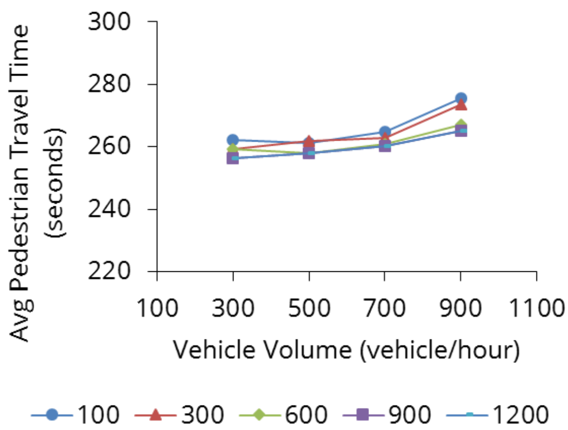


Figure 4.10: Average pedestrian travel time vs vehicle and pedestrian volumes

Figure 4.11 shows how average pedestrian travel time increases with vehicle and pedestrian demand. As expected, it increases with both vehicle and pedestrian demand.

Figure 4.12 and Figure 4.13 show the change in average vehicle and average pedestrian delays with respect to various vehicle and pedestrian demand levels.

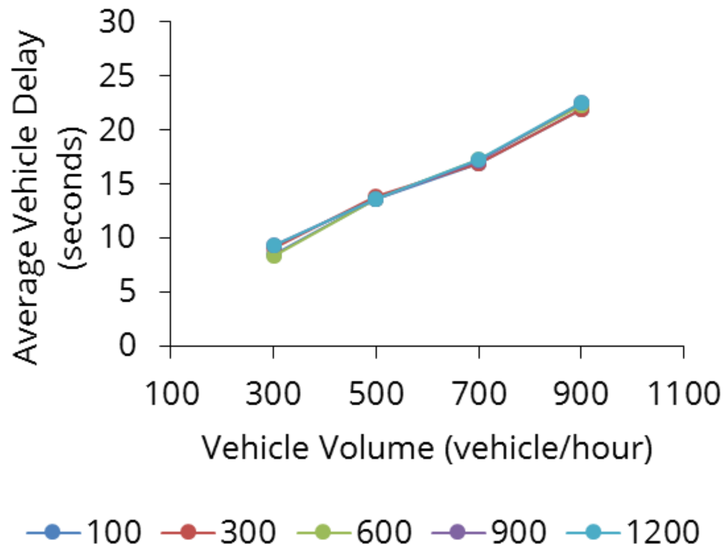


Figure 4.11: Average vehicle delay vs vehicle and pedestrian volumes

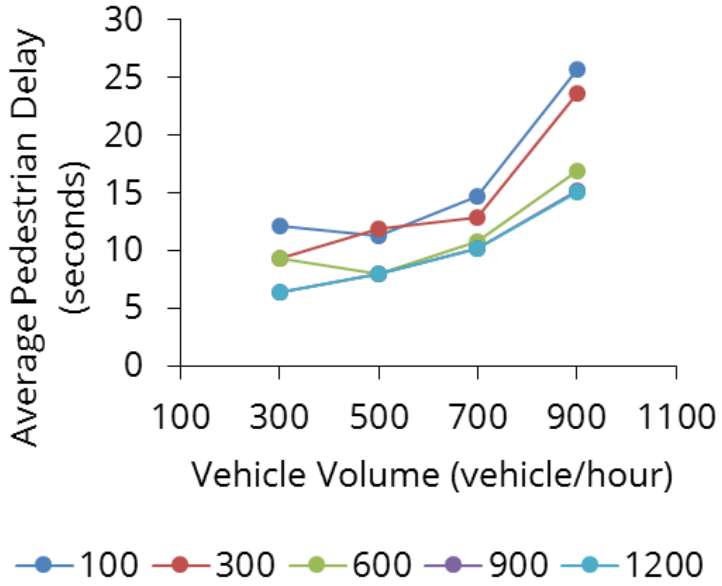


Figure 4.12: Average pedestrian delay vs vehicle and pedestrian volumes

As the performance of the brand and bound method was severely affected, therefore, it is not cost-effective to spend hours no solving a problem with exact algorithm when an approximate solution can be obtained in the vicinity of the global optimum in relatively shorter time using the stochastic global search algorithms. A stochastic global search algorithm may not provide a global optimum, however, it may give a good approximation to the global optimum in finite time which may serve the purpose from practical viewpoint.

4.5. Global Optimization Algorithm – Genetic Algorithm

The genetic algorithm implementation in the global optimization toolbox of MATLAB is used to solve the problem. Various combinations of population sizes and number of generations were tested. Finally, a population size of 300 and 1000 generations with a crossover rate of 0.8 and elite count of 5% of the population size were used. Default crossover and mutation functions are used. Constraints are in general satisfied at about 500 generations. In almost all the cases, the algorithm stopped when maximum generations reached. As genetic algorithm is a stochastic algorithm, therefore, it may provide different solutions when run multiple times. There are various ways to overcome this issue. In this study, 10 runs of genetic algorithm were carried out and the solution corresponding to the lowest objective value was selected as the best feasible solution. Constraint (9) is implemented as a conditional statement in the program.

A hypothetical network is shown in Figure 4.14. There are multiple ODs and multiple paths between each OD. Pedestrian path sets between each set generated by assuming a possible midblock crosswalk at each link. The path sets are manually generated for this relatively small sized network by avoiding paths that contain loops. The results for two scenarios are shown in the next subsections.

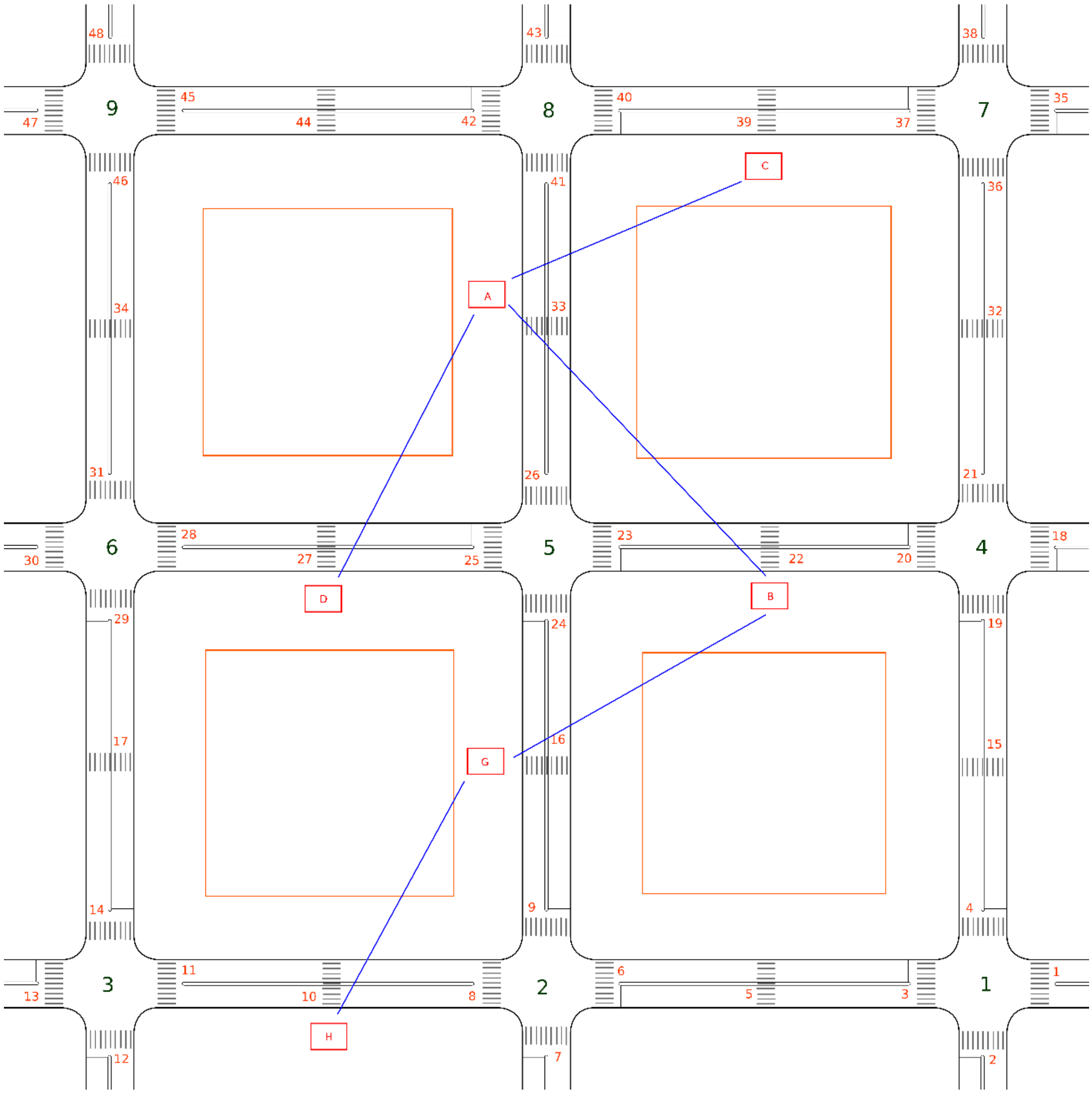


Figure 4.13: Layout of the network with pedestrian ODs

Scenario 1: veh = 500, ped = 400

The optimization problem was solved for vehicle volume of 500 vehicles per hour on each approach at all intersections and pedestrian volume of 400 pedestrians per hour between each OD. The results of each run are shown in Figure 4.15. The lowest performance index of 787 hours is obtained in Run 3 and the corresponding solution is shown in Figure 4.16.

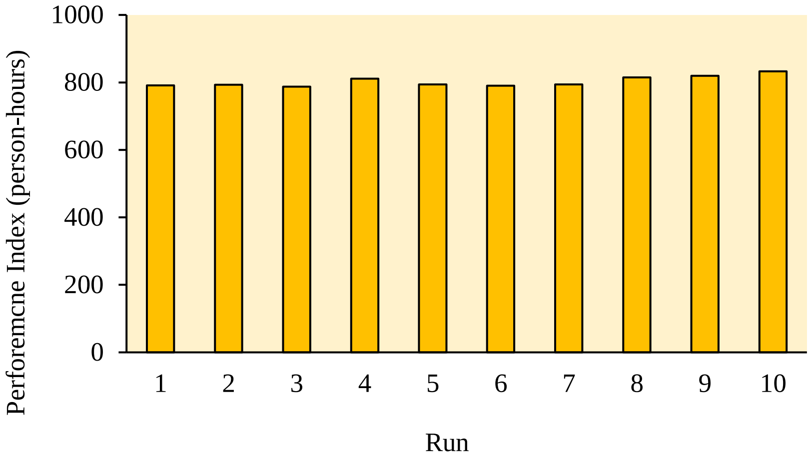


Figure 4.15: Performance indices for various runs of genetic algorithm - Scenario 1

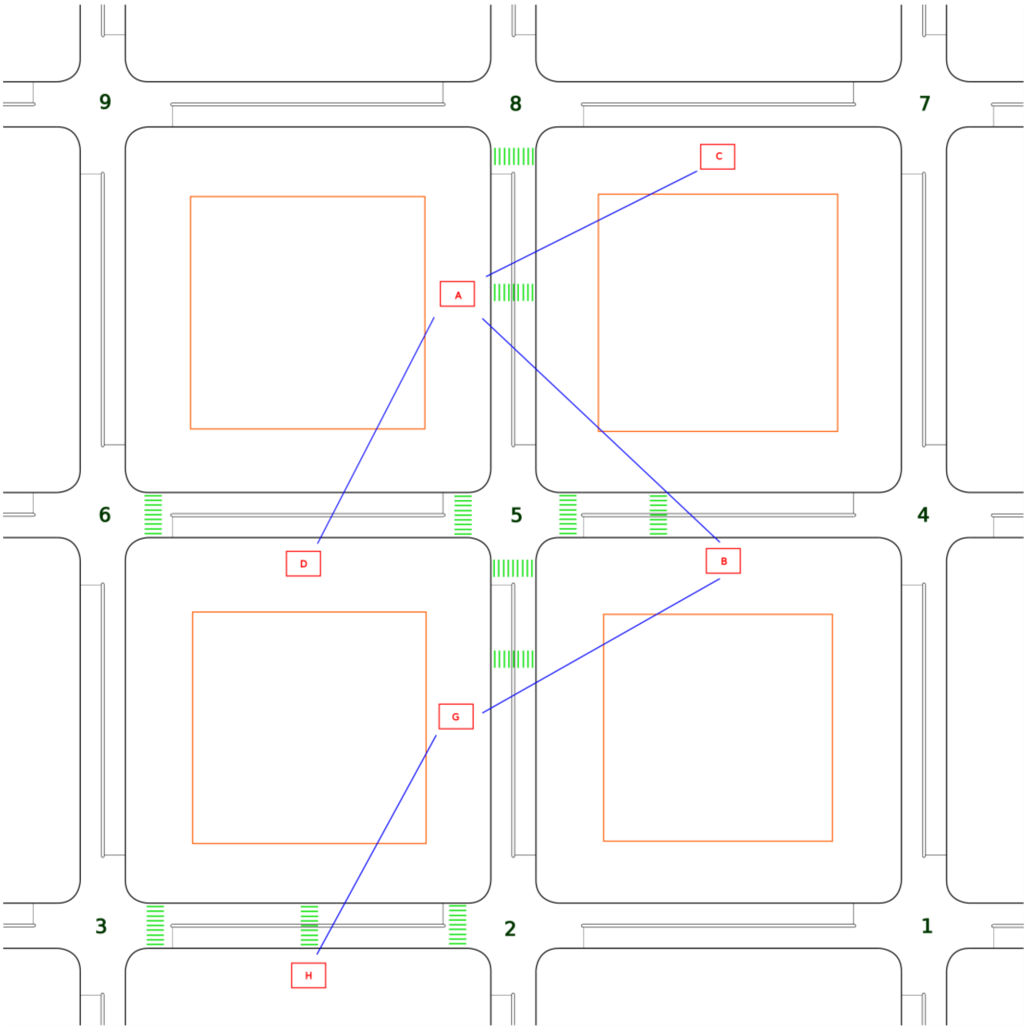
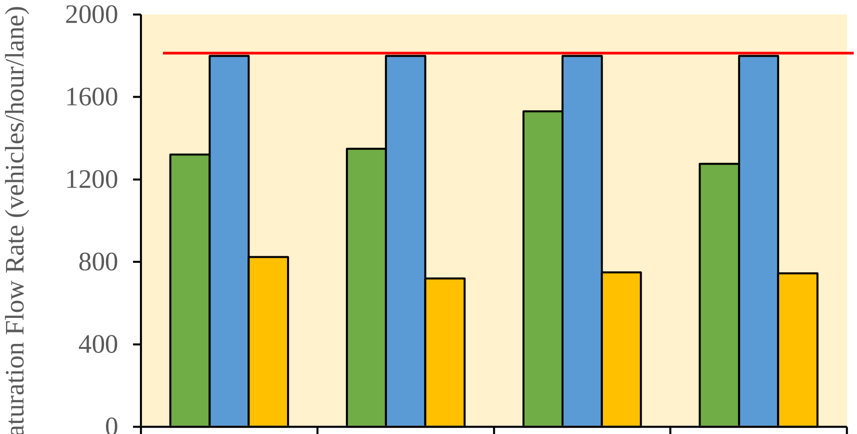


Figure 4.16: Optimized crossing facilities in the network - Scenario 1

For the given pedestrian demand, it can be seen in Figure 4.16 that both intersection crosswalks and midblock crosswalks exist. The existence of midblock crosswalks distributes the pedestrian demand to multiple locations thereby reducing the impact on the saturation flow rates of turning vehicles at the intersections. Since demand is distributed around intersection 5 in this example, saturation flow rates of all approaches are shown in Figure 4.17. The saturation flow rates for the right turning vehicles are the lowest because of the presence of opposing vehicles as well as pedestrians.



	approach 1	approach 2	approach 3	approach 4
left	1321	1349	1530	1275
through	1800	1800	1800	1800
right	823	719	749	744

Figure 4.17: Saturation flow rates at all the lanes of intersection 5 - Scenario 1

Figure 4.18 shows cycle lengths at all the main-intersections for scenario 1. There is some variation among cycle lengths at different intersections. The intersections with shorter cycle lengths may be operated at multiple cycles for coordination purposes. As the solution algorithm is stochastic in nature and provides only an approximation to the global optimum, cycle lengths are also likely to be just an approximation to optimal cycle lengths.

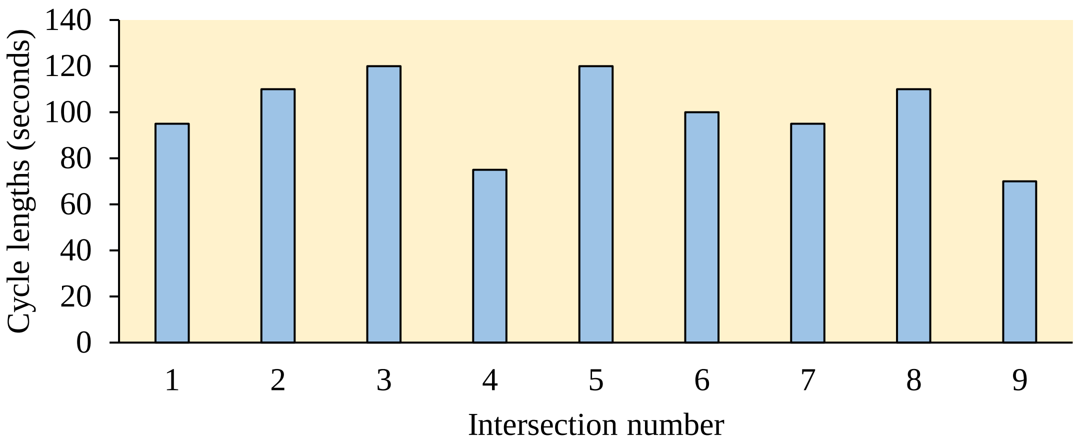


Figure 4.18: Cycle lengths at all the main-intersections in the network - Scenario 1

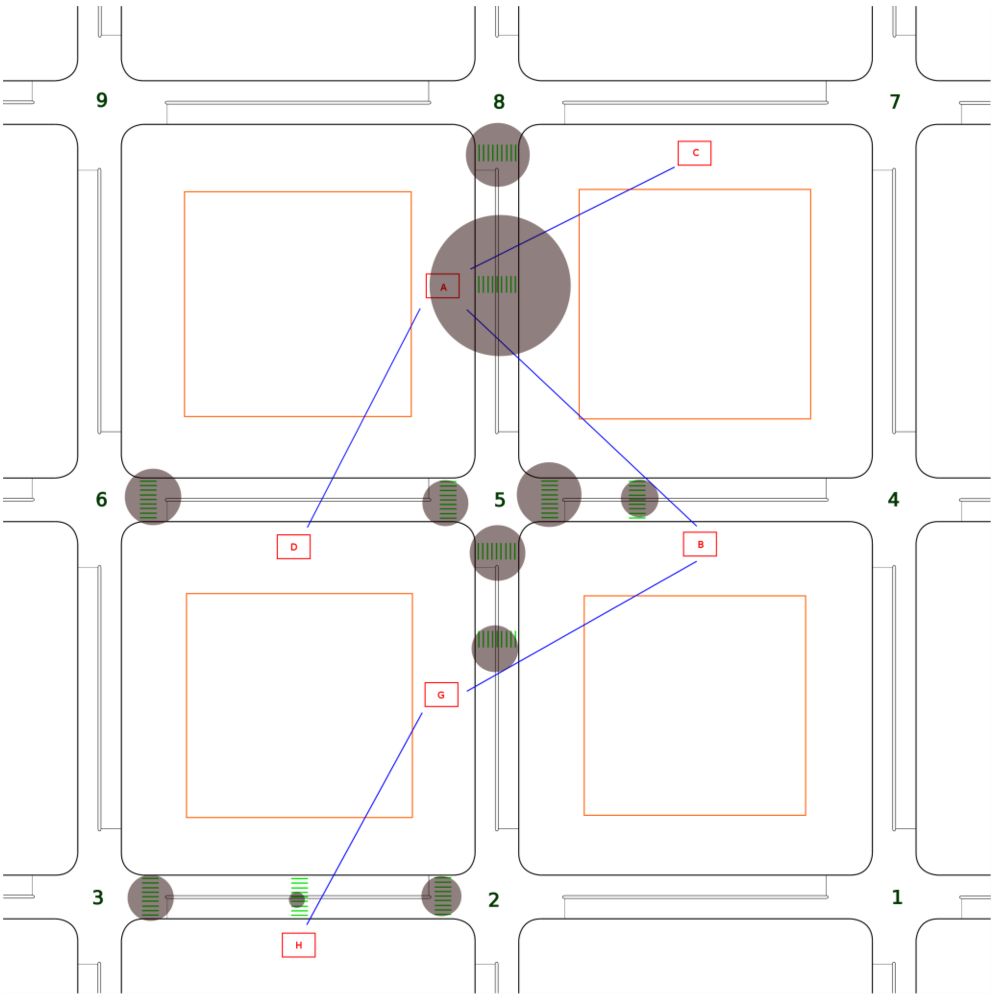


Figure 4.19: Pedestrian demand distribution across the network

Figure 4.19 shows how pedestrian demand is distributed across the network. The size of each circle represent the pedestrian demand at a particular crosswalk. Pedestrian demand is distributed across the network along both midblock and intersection crosswalks so that the pedestrian concentration can be reduced at a particular location. As soon as pedestrian presence starts decreasing the capacity of turning movements at the intersections, additional crosswalks are needed at midblock locations to divert the pedestrian demand and increase the capacity.

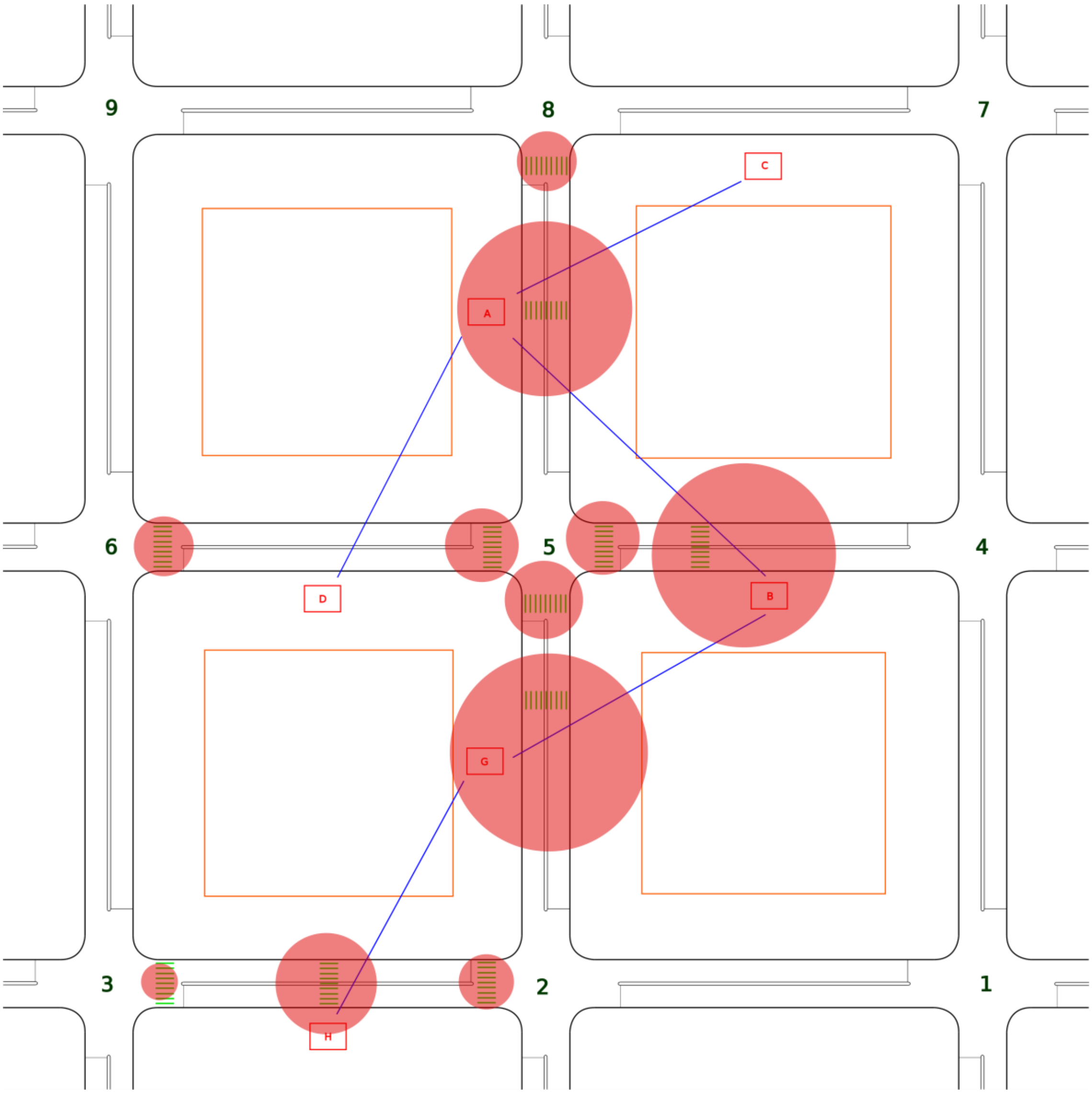


Figure 4.20: Pedestrian delay distribution across the network

Figure 4.20 shows pedestrian delay at each crosswalk. The size of each circle represent the pedestrian delay at a particular crosswalk. The larger the circle the higher the pedestrian delay at a crosswalk.

Scenario 2: veh = 500, ped = 1600

The optimization problem was solved for vehicle volume of 500 vehicles per hour on each approach at all intersections and pedestrian volume of 1600 pedestrians per hour between each OD. The results of each run are shown in Figure 4.21. The lowest performance index of 1794 hours was obtained in Run 3 and the corresponding result is shown in Figure 4.22.

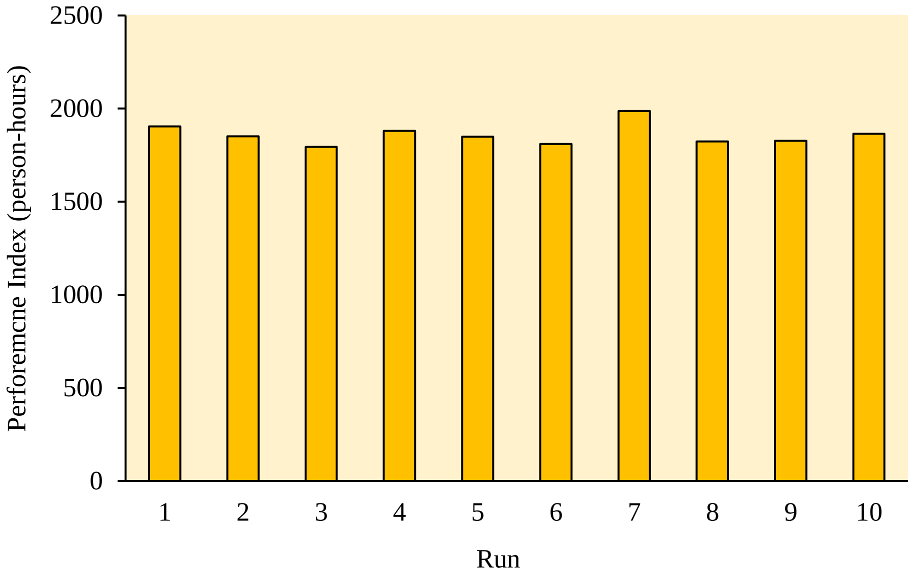


Figure 4.21: Performance indices for various runs of genetic algorithm - Scenario 2

As pedestrians are assigned under system optimal principle, therefore, some pedestrians are going to face longer travel times as compared to others. For example, the crosswalk at intersection 6 is the optimized location of crosswalk for OD pair AD while it is far from D.

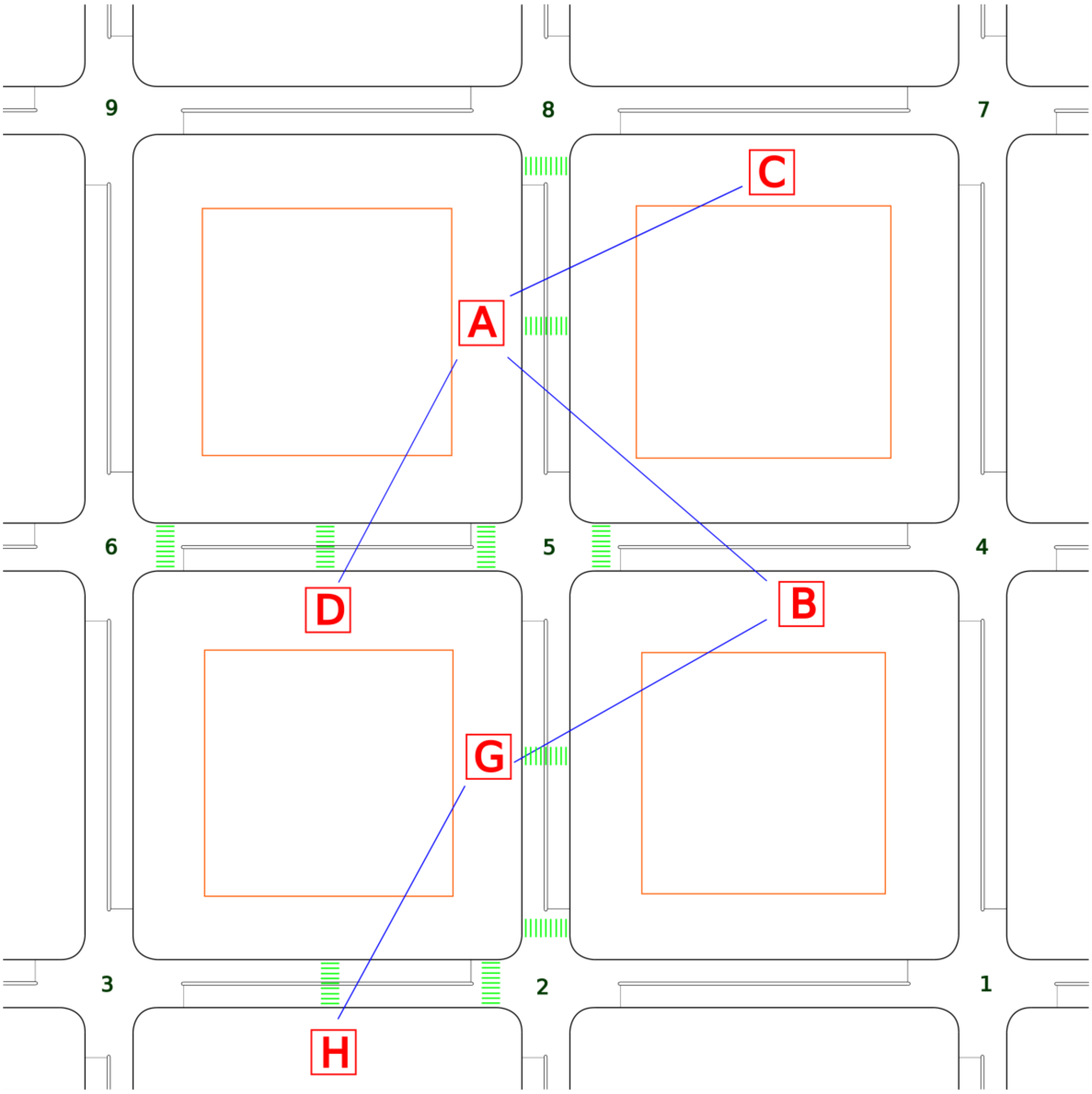


Figure 4.22: Optimal crossing facilities for the example network - Scenario 2

The saturation flow rates of all approaches at intersection 5 are shown in Figure 4.23. The removal of crosswalk from two approaches of the intersection 5 keeps the intersection undersaturated. Otherwise, the turning vehicles saturation flow rates would be reduced to such an extent that the queues may start growing and turning vehicles might not be able to clear during the green duration. Hence, this kind of solution where crosswalks can be removed from the intersection to keep an acceptable performance level is an important design consideration and its performance is evaluated in Chapter 6.

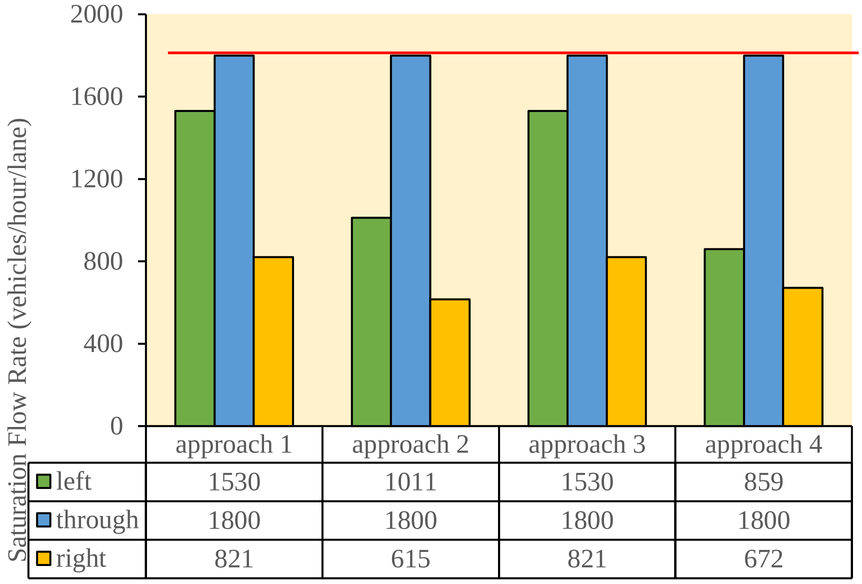


Figure 4.23: Saturation flow rates at all approaches of intersection 5 - Scenario 2

The cycle lengths for each intersection are shown in Figure 4.24.

Figure 4.24: Cycle lengths at all intersections in the network - Scenario 2

Figure 4.25 shows pedestrian demand distribution across the network and Figure 4.26 shows the pedestrian delay distribution across the network.

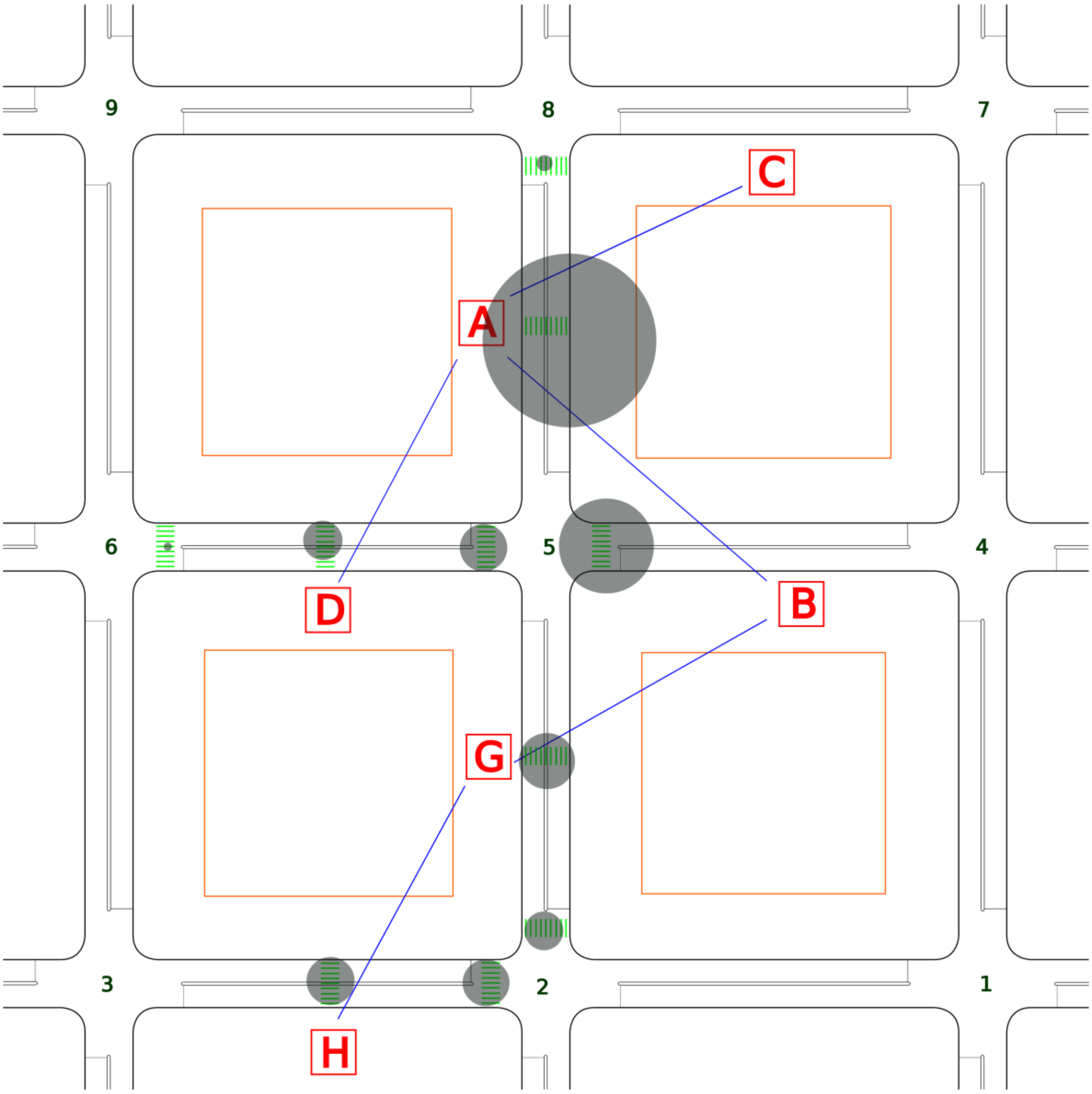


Figure 4.25: Pedestrian demand distribution across the network – Scenario 2

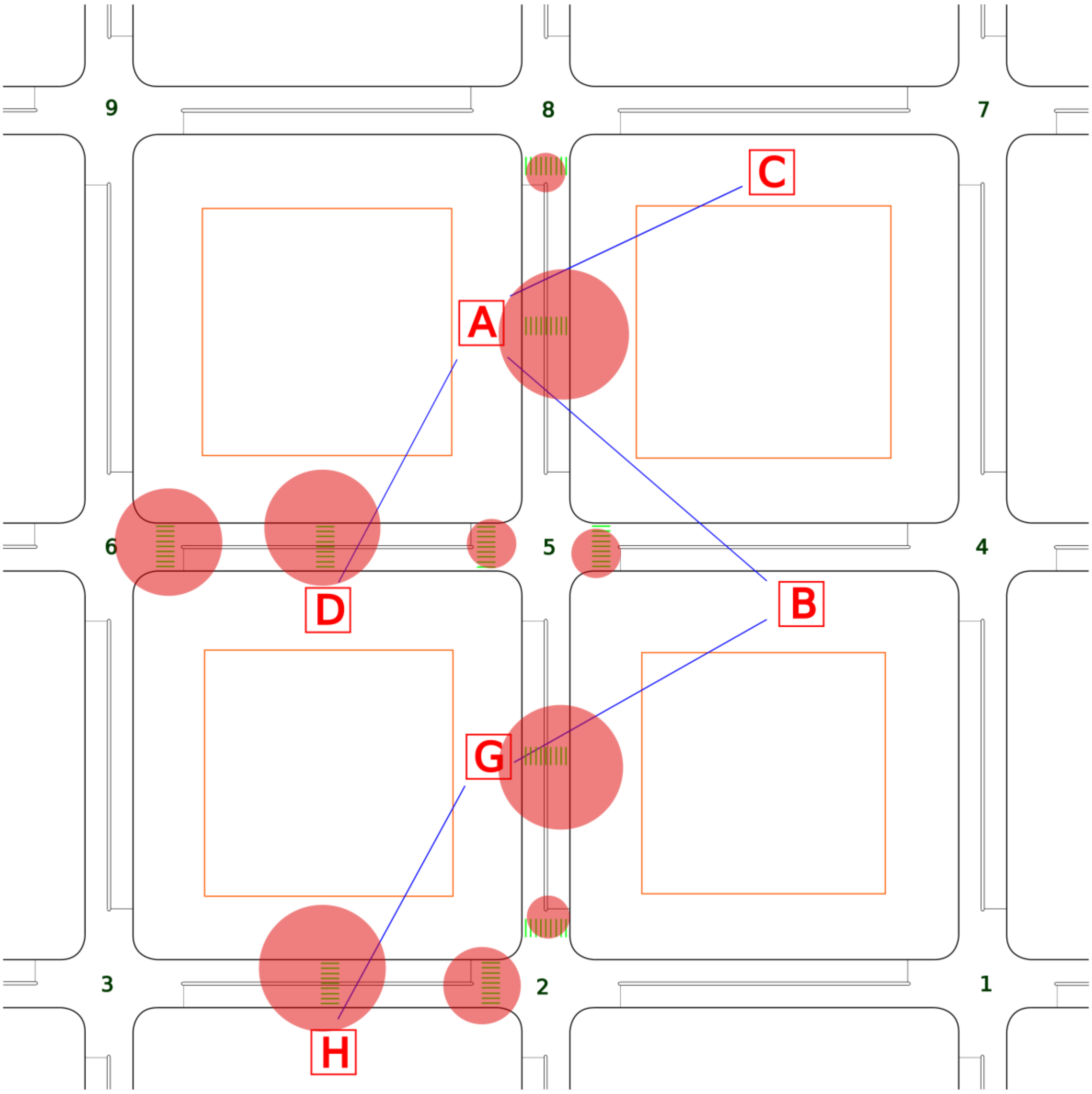


Figure 4.26: Pedestrian delay distribution across the network – Scenario 2

Finally, performance index was computed for various vehicle and pedestrian demand levels as shown in Table. Signal and geometric related parameters are same as those in Table 4.3.

Table 4.3: Vehicle and pedestrian demand scenarios

	Vehicle demand (vehs/hour/approach)	Pedestrian demand (peds/hour/crosswalk)
Levels	Total demand	Bidirectional Demand
1	400	400
2	500	800
3	600	1200
4	700	1600
Turning Ratios		
Right	20%	
Left	20%	

Figure 4.27 show the performance index for various vehicle and pedestrian volumes in the network. In general, performance index increases with vehicle and pedestrian volumes. The slight variations in the general increasing trend could be attributed to the stochastic nature of the solution algorithm. The probability of reaching the global optimum increases with each additional run of genetic algorithm. The solutions shown in Figure 27 were obtained after conducting 10 separate runs of genetic algorithm. Hence, there is a possibility that the global optimum was not reached. Nonetheless, the obtained solutions are expected to be good approximations to global optima.

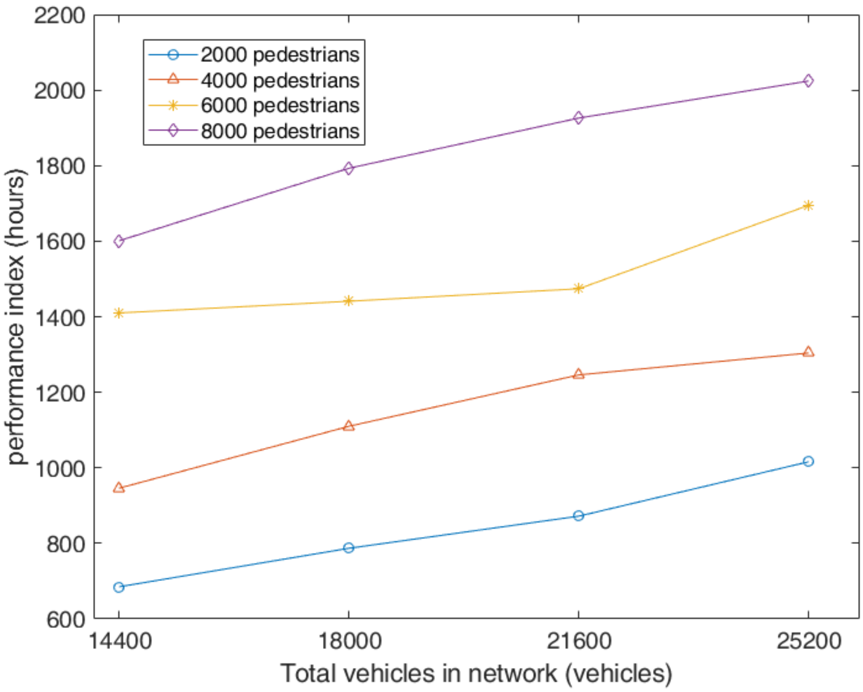


Figure 4.27: Performance index against various vehicle and pedestrian demand levels

The general trend of performance index against various total vehicle and pedestrian volumes in the network is shown in Figure 28.

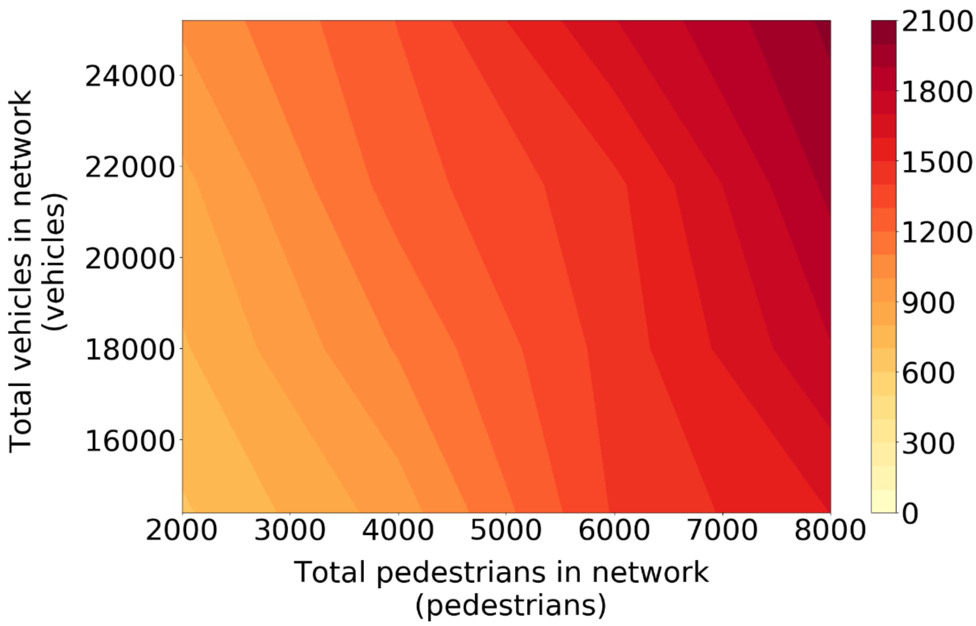


Figure 4.28: General trend of performance index against various vehicle and pedestrian demand levels

4.6. Summary

This chapter presents an optimization model to optimize the quantity, location and signal settings of crosswalks in a vehicle-pedestrian network. The formulated model was of mixed integer nonlinear type, which was solved using an exact local search algorithm and a stochastic global search algorithm. The performance of exact algorithm deteriorated with the number of binary variables. However, the heuristic global search algorithm gave satisfactory results within reasonable time. The optimization model works under system optimization principle for pedestrians. Hence, the model can be useful for planning purposes.

By distributing pedestrian demand across the network by optimizing the crossing facilities, certain advantages can be achieved. For instance, shorter cycle lengths are possible at the intersections. In addition, delay to turning vehicles can be reduced if a portion of pedestrian demand is diverted to midblock crosswalks. Moreover, special treatments such as exclusive pedestrian phase at the intersections may not be required if conflicts between turning vehicles and pedestrians are reduced.

The optimization model proposed in this chapter assigns pedestrians under the system optimal principle, therefore, it provides the lower bound and an appropriate reference for the model proposed in the next chapter.

Chapter 5

Network Design with Pedestrian Route Choice Behavior

The network optimization problem formulated in the previous chapter assigns pedestrian volume under the system optimum principle. Some pedestrians may end up incurring higher travel times as compared to others. Also, pedestrians may behave differently in reality. Therefore, the model is more appropriate for planning purposes, where only those pedestrian paths are provided/upgraded which are obtained as an output from the optimization problem so that a system optimum can be achieved.

However, pedestrian generally choose paths according to certain factors. Such pedestrian route choice behavior have extensively been modelled in the past. Discrete choice models can used to model pedestrian route choice behavior. This chapters integrates pedestrian route choice behavior into the network design problem.

As pedestrian route choice process requires path set generation. Therefore, the approach developed in this chapter differs from the one proposed in the previous chapter. Pedestrian path sets are generated as an initial step from the pedestrian network and the optimization process is then carried out as a subsequent step. Crosswalk position variable is removed from the optimization problem and integrated into the first step by generating paths through multiple possible crosswalks along a link located at short distances. The optimal paths are then determined by solving the optimization problem in the second step.

5.1. Integrated Approach

The proposed approach carries out the optimization in two separate steps as shown in Figure 5.1.

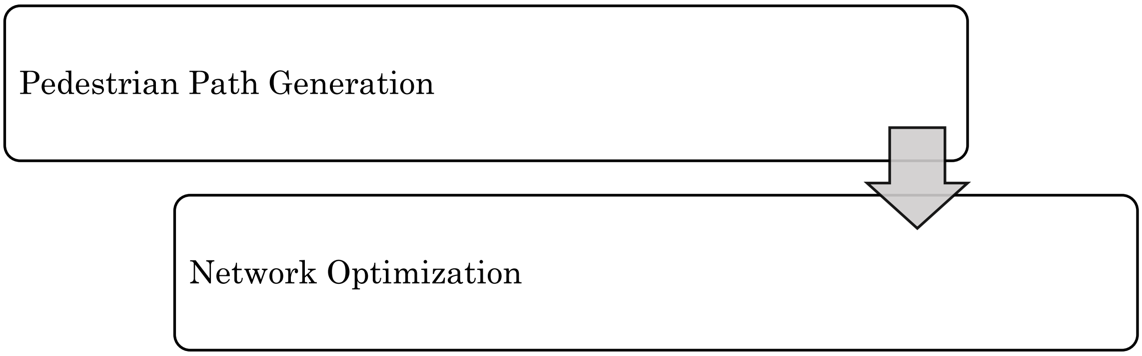


Figure 5.1: Outline of integrated approach

The steps involved in the approach are explained in the following sections.

5.1.1 Pedestrian Paths Generation

The pedestrian network is converted into a graph with edges and nodes as shown in Figure 5.2. The red dots are the nodes marked at the ends of crosswalks and blue lines are the edges between the nodes.

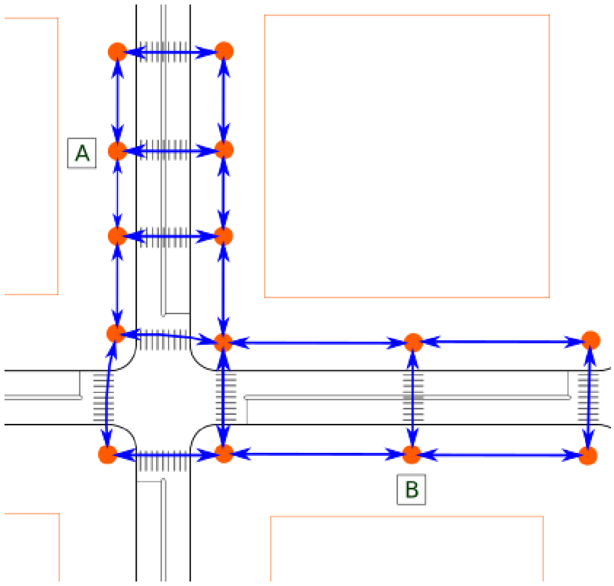


Figure 5.2: Pedestrian network represented as a graph

Yen's algorithm is employed to find the shortest path between any origin and destination nodes (Yen, 1971). There are several advantages of using Yen's algorithm. It avoids paths that include loops. It cannot deal with negative weights. Nonetheless it does not affect our problem as there are no negative weights. The weights of the edges are the pedestrian walk time along those edges. The edges representing crosswalks are assigned weights of zero. While the nodes which are not connected are assigned an edge value of infinity in the network cost matrix.

As the location of the midblock is not fixed beforehand, the links are divided into several segments and hypothetical midblock crosswalks are placed at equal distances. The shortest path algorithm can find k shortest paths which may involve more than one midblock crosswalks located close to each other, however, the number of midblock crosswalks along a link can be constrained via the subsequent optimization problem.

It should be noted that signal settings are not known when shortest paths are found, therefore, only pedestrian walk times are used in the network cost matrix and the same are used to find the shortest paths.

5.1.2. Yen's Shortest Path Algorithm

Yen's algorithm finds loopless k shortest paths between an OD pair. It uses a standard shortest path algorithm such as Dijkstra's algorithm (Dijkstra, 1959) and then moves to find k-1 deviations of the shortest paths. It does not support negative weights.

5.1.3. Network Optimization

The network optimization model proposed in Chapter 4 is used here with some modifications.

As pedestrians do not always have perfect knowledge about travel time along all links. Therefore, pedestrians may choose some paths which are longer than the shortest path. Hence, this uncertainty about route choice should be taken into account. Pedestrian route choice model is, therefore, adopted to assign pedestrian volume to various paths. Although there are several factors which affect pedestrian travel time, shortest path have been the most important factor for pedestrians when choosing a route. Therefore, only travel time is considered as a factor in the route choice model used in this study. A logit model with travel time as the sole factor while choosing a path is used as a route choice model.

The formulation is presented below:

The same notations are adopted which were used in Chapter 4.

Pedestrian delay along a crosswalk is computed as follows (Virkler, 1998):

$$d_c^p = [C - (g + 0.69A)]^2/2C \tag{1}$$

The following model is used to compute the delay for those pedestrians who undertaking diagonal crossing:

$$d_{diag} = \frac{(C - g_i)\left(g_i - {}^{L}/_{v_s}\right) + 0.5\left(g_i - {}^{L}/_{v_s}\right)}{C} \tag{2}$$

Pedestrian walk time along a path is obtained from the path generation step in this approach and is denoted as $w'_{rsk_{rs}}$.

Pedestrian walk time along a path that exists is computed as:

$$w_{rsk_{rs}} = x_{rsk_{rs}} \times w'_{rsk_{rs}} \qquad for\ \ \forall(r,s) \in RS, \forall k_{rs} \in K_{rs} \tag{3}$$

Pedestrian delay along a path is given as:

$$d_{k_{rs}}^p = x_{rsk_{rs}} \times a_c^{k_{rs}} \times d_c^p \tag{4}$$

Then pedestrian travel time along a path can be computed as:

$$t_{k_{rs}}^p = w_{rsk_{rs}} + d_{k_{rs}}^p \tag{5}$$

The probability of a pedestrian choosing a path is given using a logit model as follows:

$$P(k_{rs}) = x_{rsk_{rs}} \times \frac{e^{\left(-t_{k_{rs}}^{p}\right)}}{\sum_{k_{rs} \in K_{rs}} e^{\left(-t_{k_{rs}}^{p}\right)}} \qquad for\ \ \forall (r,s) \in RS, \forall k_{rs} \in K_{rs} \tag{6}$$

Where, P_{krs}^{rs} is the probability of choosing path krs between OD rs and t_{krs}^{p} is the travel time on path krs between OD pair rs.

After obtaining probabilities of path selection, pedestrian volume along a path can be determined as follows:

$$v_{k_{rs}}^{p} = x_{rsk_{rs}} \times a_{c}^{k_{rs}} \times P(k_{rs}) \qquad for\ \ \forall c \in C, \forall (r,s) \in RS, \forall k_{rs} \in K_{rs} \tag{7}$$

Further, pedestrian volume at a crosswalk can be computed as follows:

$$v_{c}^{p} = x_{rsk_{rs}} \times a_{c}^{k_{rs}} \times v_{k_{rs}}^{p} \qquad for\ \ \forall c \in C, \forall (r,s) \in RS, \forall k_{rs} \in K_{rs} \tag{8}$$

Now, demand weighted pedestrian delay in the network can be given as follows:

$$D_p = \sum_{c=1}^{C} d_c^p v_c^p \,/ \sum_{c=1}^{C} v_c^p \tag{9}$$

And demand weighted pedestrian walk time along a path can be given as:

$$W_p = \sum_{(r,s) \in RS} \sum_{k_{rs} \in K_{rs}} \left(x_{rsk_{rs}} w_{k_{rs}} v_{k_{rs}}^{p}\right) / \sum_{k_{rs} \in K_{rs}} \left(v_{k_{rs}}^{p}\right) \tag{10}$$

Finally, pedestrian travel time in the network can be given as follows:

$$T_p = D_p + W_p \tag{11}$$

Vehicular travel time, signal settings and the objective function are computed using the same formulation as those given in Chapter 4. Hence, they are not repeated here. Several constraints are also needed to make sure that crosswalks do not exist too close to each other.

5.2. Solution Algorithm

The formulated problem was of the mixed integer nonlinear program. Therefore, a stochastic global search heuristic (genetic algorithm) was used to solve the problem in finite time and to obtain satisfactory solutions.

5.3. Results and Discussion

A network similar to the one in Chapter 4 is evaluated using the integrated model. Path sets between each OD are generated using Yen's algorithm. Although, Yen's algorithm provides loopless paths, however, some unreasonable paths are still generated from practical viewpoint. Hence, those paths were removed before conducting the optimization. The input parameters were the same as those adopted in Chapter 4.

The performance index was evaluated for vehicle volume of 400 vehicles per hour on each approach and 1600 pedestrian per hour on each crosswalk. During the optimization pedestrians chose their paths based on the discrete choice models.

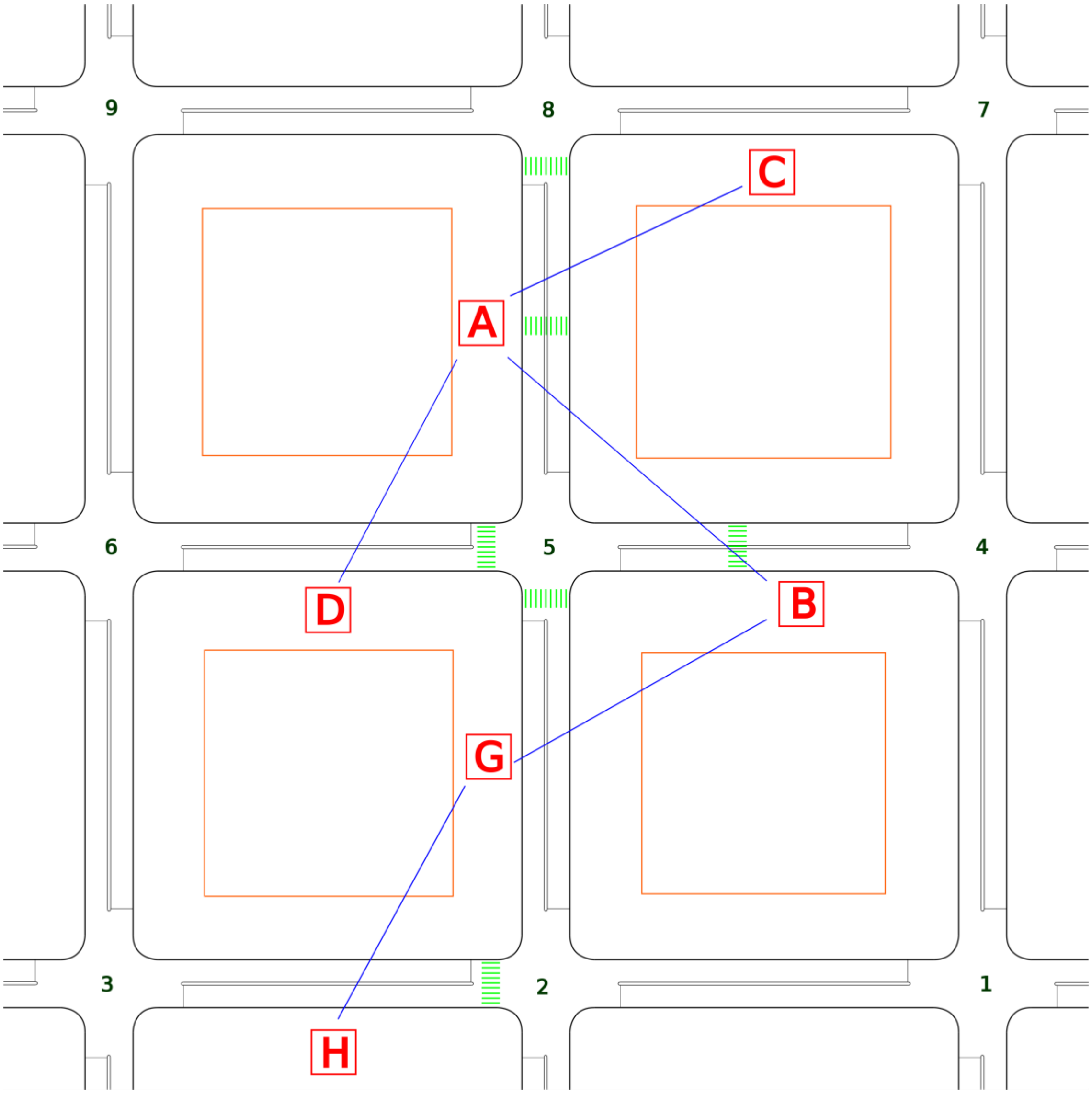


Figure 5.3: Output of the numerical example

Total aggregated travel time of 13241 hours in terms of persons was obtained as the minimum value. The optimized location and quantity of crosswalks is shown in Figure 5.3. It can be seen that based on the pedestrians' origin and destinations all crosswalks at intersections might not be need otherwise they may reduce turning vehicles saturation flow rates or cause severe vehicle-pedestrian conflicts. Figure 5.4 shows the pedestrian volume distribution across the network.

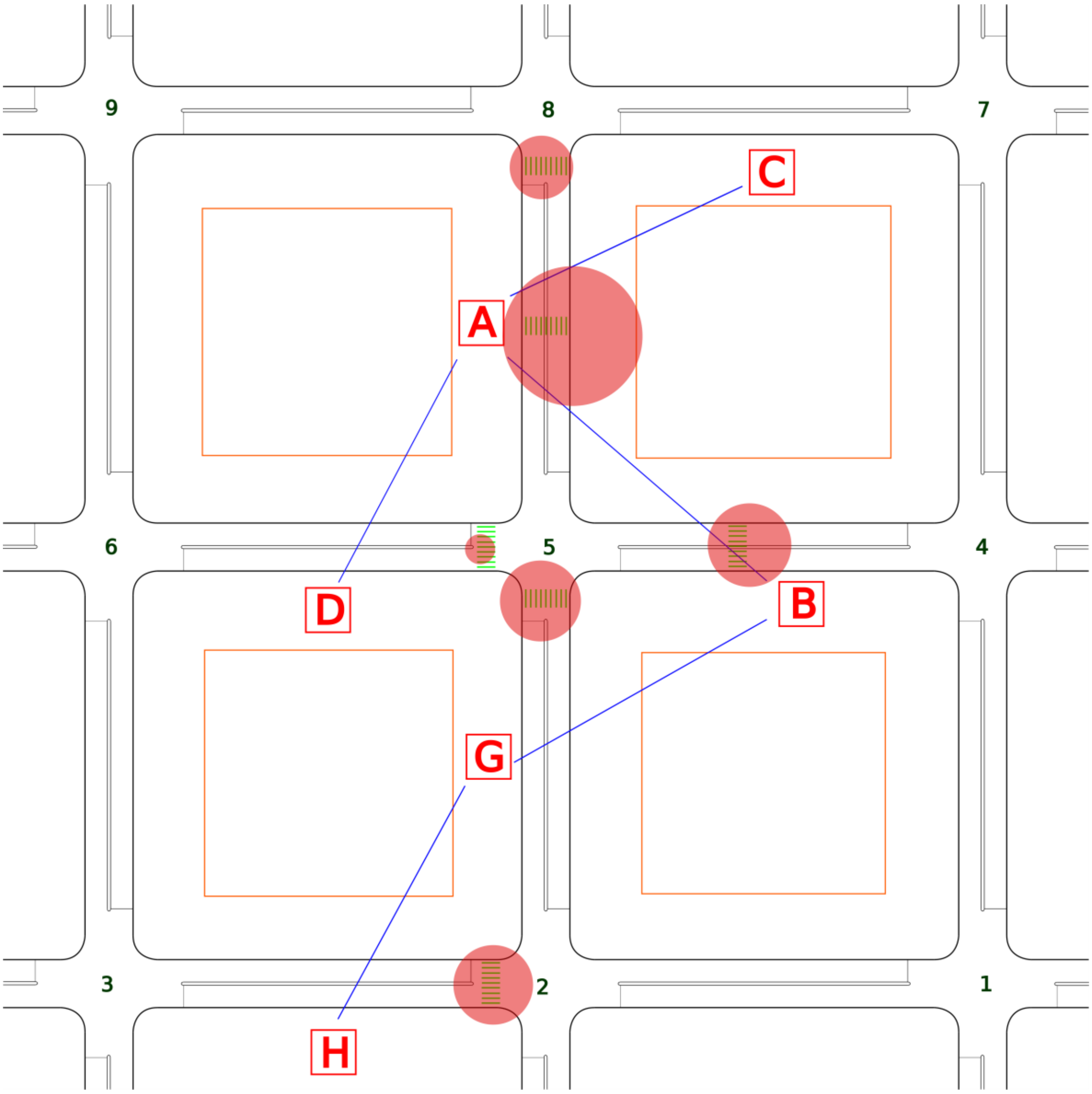
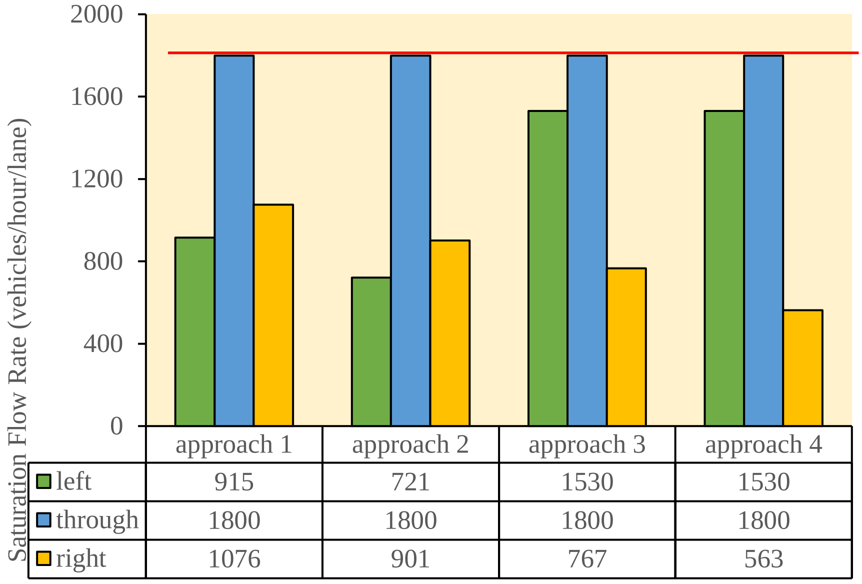


Figure 5.4: Pedestrian volume distribution across the network

The saturation flow rates at the middle intersection are affected due to the presence of crosswalks. Figure 5.5 shows how the saturation flow rate is impacted by the presence of crosswalks. The left saturation flow rate at approach 1 is not affected by pedestrians because there is no conflicting pedestrian volume due to the absence of a. crosswalk.



	approach 1	approach 2	approach 3	approach 4
left	915	721	1530	1530
through	1800	1800	1800	1800
right	1076	901	767	563

Figure 5.5: Saturation flow rates at all approaches of intersection 5

The optimized cycle lengths at all intersections are shown in Figure 5.6.

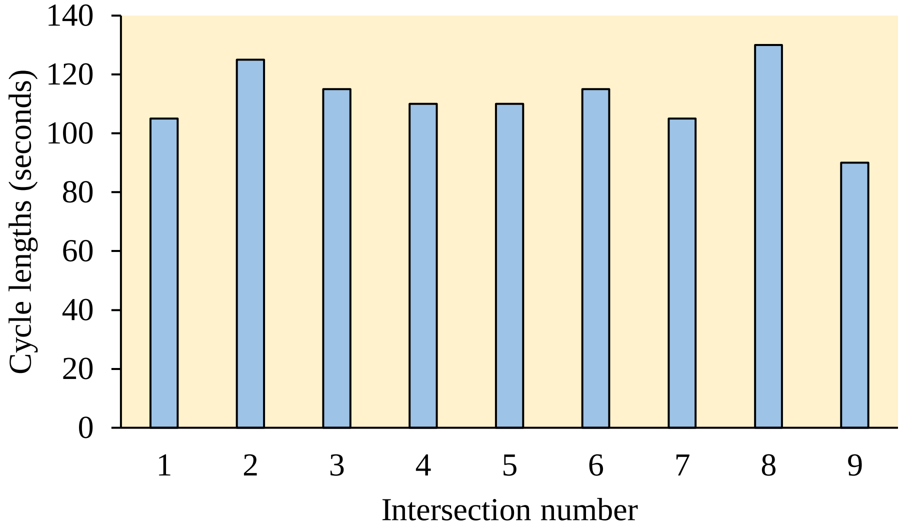


Figure 5.6: Optimized Cycle lengths at all main intersections

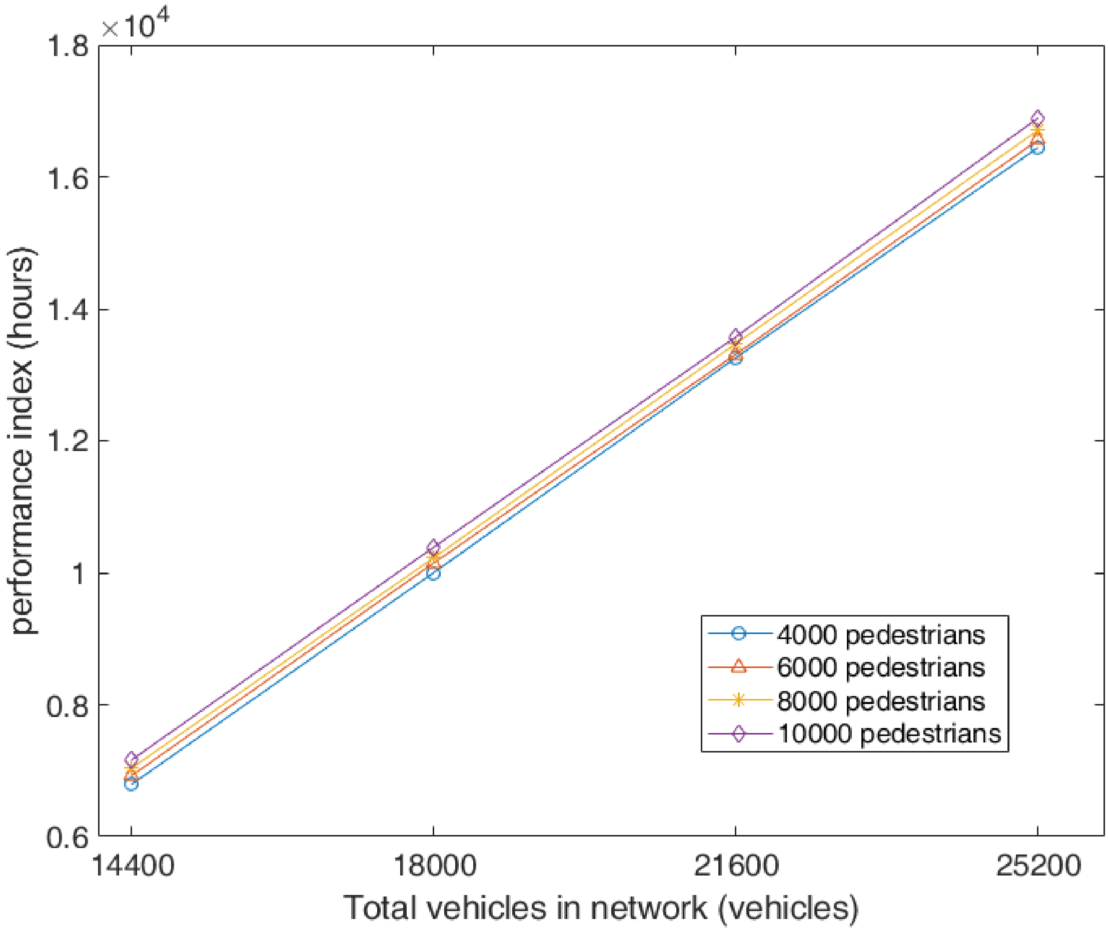


Figure 5.7: Performance indices for various vehicle and pedestrian volumes in the network

Performance index (the objective function value = total travel time in the network) was computed for various total vehicle and pedestrian volume levels in the network and the results are shown in Figure 5.7.

The general trend of performance index with respect to various vehicle and pedestrian volume levels in the network are shown in Figure 5.8.

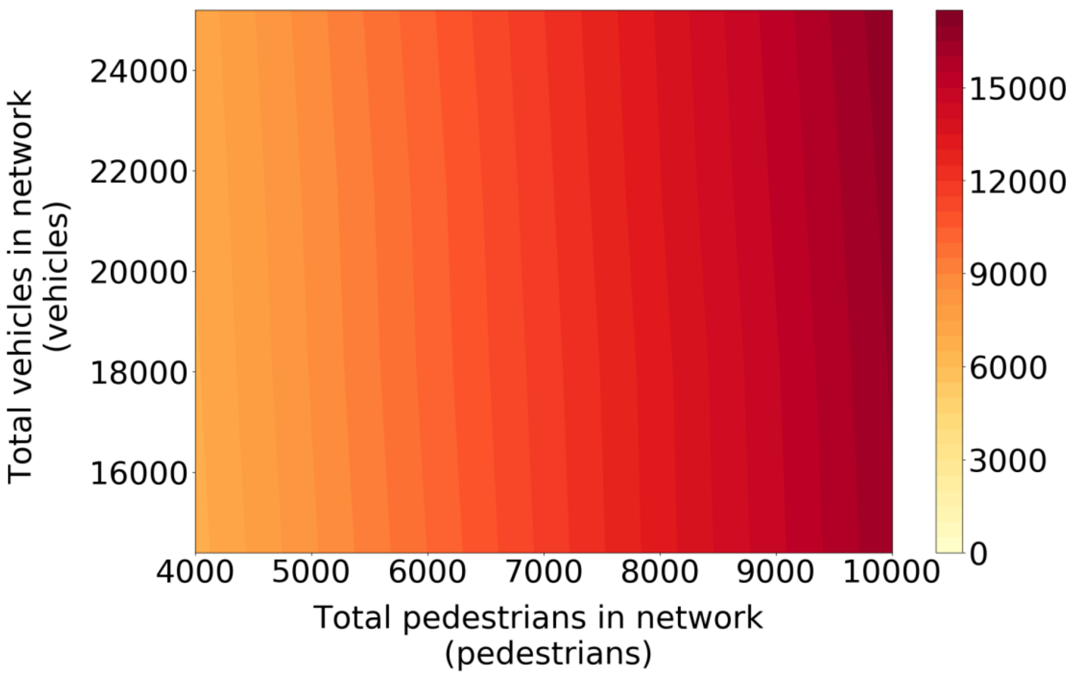
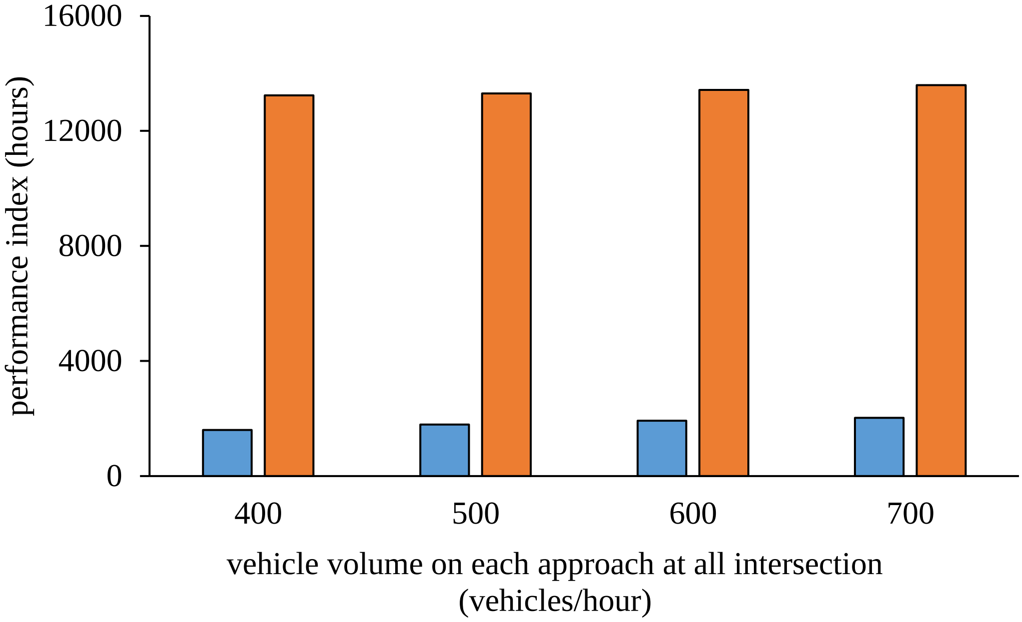


Figure 5.8: General trend of performance indices for various vehicle and pedestrian volumes in the network

5.4. Comparison with Network Design under Pure System Optimal Principle

The method proposed in Chapter 4 carries out network design under system optimal principle. Pedestrians are assigned so as to minimize the overall travel time for both vehicles and pedestrians. Therefore, some pedestrians end up incurring more travel times as compared to others. However, it provides the best possible solution from system viewpoint and it could be used as a reference to compare the solutions from other approaches where pedestrian behavior is taken into account. Such a comparison between the methodologies proposed in Chapter 4 and Chapter 5 is presented in Figure 5.9 (left and right turning ratio at each intersection is 20% of the total approach volume). As mentioned before, the approach proposed in Chapter 5 takes pedestrian behavior into account and thus causes higher performance indices.



network design - pure system optimal network design - pedestrian route choice

pedestrian volume = 1600 pedestrian per hour between each OD pair

Figure 5.9: Comparison between Chapter 4 and Chapter 5 approaches

5.5. Summary

An integrated optimization model was proposed in this chapter which took pedestrian route choice behavior into account. A numerical example was conducted by solving the integrated model. Genetic algorithm was used to solve the mixed integer nonlinear program. The results provided an insight into how pedestrians affect vehicular traffic at intersections and how the overall feasible solution can be achieved for both vehicles and pedestrians by optimizing the crosswalks quantity, location and signal settings. The approach proposed in this chapter includes pedestrian route choice behavior and therefore, the solutions obtained are worse as compared to the ones obtained through the approach proposed in Chapter 4. However, these solutions are realistic and practically achievable.

Chapter 6

Evaluation of Alternative Crossing Design for Critical Intersections

At busy intersections there are many conflicts between vehicles and pedestrians which often result in crashes. Pedestrians' presence also affect the saturation flow rates of turning vehicles during permissive phases. It is usually hard to balance the tradeoff between the efficiency and safety of vehicles and pedestrians. However, if an intersection happens to be a busy intersection with high percentage of turning vehicles and it so happens that pedestrians' origins and destinations are mostly located near midblock locations, a possible solution could be to remove the crosswalks from the intersections and place them at midblock locations. For instance, the numerical example in Chapter 4 resulted in a solution where the optimized crosswalk positions were located at midblock locations under the given OD pattern. If an intersection is a super busy intersection and pedestrians ODs are mostly located near midblock locations, this kind of solution may perform better from efficiency and safety viewpoint.

In this study, a critical intersection is defined as the intersection where turning vehicle volumes are high resulting in heavy conflicts with pedestrians and unnecessary delays for turning vehicles. Normally protected phases are provided at such busy intersections to avoid the conflicts between heavy turning volume and pedestrian traffic. However, such protected phases generally increase the number of phases at such intersections and consequently increase the waiting time for both vehicles and pedestrians.

Pedestrians start violating the traffic signals if waiting time is too long.

FHWA recommends providing midblock crosswalks nearby such busy intersections to divert the pedestrian demands to the midblock locations in order to reduce the conflicts at the busy intersections (FHWA, 2019). An empirical study evaluated such kind of design and came up with the conclusion that such design did not deteriorate the efficiency for vehicles (Chowdhury, 2014). Moreover, it provided safety benefits to both vehicles and pedestrians by reducing the conflicts at the busy intersection.

This kind of design has not achieved much attention in the literature. Therefore, there is a lack of a comprehensive performance evaluation of such alternative crossing design for critical intersections. This chapter aims to evaluate the alternative crossing design for critical intersections. It aims to determine the performance of the alternative crossing design against various vehicle and pedestrian demand levels. It also aims to compare the performance of traditional intersection with alternative crossing design. The output of this study provides the guidelines about the conditions under alternative crossing design should be implemented.

A macroscopic traffic simulation software TRANSYT15 is used to evaluate the performance. This software is used because of its vehicle and pedestrian modeling capabilities as well as its optimization capability.

6.1. Overview of Alternative Crossings Design

6.1.1. Safety and efficiency

The conflicts between turning vehicles and pedestrians are reduced if crosswalks are removed from the intersections. Pedestrians are supposed to cross at midblock locations where there are no turning vehicles and it is easier to see the oncoming vehicles.

6.1.2. Phasing schemes

Only two phases are needed at midblock locations because there are only two conflicting movements: vehicles on through lanes and pedestrians on the crosswalk. One phase is dedicated to the vehicles and the other to the pedestrians. As pedestrian demand is now distributed to different midblock locations, therefore, shorter cycle lengths are expected at midblock locations. If the common cycle length is long due to the protected phases at the critical intersection, the midblock crosswalks can be operated at multiples of common cycle length.

6.1.3. Signal coordination

Coordinating the midblock crosswalks with the adjacent intersections is very important otherwise the alternative crossing design will lose its advantages and it may perform even worse than the traditional intersection design.

6.2. Overview of Transyt15

Transyt15 consists of an optimization model and a traffic flow model. The traffic flow is modeled using a traffic flow model. TRANSYT15 uses platoon dispersion model (PTM) and cell transmission model (CTM) to model the traffic flow. The optimization process generates signal timings (both individual stage green times and offsets) for a network such that the objective function is minimized. The delays, stops and excess queues are converted into costs and summed over all the links to provide the overall cost of the network. The optimization model can be turned on and off. Moreover, the optimization process can be turned on for selected intersections. The decision variables could be offsets only or both individual stage green times and offsets. Cycle time is not considered as the part of the optimization process, however, a built-in tool "Cycle Time Optimizer" can be used to find the optimum cycle time.

The main default performance measure is a weighted combination of the delays and stops as well as the pedestrian delay in a network. The objective function (performance index) is shown below (TRL Software, 2015):

$$PI = \sum_{i=1}^{N_v} (W_v w_i d_i + (K/100) k_i s_i) + \sum_{j=1}^{N_p} \left(W_p w_j d_j\right)$$

Where,

N_v is the overall number of traffic streams and links

W_v is the overall cost per average PCU-hour of delay

K is the overall cost per 100 PCU-stops

w_i is the overall delay weighting on traffic stream (or link) i

d_i is the delay on traffic stream (or link) i

k_i is the overall stop weighting on traffic stream (or link) i

s_i is the number of stops on traffic stream (or link) i

N_p is the number of pedestrian crossing sides

W_p is the overall cost per average pedestrian-hour of delay

w_j is the delay weighting on pedestrian crossing side j

d_j is the pedestrian delay on crossing side j

There are three optimization techniques in TRANSYT15 namely Hill climb, shotgun hill climb and simulated annealing. Among these Hill climbing algorithm is the fastest while simulated annealing is the slowest but has the best performance (Department of Planning, Transport and Infrastructure, 2014). Hill climbing algorithm may not give the global optimum. TRANSYT15 uses a special way to leave local optima by using both large and small changes in the timings for each successive optimization of the signal. Shotgun hill climbing algorithm randomly generates initial signal timings and evaluate the performance index. As different initial conditions can result in different output, this technique can improve the overall optimization process.

6.3. Scenarios

Figure 6.1 shows an intersection with four phase signal phasing scheme. It is assumed to be a critical intersection with considerable turning movements. Protected phases are provided for turning vehicles so as to avoid interaction with opposing flows.

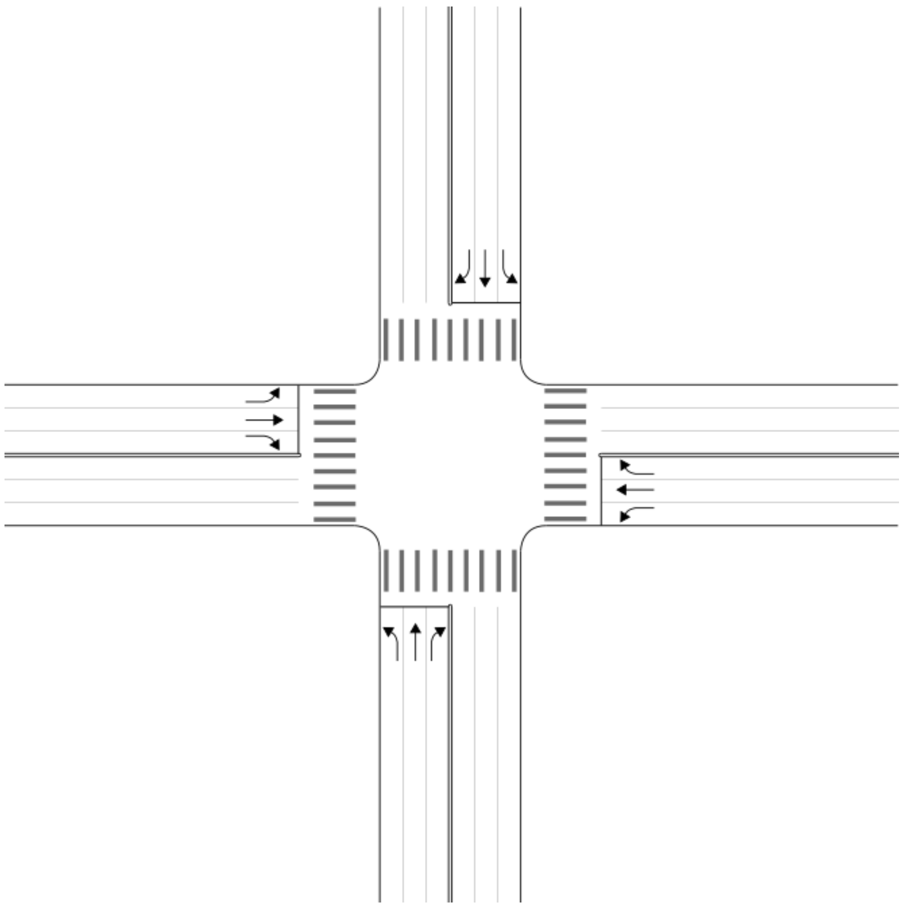


Figure 6.1: Layout of the intersection with crosswalks

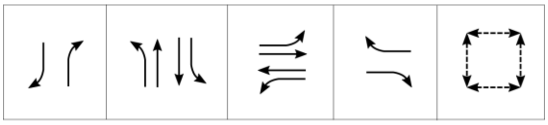


Figure 6.2: Phasing scheme 1 for intersection case

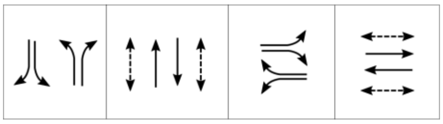


Figure 6.3: Phasing scheme 2 for intersection case

A phasing scheme for such an intersection is shown in Figure 6.2. Such kind of phasing scheme is applicable at busy intersections where turning volumes are high. Similar vehicle volumes are handled in the same phase to maximize the efficiency. Another phasing scheme for such intersection is shown in Figure 6.3 where right and left turning vehicles are allowed to move in the same phases while pedestrians are allowed to cross with parallel through traffic.

The alternative crossing design is shown in Figure 4. There are no crosswalks at the critical intersection. All the crosswalks are moved to the midblock location so as to avoid any conflicts between vehicles and pedestrians at the critical intersection. The phasing scheme for such an intersection and the crosswalks at midblock location are shown in Figure 5 and Figure 6, respectively.

Vehicle and pedestrian demand levels are shown in Table 6.2 and Table 6.3, respectively. Three different major/minor demand ratios were evaluated: 50%, 60% and 70%. Higher left and right turning ratios were evaluated i.e. 20%. The input parameters are shown in Table 6.1.

Table 6.1: Input parameters

Parameter	Value	Units
Yellow time	3	seconds
All red time	1	seconds
Lanes on each approach	3	number
Lane width	3.5	meters
Walk time	4	seconds
Delay cost	14.2	USD/person
Pedestrian clearance time	10	seconds
Additional buffer time for pedestrians	3	seconds
Vehicle speed	30	km/hour
Pedestrian speed	1.2	m/s

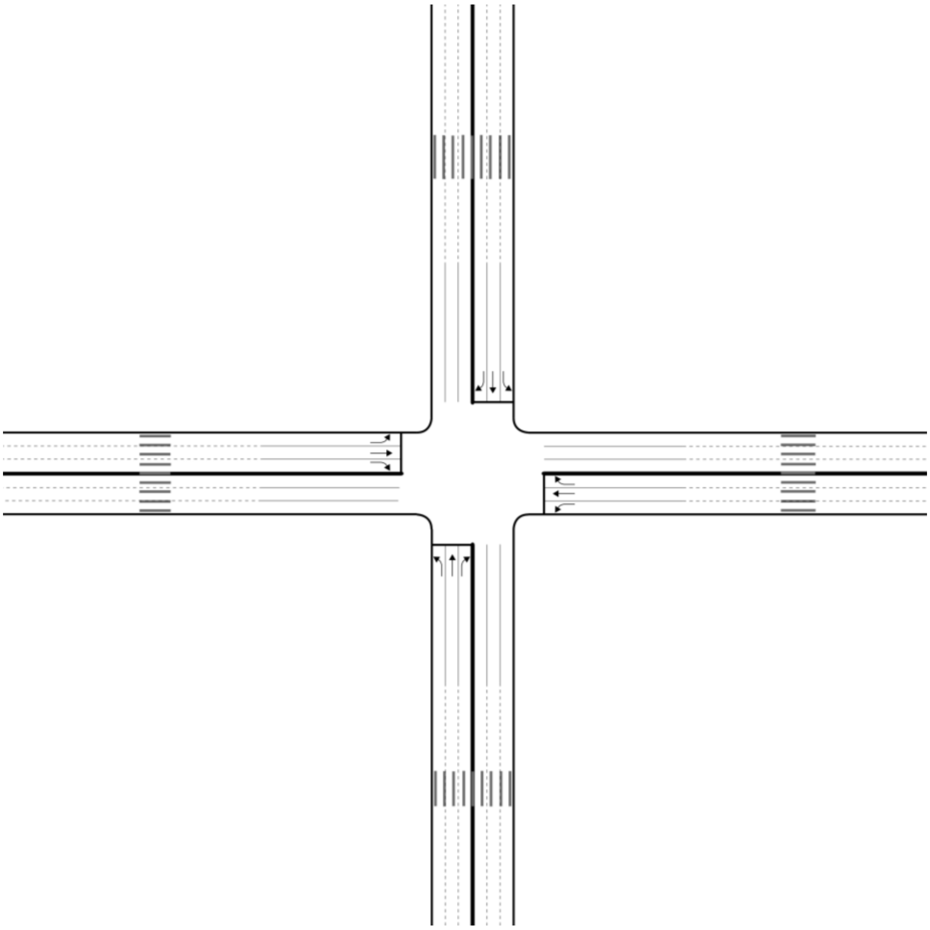


Figure 6.4: Layout of the intersection with crosswalks at midblock locations

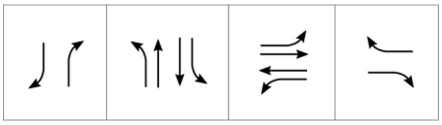


Figure 6.5: Phasing scheme for alternative crossing design

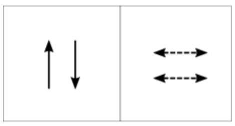


Figure 6.6: Phasing scheme at midblock crosswalks

Table 6.2: Vehicle demand levels

Scenarios							
Balanced demand (50% major demand)							
	Total	Major corridor demand			Minor demand		
		Right	Through	Left	Right	Through	Left
1	1200	60	180	60	60	180	60
2	1600	80	240	80	80	240	80
3	2000	100	300	100	100	300	100
4	2400	120	360	120	120	360	120
5	2800	140	420	140	140	420	140
6	3200	160	480	160	160	480	160
Unbalanced demand (60% major demand)							
	Total	Major corridor demand			Minor demand		
		Right	Through	Left	Right	Through	Left
1	1200	72	216	72	48	144	48
2	1600	96	288	96	64	192	64
3	2000	120	360	120	80	240	80
4	2400	144	432	144	96	288	96
5	2800	168	504	168	112	336	112
6	3200	192	576	192	128	384	128
Unbalanced demand (70% major demand)							
	Total	Major corridor demand			Minor demand		
		Right	Through	Left	Right	Through	Left
1	1200	84	252	84	36	108	36
2	1600	112	336	112	48	144	48
3	2000	140	420	140	60	180	60
4	2400	168	504	168	72	216	72
5	2800	196	588	196	84	252	84
6	3200	224	672	224	96	288	96

Table 6.3: Pedestrian demand levels

Scenarios		
Pedestrian demand		
	Total pedestrians entering (pedestrian/hour)	Demand per crosswalk (bidirectional) (pedestrian/hour)
1	1600	400
2	3200	800
3	4800	1200
4	6400	1600
5	8000	2000

6.4. Simulation Results and Discussion

6.4.1. Evaluation of Alternative crossing design

Two cases were evaluated under both balanced and unbalanced scenarios: crosswalks with single cycle and crosswalks with double cycle.

Balanced Scenario (50% Major Demand, 50% Minor Demand)

Single Cycle

Figure 6.7 shows the network performance index in monetary values. As expected, the network performance index increases with vehicular demand. Figure 6.8 shows the contribution of vehicle and pedestrian performance index to the network performance index. Figure 6.9 shows network performance index for varying vehicular flows and the corresponding optimum cycle lengths. In general, higher vehicular flows require longer cycle lengths. Performance index for various vehicle and pedestrian volumes was evaluated and is shown in Figure 6.10. Performance increase almost linearly with vehicular volume. Figure 6.11 further shows how vehicles and pedestrians contribute to the overall network performance index for various vehicle and pedestrian volumes.

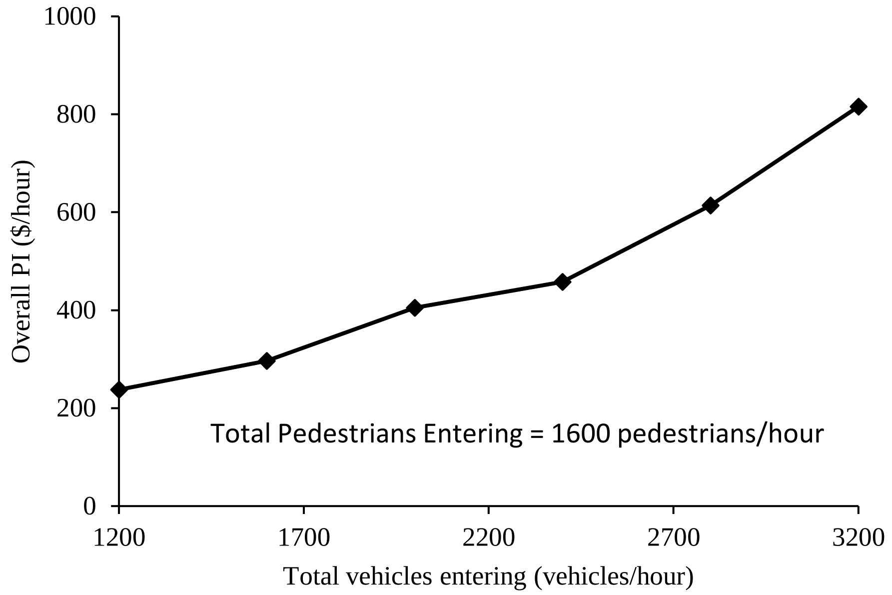


Figure 6.7: Performance index for various vehicle demand levels

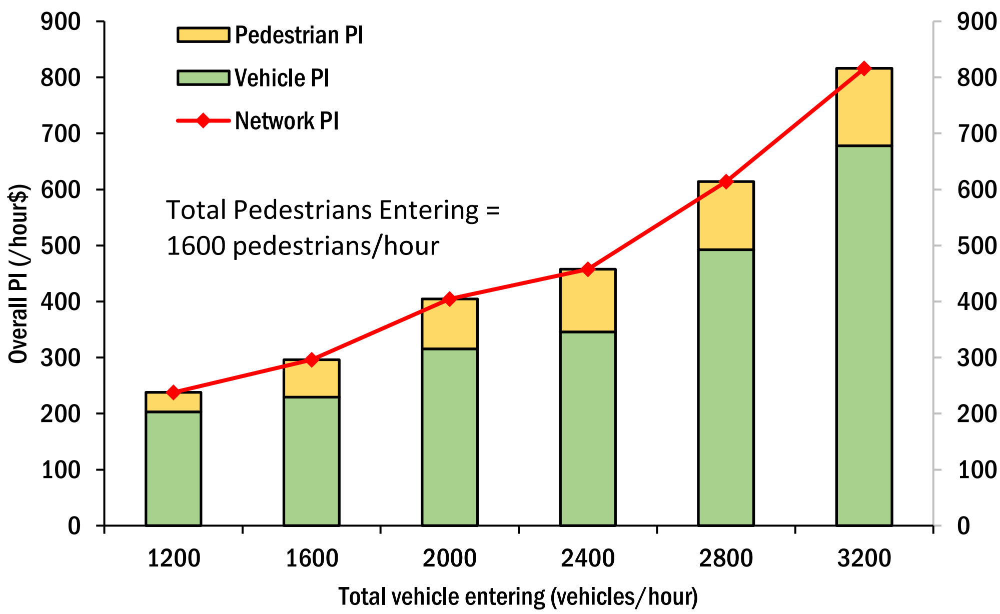


Figure 6.8: Contribution of vehicles and pedestrians to overall performance index

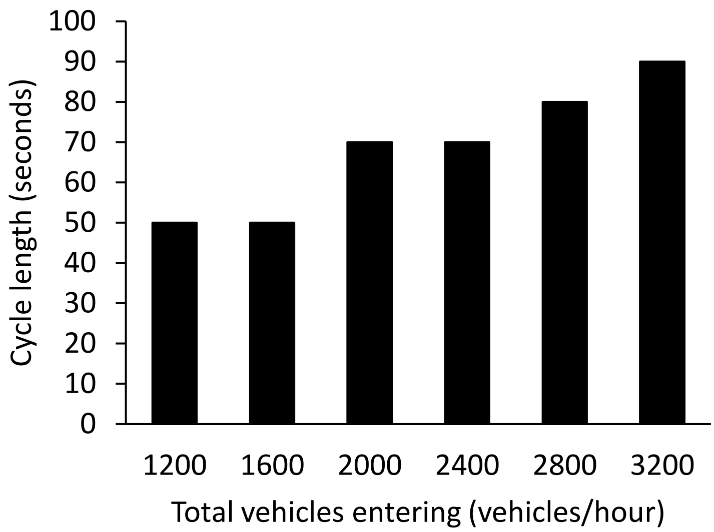


Figure 6.9: Performance index and cycle lengths against various vehicle demand levels

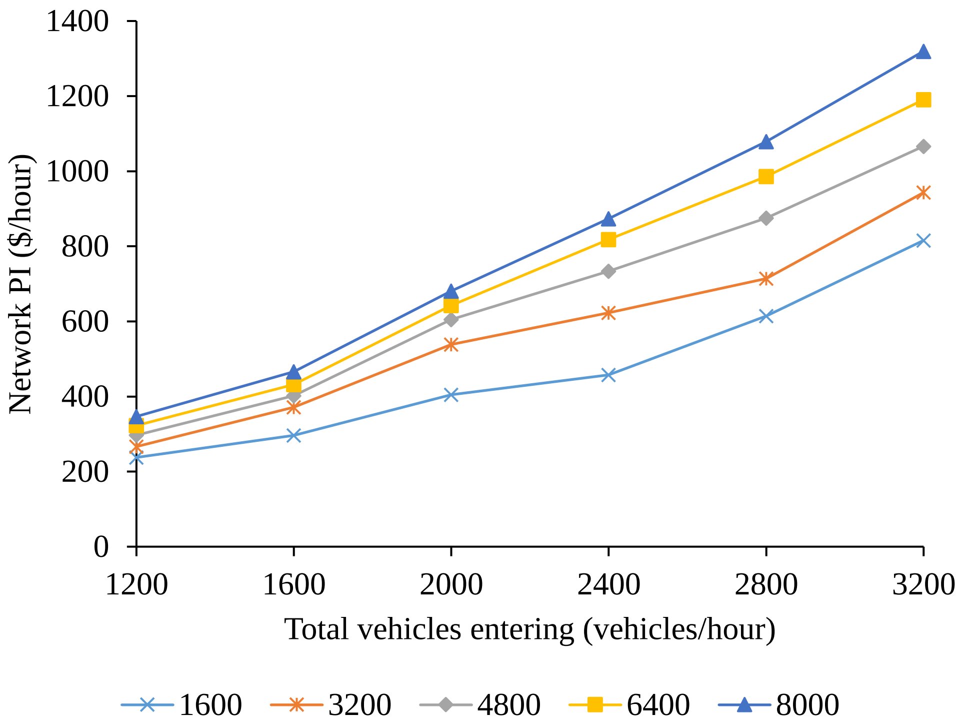


Figure 6.10: Performance index against vehicle and pedestrian volumes

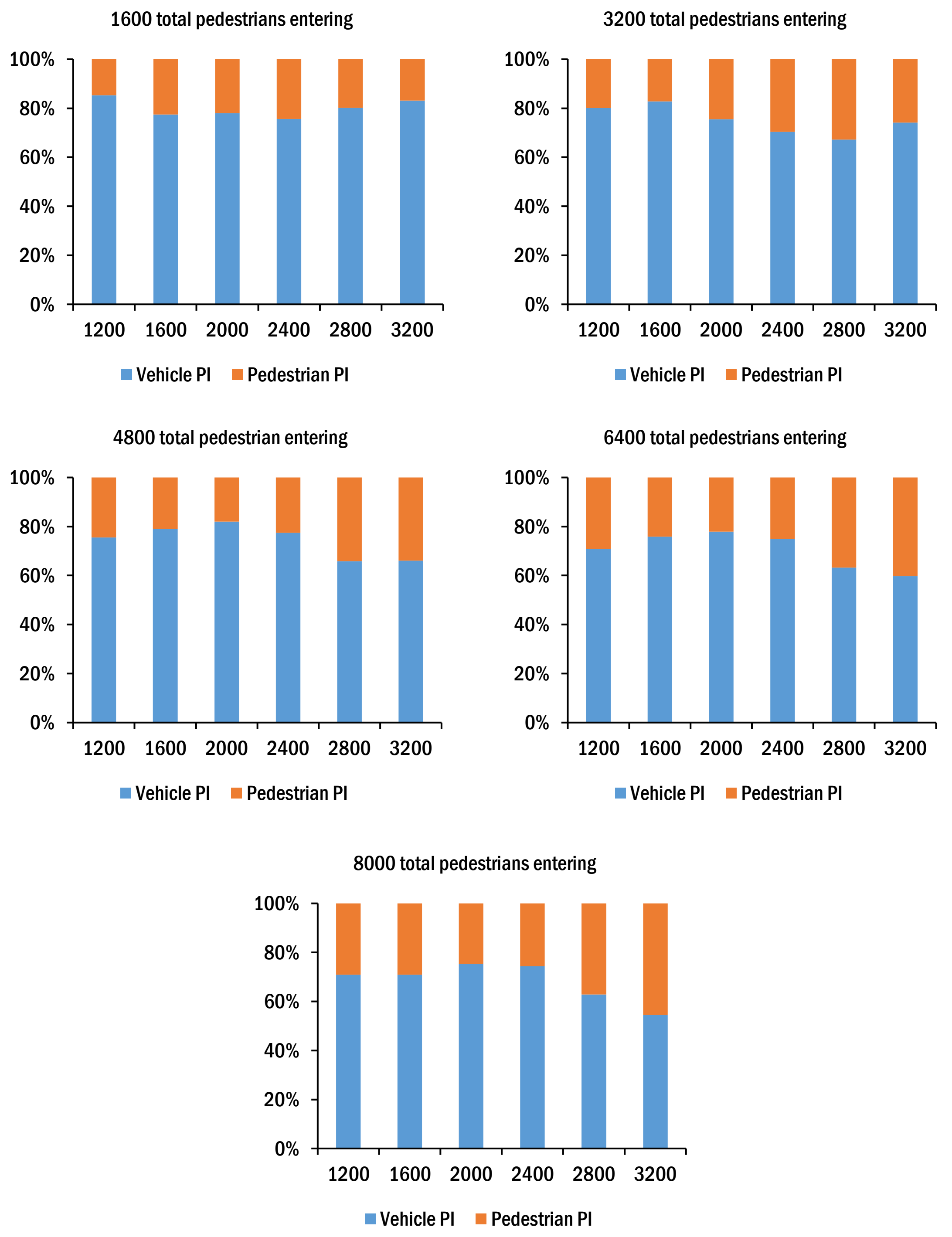


Figure 6.11: Contribution of vehicles and pedestrians to overall network performance index

Double Cycle

In general, midblock crosswalks required shorter cycle lengths as compared to intersections, therefore, crosswalks were operated at cycle lengths half of intersection cycle length. Performance index for various vehicle and pedestrian volumes was then evaluated and is shown in Figure 6.12. Figure 6.13 shows how total network delay changes with vehicles and pedestrian volumes. In general, total network delay increases almost linearly with vehicle volumes.

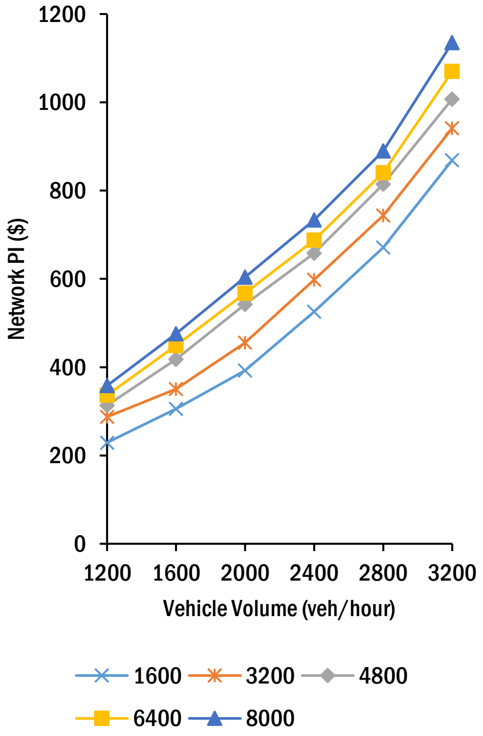


Figure 6.12: Performance index against vehicle and pedestrian volumes

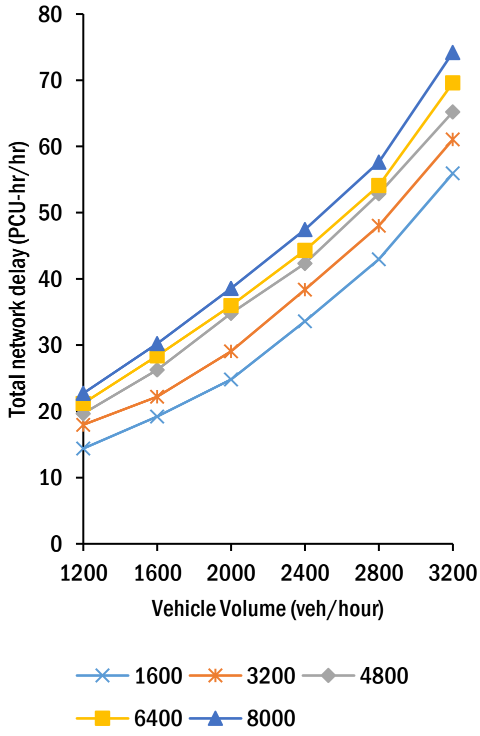


Figure 6.13: Total network delay against vehicle and pedestrian volumes

Unbalanced Scenario-1 (60% Major Demand, 40% Minor Demand)

Single Cycle

Performance index was evaluated for an unbalanced scenario where major demand was 60% of the total approach volume and minor demand was 40% of the total approach volume. The results are shown in Figure 6.14 and Figure 6.15. Unlike balanced demand case, the relationship between performance index and vehicle volume is becoming nonlinear.

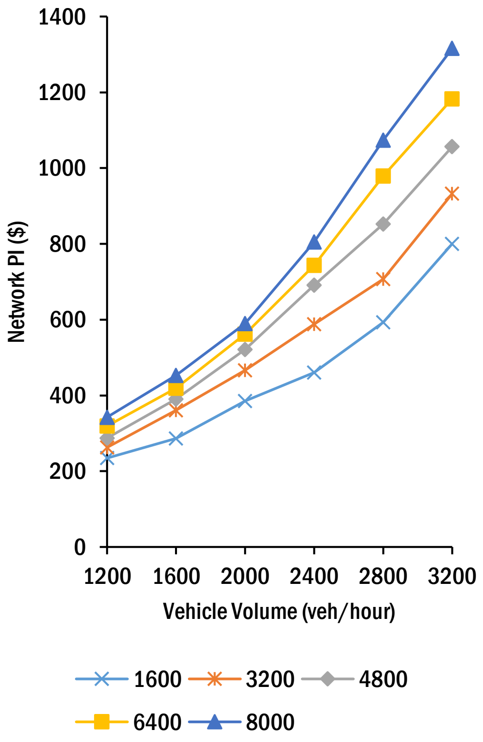


Figure 6.14: Performance index against vehicle and pedestrian volumes

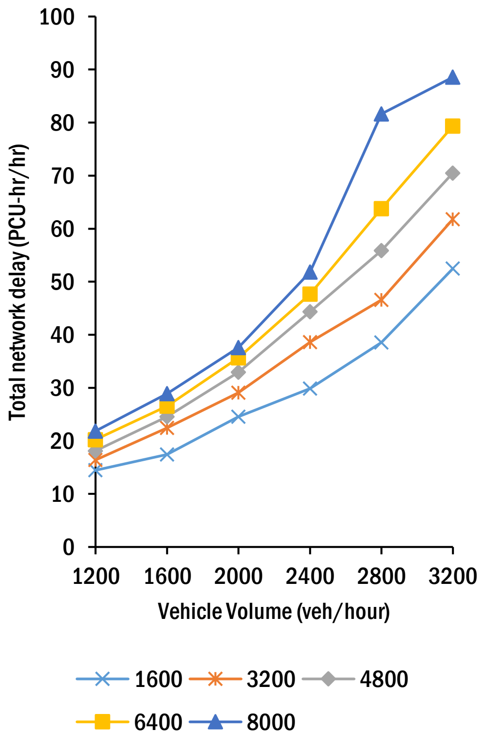


Figure 6.15: Total network delay against vehicle and pedestrian volumes

Double Cycle

The cycle lengths at crosswalks were then changed to twice that of intersection cycle length and performance index was evaluated again. The results are shown in Figure 6.16 and Figure 6.17.

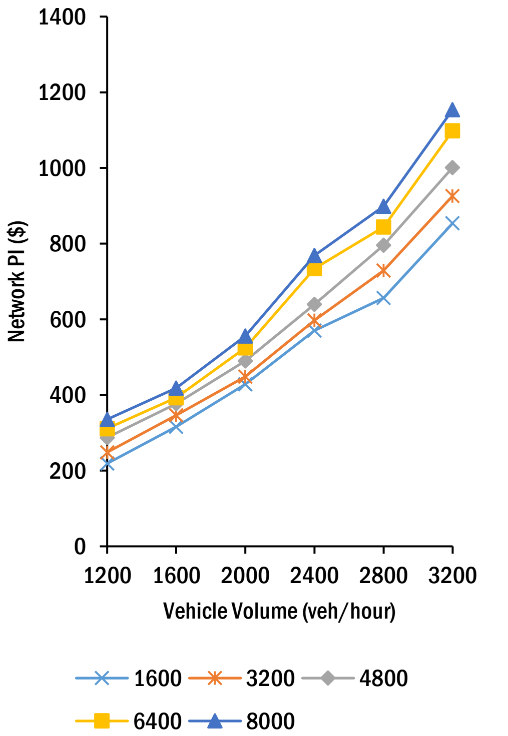


Figure 6.16: Performance index against vehicle and pedestrian volumes

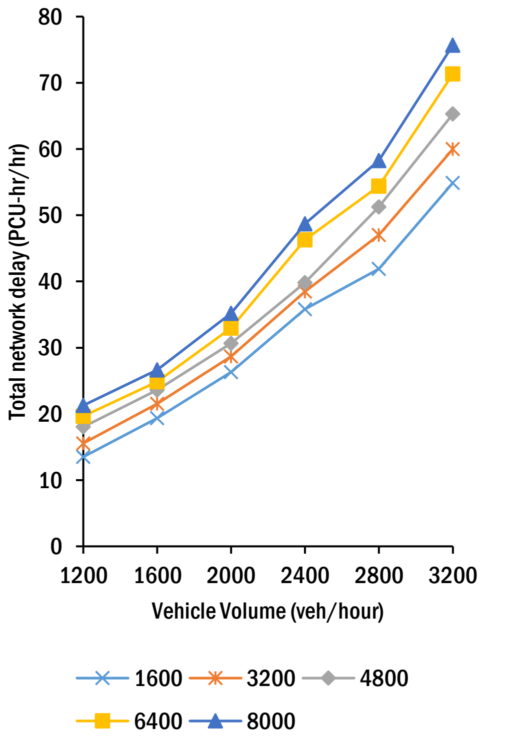
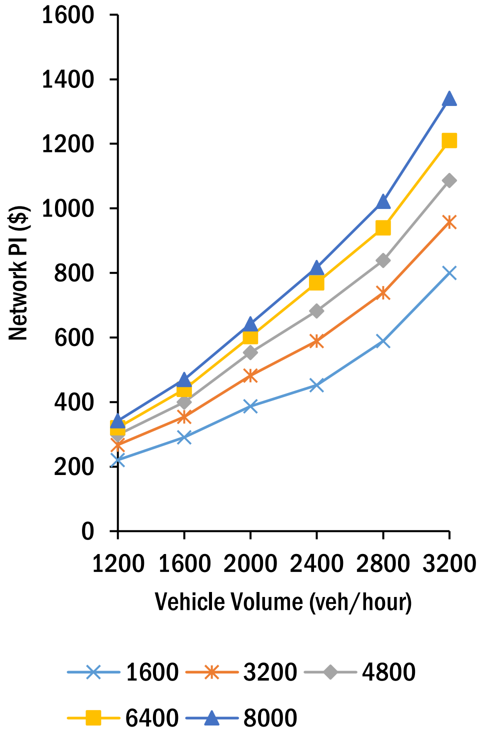


Figure 6.17: Total network delay against vehicle and pedestrian volumes

Unbalanced Scenario-2 (70% Major Demand, 30% Minor Demand)

Single Cycle

Performance index was evaluated for another unbalanced scenario where major demand was 70% of the total approach volume and minor demand was 30% of the total approach volume. The results are shown in Figure 6.18 and Figure 6.19. Again, unlike balanced demand case, the relationship between performance index and vehicle volume is becoming nonlinear.



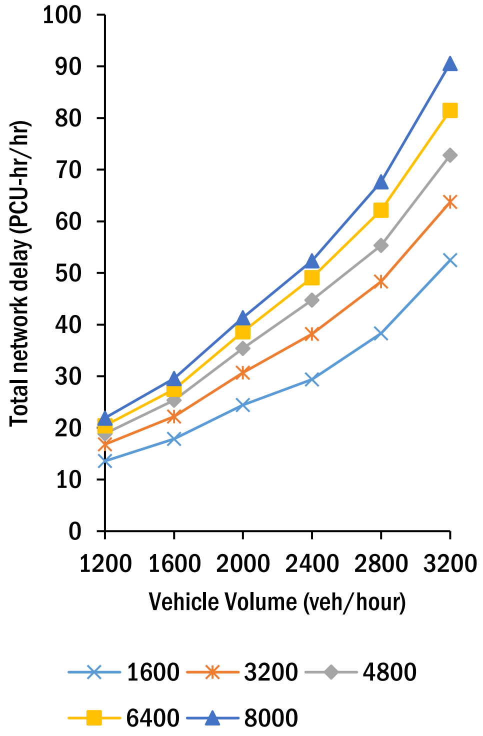
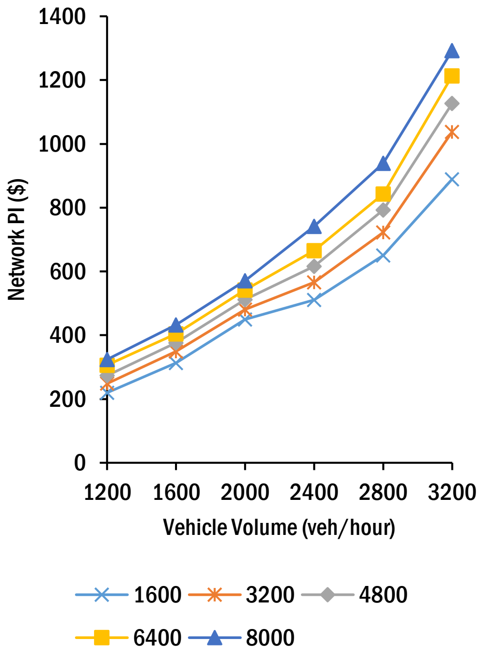


Figure 6.18: Performance index against vehicle and pedestrian volumes

Figure 6.19: Total network delay against vehicle and pedestrian volumes

Double Cycle

The cycle lengths at crosswalks were then changed to twice that of intersection cycle length and performance index was evaluated again. The results are shown in Figure 6.20 and Figure 6.21. The performance of the network decreases as compared to the 60-40 unbalanced demand scenario.



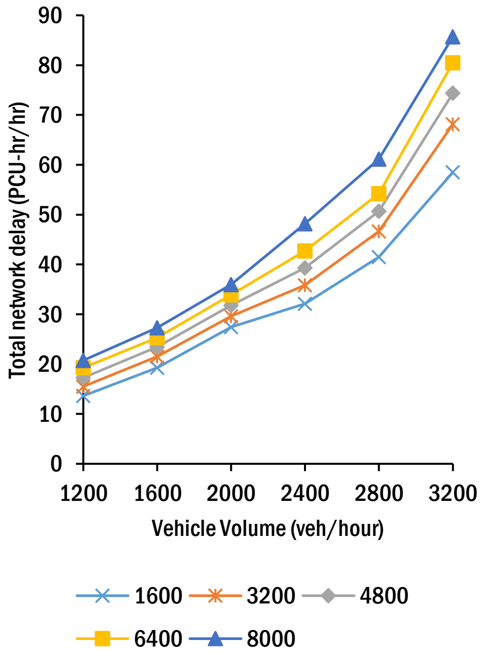


Figure 6.20: Performance index against vehicle and pedestrian volumes

Figure 6.21: Total network delay against vehicle and pedestrian volumes

6.4.2. Alternative vs Traditional design

Balanced Vehicle Demand (50% Major Demand, 50% Minor Demand)

Figure 6.22 shows the performance index for the following four designs:

1. alternative crossing design with equal common cycle length
2. alternative crossing design with half cycle lengths at crosswalks
3. intersection with phasing scheme shown in Figure 6.2
4. intersection with phasing scheme shown in Figure 6.3

Design 3 becomes oversaturated at higher vehicular and pedestrian volumes. It could be attributed to the more number of phases in this design. Other designs perform almost similar at lower vehicle volumes. However, design 4 performs better at higher vehicular volumes followed by design 1. Figure 6.23 and Figure 6.24 show vehicle and pedestrian performance index respectively.

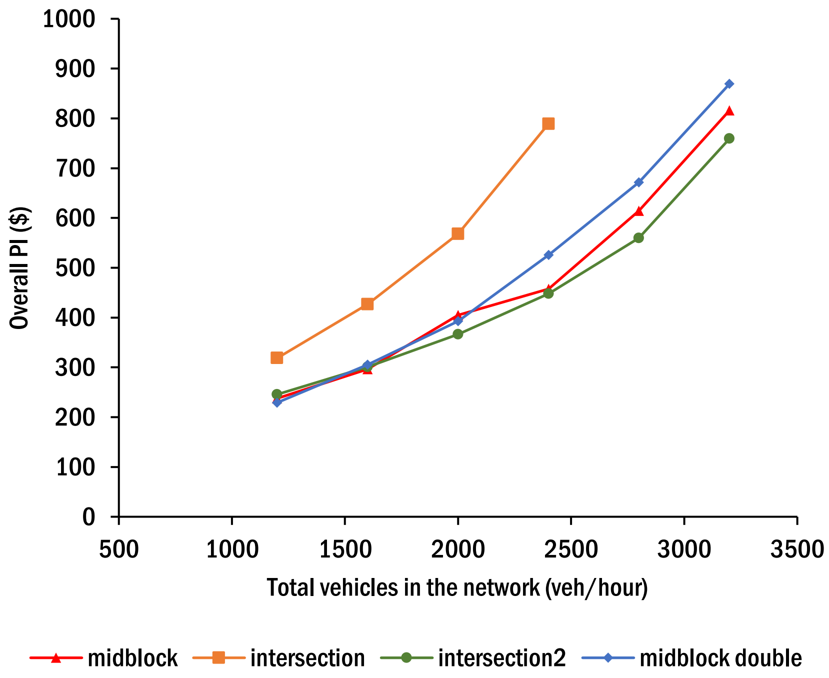


Figure 6.22: Performance index for alternative and traditional crossing designs

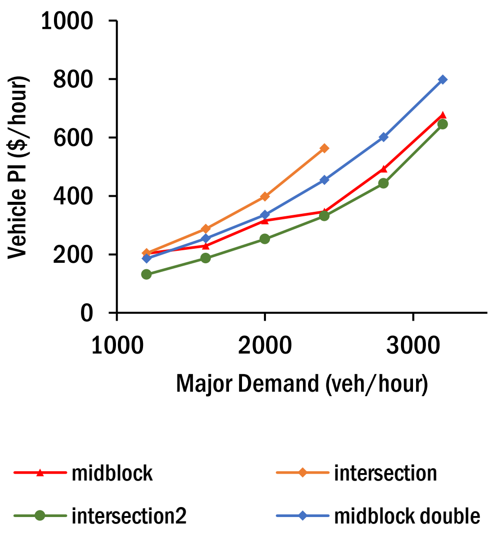


Figure 6.23: vehicle performance index against vehicle and pedestrian demand levels

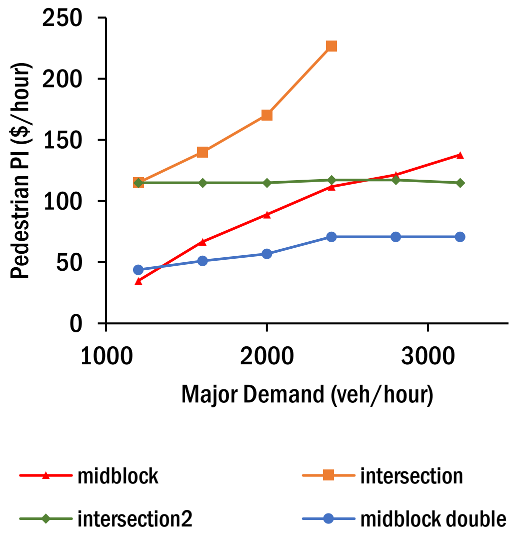


Figure 6.24: pedestrian performance index against vehicle and pedestrian demand levels

Figure 6.25 shows general trend of performance index against vehicle and pedestrian volumes for all four designs

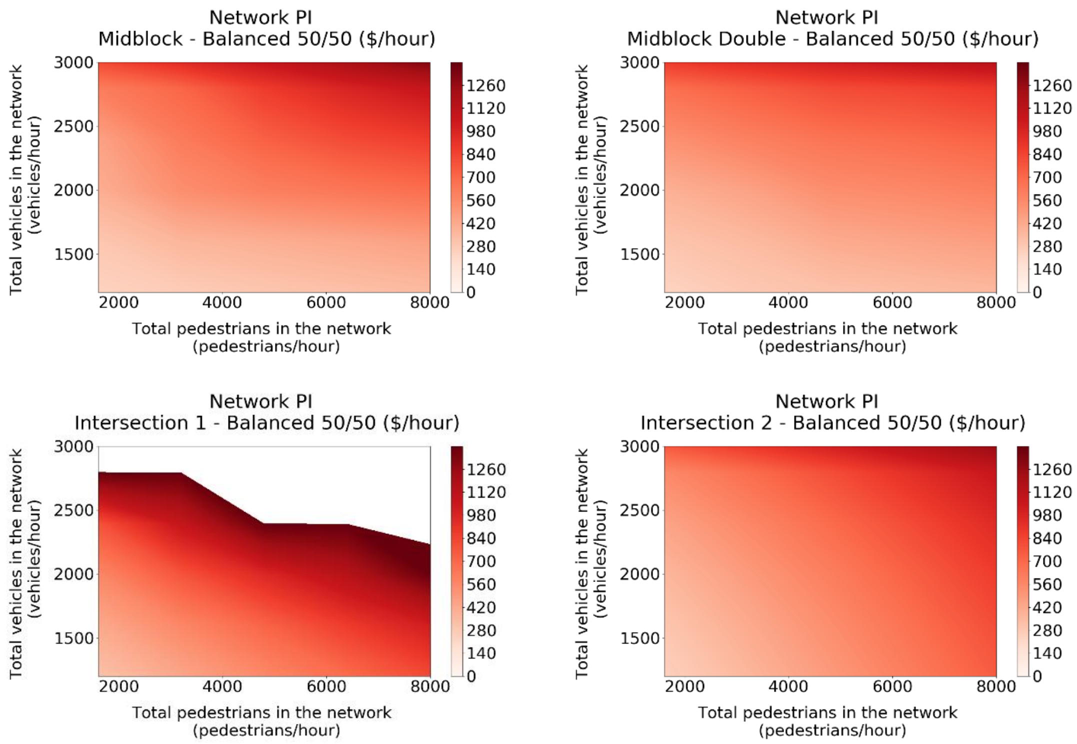


Figure 6.25: Performance index trend for various scenarios
(Balanced vehicle demand 50-50)

Figure 6.26 shows cycle lengths for various vehicle flow levels for both the cases. Shorter cycle lengths are required for alternative crossing design given the fact that there is no additional pedestrian phase at the busy intersection.

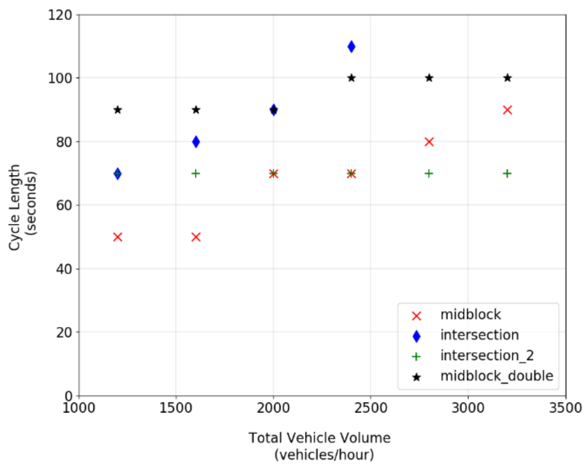


Figure 6.26: Cycle lengths for alternative and traditional crossing designs

Figures 6.27, 6.28 and 6.29 show the applicability range of all four designs for critical intersections for both balanced and unbalanced vehicle volume scenarios. The applicability of the design 2 increases with more unbalanced vehicle demand. Whereas the applicability of design 4 decreases with unbalance in vehicle demand. Generally, design 2 is better for higher pedestrians' volumes especially for unbalanced vehicle demand scenarios.

Design 4 is better for lower vehicle and pedestrian volumes especially for relatively balanced demand scenarios. However, design 1 outperforms design 4 when vehicle demands gets more unbalanced.

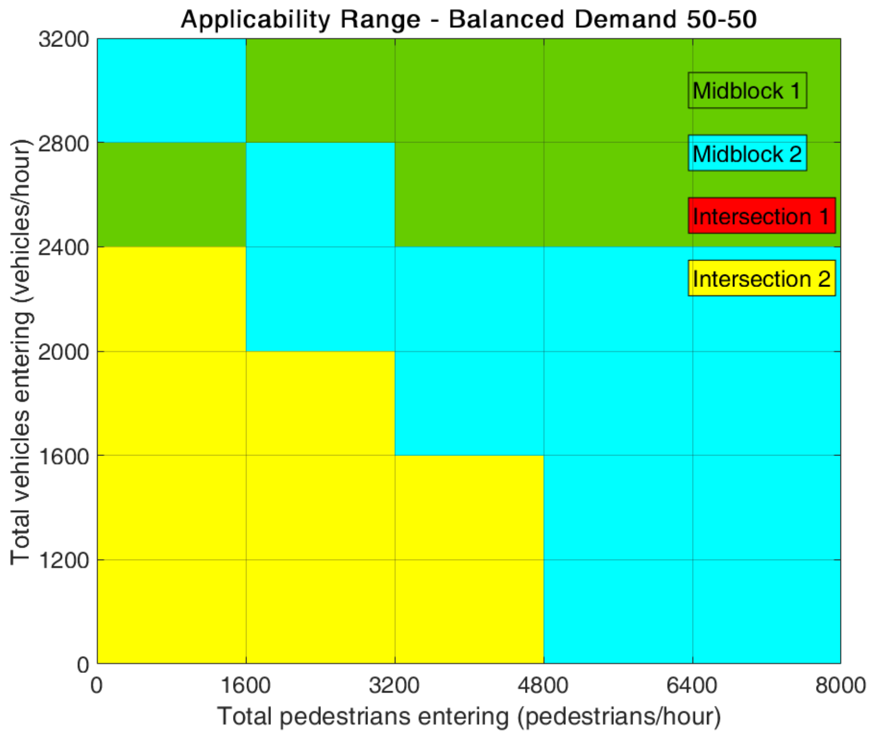


Figure 6.27: Applicability Range – Balanced Scenario 50-50

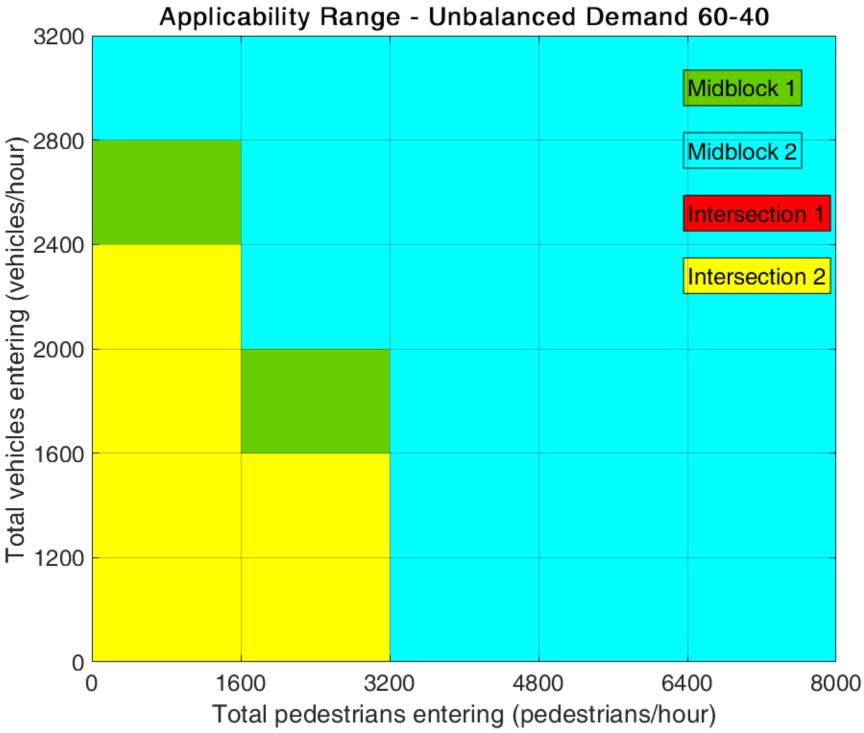


Figure 6.28: Applicability Range – Unbalanced Scenario 60-40

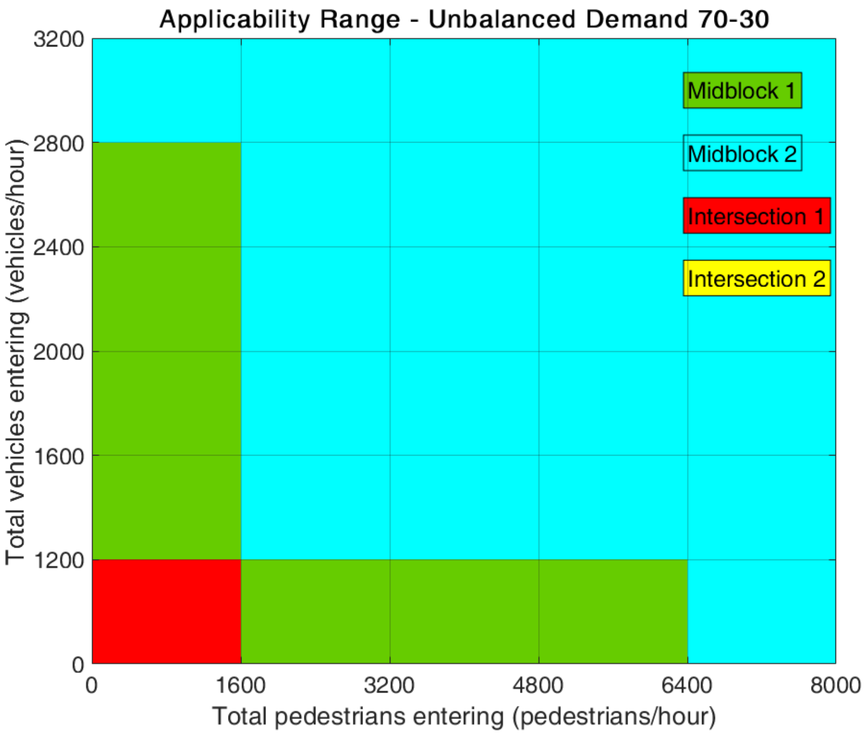


Figure 6.29: Applicability Range – Unbalanced Scenario 70-30

6.5. Summary

Performance evaluation of four different designs of critical intersections was carried out in this chapter. Alternative crossing scenario with half cycle lengths at midblock crosswalks performed better especially at higher pedestrian volumes and unbalanced vehicle demand scenarios. Traditional phasing scheme where pedestrians can cross with parallel through traffic performed better at balanced demand scenarios, however, its performance deteriorated at unbalanced scenarios. Alternative crossing design with similar cycle lengths at the intersection and midblock crosswalks outperformed the traditional phasing scheme at unbalanced vehicle demand scenarios.

Chapter 7

Final Remarks

This dissertation incorporated crosswalk design into network design process. A summary of the approaches proposed in the dissertation is presented here.

7.1. Conclusions and Recommendations

7.1.1. Pedestrian behavior

Initially, researches on pedestrian behavior at various crossing locations was explored. It is vital to understand the pedestrian behavior while designing pedestrian network. Designing a pedestrian network without taking pedestrian behavior into account may not provide the expected benefits. Extensive literature exists on pedestrian behavior at intersection crosswalks. Therefore, only pedestrian behavior at unmarked midblock locations was deemed necessary for the purposes of this study. In order to explore unobserved factors of pedestrian behavior, a self-reported pedestrian behavior survey was conducted. Factor analysis produced four underlying factors including risk-taking. Pedestrian reported more risk-taking behavior at unmarked midblock locations in the absence of crosswalk or when intersection crosswalks were far. Hence, it was concluded that providing the crosswalks at appropriate locations can reduce risk-taking behavior and converge pedestrians to a single point. The self-reported behavior did not significantly differ between respondents from developing and developed countries. Hence, the results could be generalized to any area. However, it should be kept in mind that self-reported behavior is not always similar to revealed behavior. The revealed behavior might be different from the reported behavior.

7.1.2. Network design

The literature review showed that crossing facilities design can impact the performance of a network. Therefore, it is necessary to incorporate the pedestrian crossing facilities design into the network optimization problem. Hence, an optimization model formulation was proposed to optimize the existence, number, location and signal settings of midblock crosswalks in vehicle-pedestrian networks. The optimization model was formulated under the system optimum principle from pedestrians' viewpoint, therefore, the model can be used for planning purposes. As the model was based on minimization of the total vehicle and pedestrian travel time, therefore, some optimized crosswalk locations, though optimal from system viewpoint, were not appropriate from practical viewpoint. Because pedestrian behavior is quite complex in reality and it seems hard to guide pedestrians to use the system optimized routes.

When optimization model formulation gets complex, it becomes harder to obtain the optimum solution. Therefore, it is reasonable to make some assumptions while formulating the optimization model. The model proposed in this study was no different. Some factors such as signal coordination was not considered in the formulation, instead an adjustment factor was applied for platooned arrivals. Signal coordination can carried out as a separate step after obtaining the optimum solution. Similarly, other assumptions were meant to formulate the problem in such a way so as to obtain the optimum solution as efficiently as possible.

The results suggested that intersections can be operated at shorter cycle lengths even for higher vehicular volumes when pedestrian crossing facilities design is optimized simultaneously. Furthermore, the impact of pedestrians on saturation flow rates of turning vehicles at intersections can be reduced if excess pedestrian demand is diverted to nearby crosswalks. Midblock crosswalk, in general, required shorter cycle lengths. Therefore, they can be operated at multiple cycles for coordination purposes.

An integrated approach, which incorporated pedestrian route choice behavior, was then proposed to design vehicle-pedestrian networks considering pedestrian crossing facilities. Pedestrians were assigned to various routes between each origin and destination pair based on discrete choice model. The solution obtained through system optimum principle always provides a lower bound and can be used as a reference to compare the solution of any other optimization model that takes pedestrian behavior into account. As the integrated approach took pedestrian behavior into account, therefore, the network performance was lower than the system optimum solution.

7.1.3. Alternative crossing design for critical intersections

The optimization models proposed in this dissertation often resulted in a solution where crosswalks were not needed at the intersections under the given inputs. Such designs improved the performance of the network. Therefore, the performance evaluation of such a design where crosswalks are removed from critical intersections and placed at nearby locations was conducted. Such a design completely prevents the conflicts between turning vehicles and pedestrians. Existing traffic simulation and optimization model was used to evaluate the performance of such a crossing design.

Performance evaluation of four different designs of critical intersections was carried out for comparison purposes. Alternative crossing design with half cycle lengths at midblock crosswalks performed better especially at higher pedestrian volumes and unbalanced vehicle demand scenarios. Traditional phasing scheme where pedestrians can cross with parallel through traffic performed better at balanced demand scenarios, however, its performance deteriorated at unbalanced scenarios. Alternative crossing design with similar cycle lengths at the intersection and midblock crosswalks outperformed the traditional phasing scheme at unbalanced vehicle demand scenarios.

7.2. Areas of Future Research

The research possibilities arisen as a result of this dissertation are presented here.

7.2.3. Signal coordination

Positioning a crosswalk along a road segment impacts the vehicular progression when the adjacent intersections are coordinated. Therefore, it is important to coordinate the crosswalk with adjacent traffic signals in order to minimize the impact on the vehicular progression. Incorporating the signal coordination into the optimization model generally requires vehicle progression models and make the formulation cumbersome. Therefore, signal coordination was not considered in the optimization formulations presented in this dissertation. Nonetheless, a possible approach could be to optimize the offsets after obtaining the optimized solution through the optimization formulation proposed in this dissertation.

7.2.3. Pedestrian route choice behavior

Multinomial logit model (MNL) was used in this study to model pedestrian route choice behavior. However, MNL has its own limitations such as the random components of the utilities of various alternatives are assumed to be independently and identically distributed (IID). Therefore, a better way could be to utilize Multinomial Probit Model (MNP). Moreover, a path based formulation is proposed in this dissertation, therefore, pedestrians choose their route before starting on their trip. However, in reality, pedestrians may choose to change their decisions at various decision points. For instance, if a pedestrian reaches a red indication at a crosswalk, he or she may choose to avoid crossing the road at this crosswalk and instead keep walking to another crosswalk to cross the road. Hence, such dynamic behavior can improve the performance of the optimized output of the model.

7.2.3. Crossing facilities types

Only single-stage crosswalks are considered in this dissertation. Two-stage crosswalks are the crosswalk where a crosswalk is divided into two crosswalks and can operated independently of each other. Two stage crosswalks are known to perform better than single stage crosswalks under various conditions. Because pedestrians need less time to clear the crosswalks. Moreover, they have benefits for coordinated corridors because they can operated independently of each other providing more flexibility in adjusting the offsets. Hence, considering the two-stage crosswalks in the network design problem can bring about positive changes in terms of overall performance.

7.2.3. Combined assignment and signal control optimization

The changes in signal settings and crosswalk design can impact the vehicle and pedestrian route choice behavior. Pedestrians may change their paths based on the changes in the network design. Similarly, vehicles may also changes their route choice pattern depending on signal settings as well as the presence or absence of crosswalks. Therefore, it is recommended that such an impact of vehicle and pedestrian route choice be evaluated.

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