University of Nevada, Reno

Signal Phasing Strategies for Intersections with an Exclusive Bicycle Path

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ABSTRACT

Over the past few years in the United States, there has been a gradual increase among many public agencies installing experimental exclusive bicycle traffic signals in conjunction with vehicular traffic signals. These signals, mostly found at intersections with protected two-way bicycle paths, may cause operational inefficiencies if unsatisfactory phasing strategies are used. The source of the issue stems from difficulty in developing a phasing strategy where simultaneous vehicular movement is to not come into conflict with any concurrent bicycle movement, particularly the vehicular right-turn movement adjacent to a bicycle path. Additionally, as a new signal type, there has been a lack of general guidelines on how to develop an efficient strategy that not only accommodate bicycle traffic signals, but also pedestrian signals.

The goal of this research was to develop different strategies to accommodate bicycle traffic signals. The strategies are based on a case study intersection where a bicycle signal has been installed and is causing operational inefficiencies. Three strategies was developed for each split and lead-lag phasing using a combination of overlaps, dummy phases, and phase modifiers. Using the simulation software VISSIM, a model was developed based on the case study's intersection roadway geometry and signal timing. Each strategy is then implemented and evaluated for the capacity and delay of the right-turn lane by varying bicycle and pedestrian volumes. Analytical models based on Poisson distribution were developed for the capacity and delay of the right-turn lane and checked with simulation results for validation. The current intersection operation was also evaluated using current traffic volumes, and implementing all three split design strategies.

The results from simulation showed low delays and high capacity for the vehicular right-turn lane at low bicycle and pedestrian volumes. Vice versa, higher delay and lower capacity for the vehicular right-turn lane at higher bicycle and pedestrian volumes resulted, which is expected. A reduction of the current operation's right-turn lane average delay was observed with the implementation of all three solutions. And finally, the results from simulation indicate that each strategy will be advantageous at different bicycle and pedestrian demands.

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CHAPTER 1: INTRODUCTION

Problem Statement

In recent years, there has been a gradual shift of emphasis towards multimodal based transportation systems in many U.S. cities. One in particular, the mobility and safety of bicyclists. Public agencies have been implementing dedicated bicycle traffic signals to control bicycle movements along exclusive bicycle lanes or paths. However, there are limited literature and guidance available for efficiently accommodating the bicycle phases within the current signal control scheme. As a result, poor phasing schemes may be implemented and cause reduced efficiency for the overall signal operation. One difficulty of developing a phasing strategy is to prevent any simultaneous vehicle movement coming into conflict with any concurrent bicycle movement, (Lindley, 2013) to enhance cyclist safety.

Research Objectives

This research is based on a case study intersection located in Sparks, NV (Figure 2), where a bicycle signal has been installed and is causing operational inefficiencies, particularly effecting the right-turn lane adjacent to a two-way bicycle path. The goals of this research are (a) to develop several split and lead-lag phasing strategies that improves a protected right-turn lane adjacent to a dedicated bicycle signal , (b) to evaluate each strategy with micro-simulation and determine capacity and delay values of the right-turn lane with varying bicycle and pedestrian volumes, (c) to develop and validate analytical capacity and delay models, and (d) to determine how much efficiency is gained by implementing each split strategy to the case study's current operation. Two specific objectives of this research include the following:

- Develop phasing strategies in a way that mostly follows the current case study's operation to make evaluations less complex and ensure consistency.
- Determine which developed phasing strategies would work best based on bicycle and pedestrian volumes.

Literature Review

Exclusive bicycle lanes and paths, through the use of physical barriers such as a raised curb have been an increasing practice across many U.S. cities to separate vehicular and bicycle movements (Dill & Carr, 2003). This enhances bicyclists' experience, and increase perception of safety, promote increased ridership while curbing vehicular pollution and congestion (Dill & Carr, 2003). Many dedicated bicycle lanes and paths are adjacent to vehicular traffic, and thus there has been an increase in the use of exclusive bicycle traffic signals to accommodate bicycle movements on roadways and intersections. Figure 1 below shows a typical exclusive bicycle signal head installed along with a vehicular signal head.

Figure 2: Standard Exclusive Bicycle Signal Head (Golgowski, 2012)

A joint study of the Federal Highway Administration and the Oregon Department of Transportation has found that more cities are installing the signals to enhance not only bicyclists' safety, but that of pedestrians and commuters (Monsere, Figliozzi, Thompson, & Paulsen, 2013). In recent years, there have been several types of bicycle-specific signals implemented in U.S. cities. Depending on the vehicular traffic demand, some signals can provide a shorter green time for bicycles than for adjacent vehicles to allow enough time for bicyclists to clear an intersection (Thompson, Monsere, Figliozzi, Koonce, & Obery, 2013). Some have a leading interval to allow cyclists to enter an intersection a few seconds ahead of vehicles so that they are more visible to drivers (Federal Highway Administration , 2015). However, these signals may not reduce the risk of right-turn conflict. Dedicated bicycle signals, which let bicycles cross in a separate phase inhibiting conflicting vehicular movement, have been implemented on an experimental basis in some cities (Monsere, Figliozzi, Thompson, & Paulsen, 2013), and was endorsed by the Federal Highway Administration (FHWA) for general, non-experimental use in December 2013 (Lindley, 2013).

Dedicated bicycle signals can either be pre-timed or actuated to accommodate bicycle traffic. Pre-timed bicycle signals generally provide a bicycle-specific phase with pre-set length that is at least the required crossing time in each cycle. While actuated signals only activate the bicycle phase when a bicycle is detected by loop, camera detection or a bicycle button is pressed.

According to a survey conducted in 2012, a majority of reviewed bicycle signals in the U.S. are operating as dedicated phases (Thompson, Monsere, Figliozzi, Koonce, & Obery, 2013). As discussed in the last section, exclusive bicycle phases protect cyclists from any conflicting vehicular movements and therefore significantly increases their safety. Its impact on traffic operation mainly affects adjacent through and right-turn vehicular movement. However, there's little research conducted so far to quantitatively evaluate the impact of dedicated phase on traffic operation in terms of intersection capacity and delay.

For the past eleven years, there have been a few manuals that have offered guidelines on the design of dedicated bicycle signals. All manuals have more emphasis on geometric design and layout of bicycle lanes and paths. However, most are lacking details on how to develop strategies of dedicated bicycle signals operating efficiently along with other traffic signals in an intersection.

Review of Existing Guidelines

In March of 2004, the Transportation of Canada released a report on traffic signal guideline for bicycles (TAC, 2004). The manual goes into detail and addresses some of the safety, implementation and operational issues on bicycle signals. In terms of developing an efficient phasing strategy, the manual does offer a brief description on how a bicycle signal should be timed. It suggested that timing of the bicycle signal should take into consideration, the acceleration, deceleration and typical cruising speeds of cyclists.

The National Association of City Transportation Officials released the Urban Bikeway Design Guide (NACTO, 2011), with the aim to help agencies with solutions more geared towards complete streets. This manual primarily covers the geometric design, layout, and the placement of bicycle signals, signs, markings, and detection. There is no information related on how to develop a phasing strategy, however, it does give a brief guidance on how to calculate a clearance interval for bicycles. It does suggest using a bicyclist speed of 9.5mph to calculate the timing based on the intersection's width plus three seconds. It leaves it up to the practicing engineer's discretion and judgment on using the appropriate yellow and all-red times.

The California MUTCD (California Department of Transportation , 2012) is a special edition manual of the MUTCD exclusively for use in California. The manual, incorporates more guidelines and standards that are intended for use by CalTrans, and includes all existing standards from the 2009 MUTCD. In this manual, it introduced a bicycle signal warrant method that justifies a bicycle signal when the volume and collision or volume and geometric warrants have been met. The warrant addressed the issue from safety and demand point of view, but did not consider the impact of bicycle signal on overall intersection operation. Also, the manual gives guidance on calculating bicycle crossing times. Its calculation is a more conservative design where the vehicle movement green, yellow and all-red time are included. There are no guidance anywhere in the manual addressing efficient bicycle phasing schemes.

Guide for the Development of Bicycle Facilities discusses minimum green time for standing bicyclist and rolling bicyclist (American Association of State Highway and Transporation Officials , 2012). The manual provides different formulas on how to calculate such. However, the guide provides more description around the topics of geometric design, layout, signs, markings and detection for bicycle facilities. There is no discussion on efficient bicycle phasing schemes. The second edition of the Signal Timing Manual (Transportation Research Board, 2015), also has very limited guidance pertaining to bicycle phasing schemes. It briefly discusses the placement of bicycle signal displays and detection.

The most update manual in regards to the planning and development of bicycle pathways is found in the Separated Bike Lane Planning and Design Guide by the FHWA (Federal Highway Administration , 2015). It provides some general guidance on how to develop a phasing strategy for accommodating bicycle movements. One method is to provide a leading bicycle interval. Another, is separating bicycle movements from conflicting vehicle movements by using a combination of right-turn restrictions during bicycle through movement. For two-way bicycle paths, bicycle lanes should be separated from any conflicting vehicle turning movements. It states that even with low vehicle traffic, a bicycle scramble phase is not permitted. This is in reference to the interim approval (Lindley, 2013). However, the manual does not discuss a suitable efficient phasing strategy for bicycle signals.

To the authors' best knowledge, there has not been any research on how a bicycle signal would affect an adjacent right-turn lane's operation. It is necessary to further investigate other potential design strategies with dedicated bicycle signals, and their impact on its efficiency.

Organization of the Thesis

This thesis includes a total of five chapters, including this introductory chapter. Chapter two discusses the three types of design strategies for dedicated bicycle signal under split and lead-lag phasing and the advantages and disadvantages of each are discussed. In chapter three, analytical models are proposed to examine the operational efficiency of each alternative in terms of capacity and delay of vehicle movement. The model especially evaluates the traffic efficiency of right-turn movements adjacent to the bicycle movement. Chapter four includes three parts that will be discussed. The results from simulation for each strategy. The analytical models that are checked with the results from simulation for validation under various bicycle and pedestrian scenarios. And finally, an evaluation of the case study's current operation using developed split strategies. Chapter five concludes and discusses the results of the proposed models and simulation results. Three types of design strategies for dedicated bicycle phases for both split and lead-lag phasing are discussed. Its impact of each on the traffic operation will be identified and to see which strategy will work best under different pedestrian and bicycle volume scenarios.

CHAPTER 2: BICYCLE PHASING STRATEGIES

This chapter discusses three different bicycle design strategies for two types of intersection control, split and lead-lag phasing. The need for these strategies stems from a case study of an intersection located in Sparks NV, that is operating in split configuration. A dedicated bicycle signal has been installed and is causing its intersection operation to run inefficiently. The reason for this inefficiency is that the bicycle signal is tied to westbound through movement, which for every cycle, the bicycle signal will turn green regardless of bicyclist presence. This inhibits the westbound-right movement from proceeding, causing unnecessary delays to motorists. Figure 1 below shows an overview of the case study intersection. E. McCarran Blvd serves as the north-south major street, and Nichols Blvd serves as a west-east minor street. The direction of the major and minor street hereinafter, will be referenced and remain the same change. The bike and pedestrian path are located adjacent to the westbound movements.

Figure 3: Case Study Intersection

For this thesis, in order to simplify the evaluation procedure, the strategies will be based on the case study's current operation and operate in a similar fashion. Since the issue with the current operation is primarily the operation of the westbound right-turning movement, the main focus of these designs are on improving that. The difference between the current operation and the designs vary from the phasing of the vehicle, bicycle and pedestrian movements, and the sequence and timing of the side-street. There are no changes made for the major street in all strategies.

Split Design Strategies

The following three strategies were developed using split phasing for the minor street. For split phasing, it consists of having two opposing approaches time consecutively rather than concurrently (FHWA, 2004). These strategies can be implemented due to geometric constraints of left-turning vehicles or shared through and left lanes (Transportation Research Board, 2015). It is not advisable to implement these strategies when the intersection is running coordination as split phasing generally has lower operation efficiency. These strategies will use the same geometry and phasing scheme as the case study intersection.

Design Strategy #1

For this strategy, the bicycle signal is tied to the vehicular through movement. The bicycle phase is activated in every cycle regardless of the number of bicyclists present. The duration of the phase is determined by the longer of required cyclists crossing time or required time to serve vehicle demand. The required green time for the bicycle movement is equal to the crossing time that is based on bicycle speed and intersection width. The crossing time is set in the minimum green parameter of the vehicular through movement in the controller so that a stopped bicyclist has enough time to cross the intersection. Once the minimum green time has passed, the vehicular through movement will either gap out due to the presence of no vehicles, or extend the green time if there are vehicles continually being detected. The clearance time for the through vehicle movement is set to accommodate any rolling cyclists caught at the end of the vehicular green, the yellow time should be enough to accommodate their crossing. According to FHWA's Interim Approval, the yellow time should be set between 3 - 6 seconds (Lindley, 2013).

Typical geometry and split phasing scheme for an intersection with bicycle signals operated together with adjacent side-street through-vehicle movement is illustrated in Figure 2. It can be seen that under this phasing scheme, the dedicated bicycle phase is running concurrently with $\phi 4$. Any conflicting turning-vehicular movements are prohibited during $\phi 4$. Once $\phi 4$ has gapped out, the adjacent side-street right-turn vehicle movement can proceed. In this strategy, the right-turn movement is setup as an overlap phase that has $\phi 1$ as its parent phase. Thus once the vehicular through and bicycle movement has gapped out, the vehicular right-turn movement can proceed with the southbound-left movement ($\phi 1$). Also, the right-turn detector is tied to $\phi 1$ because if there are no vehicles for the southbound-left movement, then the right-turning vehicles can place a call and still be served (this applies to all strategies).

This design strategy provides the dedicated bicycle phase in every cycle and always accommodates the required bicycle crossing time, regardless of bicycle demand. It’s advantageous to implement this design alternative when bicycle volume is sufficient (i.e. there is a bicycle demand every cycle). However, it has adverse impact on the capacity and delay of the side-street right-turn movement.

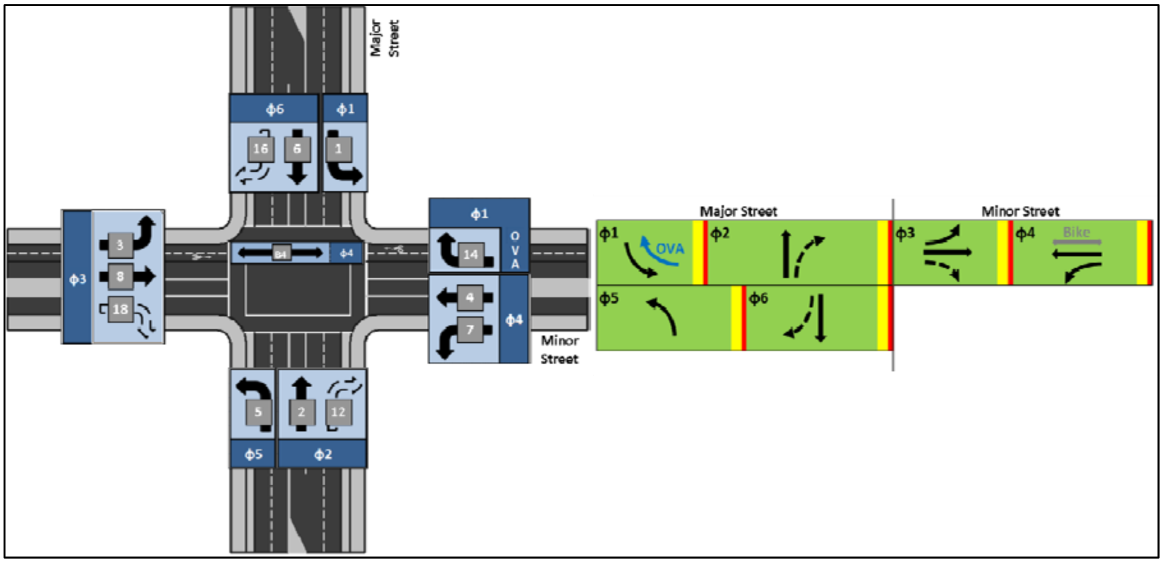


Figure 4: Intersection Geometry and Phasing Scheme of Strategy #1

<u>Design Strategy #2</u>

The difference between strategy #1 and this strategy is that there is a pedestrian movement. The pedestrian and bicycle movement are actuated and are activated only when bicycles and/or pedestrians are present. These signals employ certain types of detection (e.g. loop, video, and push-button) to activate these phases.

For this strategy, the actuated bicycle and pedestrian phases are tied together. The presence of either a pedestrian or a bicycle will activate the bicycle/pedestrian phase. The duration of the this phase is determined by required pedestrian crossing time due to the fact that pedestrians take a longer time to cross. Typical phasing scheme for an intersection with bicycle signals operated together with side-street pedestrian movement can be as illustrated in Figure 2.

The setup of this is done by designating the bicycle movement as a vehicular movement, which from figure 4 below, is ϕ 8. The pedestrian movement will be tied to ϕ 8 as ped ϕ 8. As mentioned, the bicycle movement will be tied to the pedestrian movement and run pedestrian timing, thus the bicycle and pedestrian detection should be tied to ped ϕ 8. Which then if there is a bicycle present and no pedestrian, the bicycle detection will activate ped ϕ 8 and run pedestrian timing. If there is a presence of just pedestrians or both pedestrians and bicyclist, this will also activate ped ϕ 8 and run pedestrian timing.

It can be seen that under split phasing scheme, that the right-turn movement is setup as an overlap where the parent phases are ϕ 1 and ϕ 4, and a modifier phase ϕ 8. When no pedestrian or bicycle demand is present, ϕ 8 will not be activated, and right-turn vehicles can be served with side-street through-vehicle movement ϕ 4 and continue to be served until ϕ 1 gaps out. When ϕ 8 is activated, it will run with ϕ 4 and side-street right-turn movement will be prohibited during ϕ 8 operation due to its setup as a modifier phase. Once ϕ 8 has gapped out, then the right-turn movement can be served with the remaining time left in ϕ 4 plus ϕ 1. The green time of the right-turn movement will dependent on whether there is a bicycle and/or pedestrian detection, and the amount of vehicles on the side-street through movement.

Also, the use of two barriers must be used and set prior to ϕ 3 and ϕ 4. The reason to set the extra barrier prior to ϕ 4 is due to the operation of the NEMA ring structure. This will allow the bicycle and pedestrian movements to run concurrent with the through movement ϕ 4, otherwise, the bicycle and pedestrian movements will run concurrently with ϕ 3 and come into vehicular conflict. A dummy phase must also be used and set after the bicycle and pedestrian phase so that phase can terminate and allow the right-turn movement to proceed with ϕ 4. Placing a one second min green recall for the dummy phase is the only parameter that needs to be set. Other parameters such as yellow, all-red time, gap time, etc. does not need to be set for the dummy phase.

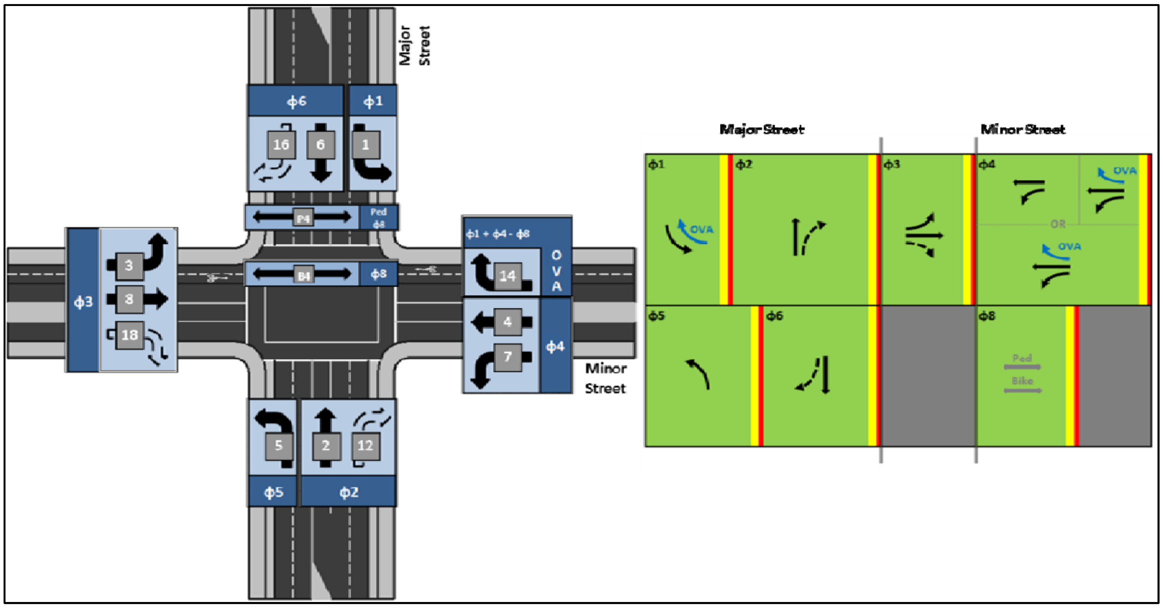


Figure 5: Intersection Geometry and Phasing Scheme of Strategy #2

This strategy provides an actuated dedicated bicycle phase depending upon bicycle and pedestrian demand. The activation of bicycle/pedestrian phase may lengthen the green time of adjacent side-street movement and shorten that of major-street through movement. It can also be expected that a higher pedestrian or bicycle demand will significantly impact the efficiency of side-street right-turn movement.

<u>Design Strategy #3</u>

Another design strategy for actuated bicycle phases is to separate the bicycle phase from pedestrian movement. Figure 5 shows the ring structures with the side street running split phasing.

The setup for this strategy is similar to strategy #2, the only difference is the bicycle and pedestrian will be running different timing, the bicycle detector is tied to ϕ 8, and the pedestrian detector is tied to ped ϕ 8. And thus if there is a bicycle detection, ϕ 8 will be activated to run bicycle timing, and vice-versa, if there is a pedestrian detection, then ped ϕ 8 will be activated to run pedestrian timing.

If no bicycle or pedestrian is present on the side street, the duration of side-street through movement (ϕ4) is determined only by the required time to serve side-street through vehicles. Right-turn vehicles will be allowed to pass during ϕ4. When bicycle demand is present but not pedestrian, only the bicycle ϕ8 will be activated and run concurrently with ϕ4. When pedestrian demand is present but not bicycle, pedϕ8 will be activated and run concurrently with ϕ4. When both pedestrian and bicycle demand are present, ϕ8 and pedϕ8 will be activated and run concurrently with ϕ4. Out of compliance and operational efficiency concern, when only a pedestrian demand is present, it's advantageous to also activate the bicycle phase ϕ8. The activation of either ϕ8 or ped ϕ8 will prohibit side-street right-turn movement during the operation. Same placement and parameters of the dummy phased used in strategy #2 must also be used in strategy #3.

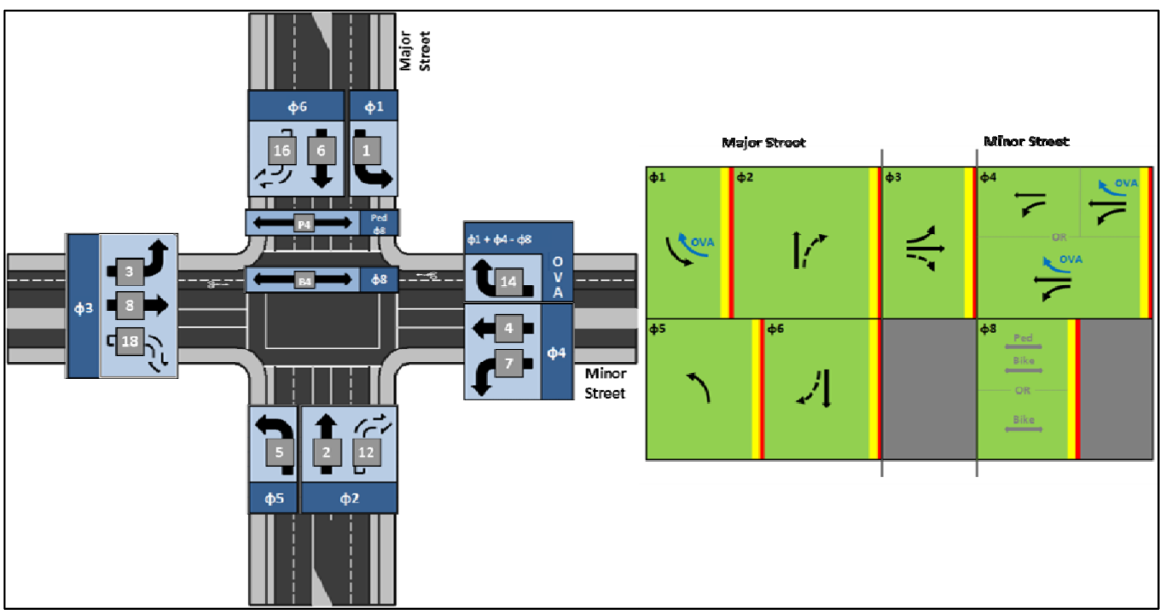


Figure 6: Intersection Geometry and Phasing Scheme of Strategy #3

This strategy provides separate phases for side-street vehicles, pedestrians and bicycles. The required pedestrian crossing time is generally greater than bicycle crossing time, and bicycle crossing time greater than the required time to serve side-street vehicles. Therefore the activation of pedestrian and bicycle phases will lengthen the duration of vehicular phase ϕ 4, and prohibit side-street right-turn movement. In the cases that the time needed to serve through vehicles is longer than the bicycle phase, the adjacent right-turn phase can be turned on after the bicycle phase is terminated whilst the through vehicle phase is still being served. It can be expected that frequent activation of pedestrian and bicycle phases will significantly reduce intersection capacity and increase delay.

Lead-Lag Design Strategies

The following strategies are lead-lag configuration in both the major and minor street approaches. In lead-lag, it consists of having two opposing approaches time concurrently (FHWA, 2004). If the given street geometry allows to run these schemes, it is recommended as the operation of the intersection would run more efficiently and is better to run in coordination (Transportation Research Board, 2015). Shorter cycle lengths can be achieved, thus reducing delays for all approaches, whereas split phasing cannot easily achieve this. The drawbacks of these designs is the complexity of setting it up in the controller and wiring everything together.

Design Strategy #1

Similar to split phasing strategy #1, the only difference with lead-lag phasing is the use of all eight phases. ϕ 3 and ϕ 7 are the minor street left turns, and ϕ 4 and ϕ 8 are the minor street through movements. The geometry and phasing scheme are illustrated below in Figure 6. The bicycle movement is tied to whichever is the adjacent through movement. In this case, the bicycle is tied to ϕ 8. Once the conflicting movement ϕ 7 terminates, ϕ 8 and the bicycle movement will proceed along with either the opposite through movement ϕ 4 or left-turn movement ϕ 3. The right-turn movement, which is still an overlap tied to ϕ 1 (southbound left) will then proceed. The minimum amount of green time for a bicyclist needed to cross the intersection is to be set under the minimum green time parameter of ϕ 8. The yellow time should be 4-6 seconds to accommodate any rolling bicyclist entering the intersection at the end of green.

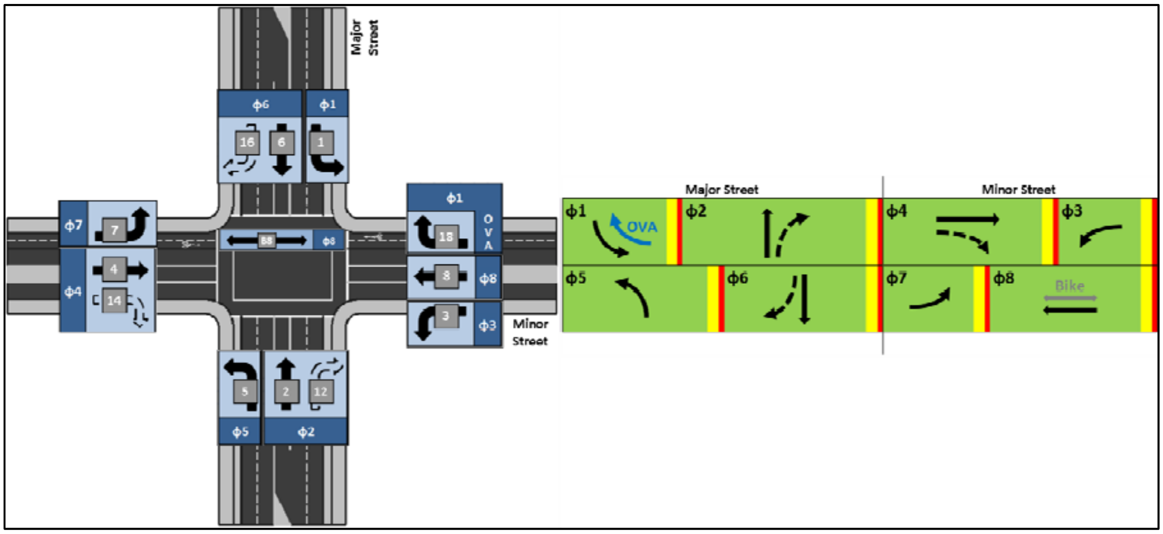


Figure 7: Intersection Geometry and Phasing Scheme of Strategy #1

<u>Design Strategy #2</u>

Design strategy #2 for lead-lag is similar to the split design. The bicycle movement will be tied to the pedestrian movement and run pedestrian timing. However, the setup of this is more complex and requires the use of two dummy phases, duplicate detector calls, up to 11 phases and a third row in the ring barrier structure. For the right-turn movement, the overlaps will be the same as the split strategies, but with different phase number assignment. The right-turn overlap will consist of parent phases ϕ 1 and ϕ 8, and modifier phase ϕ 10.

The use of dummy phases is needed in order for this strategy to work. The ring and barrier structure illustrated in figure 7 shows the dummy phases (shaded in grey) placed before and after the ϕ 10 (bike and pedestrian movement). The purpose of the of the first dummy phase (under ϕ 7) is to run a concurrent scheme with ϕ 7 so that ϕ 10 will begin with the start of ϕ 8. This dummy phase will share the same timing parameters as ϕ 7 (i.e. min green, yellow, all-red, veh extension, etc). A detector for ϕ 7 is tied to the phase itself and the dummy phase. This will ensure that the dummy phase will run and terminate concurrently with ϕ 7. The second dummy phase (after ϕ 10) will run the same way as described in split design #2. The minimum green for this will be set to one second. This will ensure that ϕ 10 does not extend past the desired pedestrian and bicycle times, so that the right-turn movement can proceed. In the case where ϕ 8 is leading, the first dummy phase as described earlier does not have to be used due to the barrier. However, the dummy phase after ϕ 10 will still need to be used.

After ϕ 6 and ϕ 2 terminates, ϕ 4 and ϕ 7 will begin. ϕ 7 will provide the green time to accommodate the eastbound left-turning vehicles. With the detector for the left-turn set to control ϕ 7 and the dummy phase, the dummy phase will run concurrently with ϕ 7. Once ϕ 7 terminates, ϕ 8 can proceed. If there is a call for the pedestrian and/or bike movements, then ϕ 10 will run pedestrian timing and proceed with ϕ 8, the right-turn movement will be prohibited until ϕ 10 gaps out. If there are no calls for either the pedestrian or bicycle movements, then the right-turn movement will proceed at the beginning of ϕ 8.

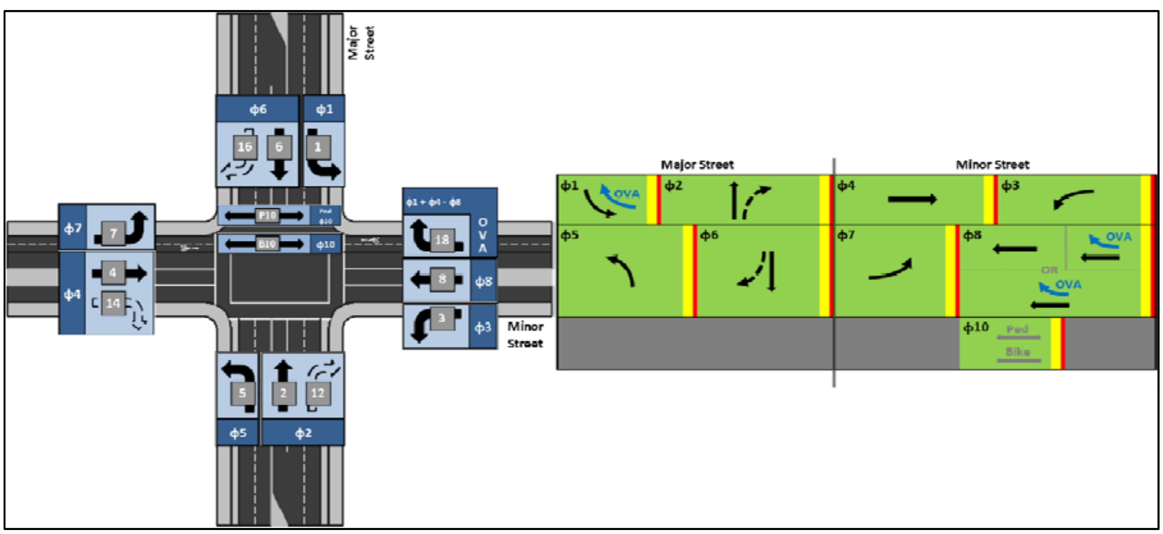


Figure 8: Intersection Geometry and Phasing Scheme of Strategy #2

Design Strategy #3

This strategy operates similar to the previous strategy and design #3 under split configuration. Refer to the previous section (lead-lag strategy #2) for the setup and operation of design #3. The bicycle and pedestrian movements are separated. As mentioned before, this design works best for wide intersections. Pedestrian and bicycle crossing times will differ. The detector for ϕ 10 will be separated so that if there is only a bicycle call, ϕ 10 will run bicycle timing and pedestrian movements will not be accommodated. If ped ϕ 10 is called, then ϕ 10 and ped ϕ 10 will run pedestrian timing.

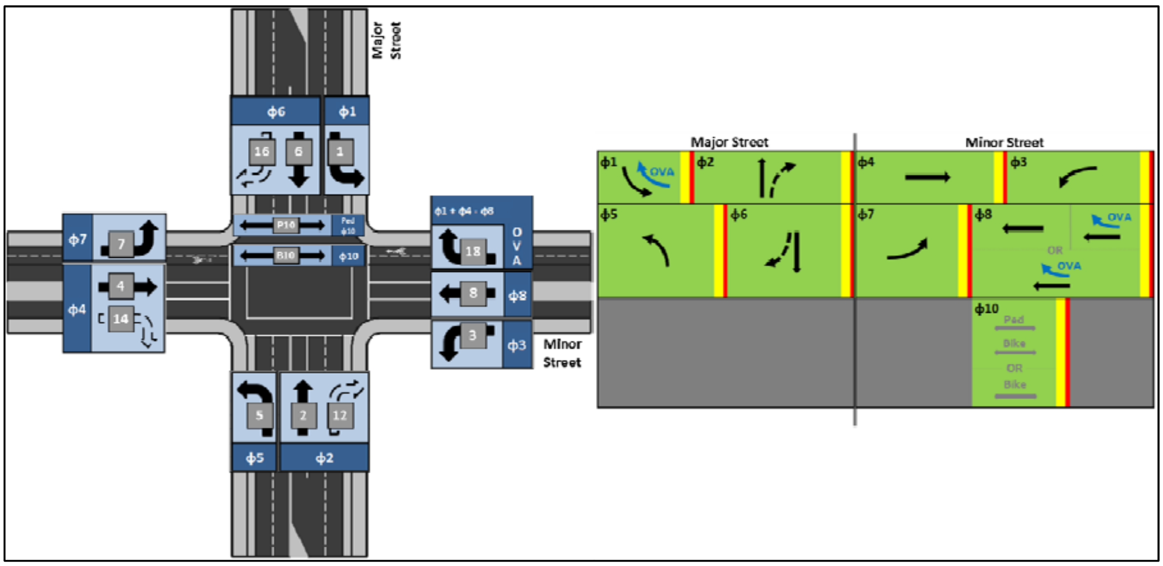


Figure 9: Intersection Geometry and Phasing Scheme of Strategy #1

Summary

This chapter presents the various strategies on how to accommodate bicycle and pedestrian movements at an intersection. Configurations in both split and lead-lag phasing were developed to provide options on what is best to implement at intersections. However, these designs need to be evaluated to determine the delays and capacity of the right-turning movement. Implementing these solutions to the case study and comparing results of the current operation and solution is necessary to justify that the solutions are indeed beneficial when implemented.

In order to evaluate the right-turn capacity and delay of the phasing designs, the designs must be modeled in micro-simulation software. Analytical models were also developed to represent the nature of the right-turning movement. Chapter three discusses the development of such models. In chapter four, the results of the solutions and the evaluation of the current case study operation will be discussed.

CHAPTER 3: CAPACITY & DELAY MODELS

Both bicycle and pedestrian arrivals are considered random events. The current procedure in the Highway Capacity Manual 2010 (Transportation Research Board, 2010) for analyzing actuated signalized intersections does not account for the stochastic nature of bicycle arrival.

Bicycle and Pedestrian Arrival Process

To develop an analytical model to evaluate the intersection operation, the bicycle and pedestrian arrival process is important since it determines when the bicycle and pedestrian phases are activated. For the pedestrian flow, the most common arrival model is the Poisson model (Cheng, Tian, & Liu, 2008). For the bicycle flow, the Poisson model can also be applied. Applying the Poisson process in general can reflect the random process of pedestrian and bicycle arrival, and is widely accepted by researchers (Cheng, Tian, & Liu, 2008) (Wei, Kumfer, Tian, & Yuan, 2013) (Wei, Liu, & Tian, 2015).

Let random variable X and Y denote the number of pedestrians and bicycles arriving at an intersection in a cycle, respectively, then the probability of having k pedestrians in a cycle is given by

$$\Pr(X = k) = \frac{\lambda_p^k e^{-\lambda_p}}{k!}, \lambda_p = \frac{q_p C}{3600}$$

(1)

where the following terms are defined as,

q_p : the hourly pedestrian volume on the side street,

C: cycle length,

λ_p : the average pedestrian volume per cycle,

e: Euler's number,

k : probability of event k occurring.

The probability of having j bicyclist in a cycle is given by

$$\Pr(Y = j) = \frac{\lambda_b^j e^{-\lambda_b}}{j!}, \lambda_b = \frac{q_b C}{3600} \tag{2}$$

where the following terms are defined as,

q_b: the hourly bicyclist volume on the side street,

C: cycle length,

λ_b: the average bicyclist volume per cycle,

e: Euler's number,

j: probability of event j occurring.

Capacity Models

All six of the proposed strategies provide dedicated bicycle phases restricting any conflicting vehicular movements, however, each has different schemes to deal with bicycle and pedestrian demand. Assuming the cycle length is fixed, the activation of either the dedicated bicycle or pedestrian phases would impact the duration of side-street through and right-turn movements, as well as the major street phase splits. In order to evaluate the efficiency, three models to estimate movement capacity are proposed for strategies #1 though #3 for both split and lead-lag sequences. The parameters common to all the proposed capacity models for the right-turn vehicular movement are listed below.

C: cycle length $(\sec)$,

$g_{i,v}$: effective green time of movement i without pedestrians or bicycles,

$g_{i,p}$: effective green time of movement i when pedestrian crossing time is accommodated,

$g_{i,b}$: effective green time of movement i when bicycle crossing time is accommodated,

$c_{i,v}$: capacity of movement i without pedestrians or bicycles,

$c_{i,p}$: capacity of movement i when pedestrian crossing time is accommodated,

$c_{i,b}$: capacity of movement i when bicycle crossing time is accommodated,

s_i : saturation flow rate for movement i $\left({}^{veh}\!/_{hr} \right)$,

$c_{i,1}$, $c_{i,2}$, $c_{i,3}$: average capacity of movement i for strategies #1, #2, and #3.

Capacity Model for Strategy #1

Because the bicycle phase is tied to adjacent through movement, bicycle demand will not impact the capacity of any movements. The capacity of movement i for strategy #1, $c_{i,1}$, is determined by

$$c_{i,1} = c_{i,b} = \frac{g_{i,b}}{C} s_i \,. \tag{3}$$

Capacity Model for Strategy #2

Strategy #2 ties the bicycle phase with pedestrians, so the activation of the bicycle and pedestrian phase depends on their arrival. The probability of having no pedestrian and bicycle in a cycle is given by

$$\begin{aligned} p_v &= \Pr(X = 0 \cap Y = 0) = \Pr(X = 0)\Pr(Y = 0) \\ &= e^{-\frac{q_p C}{3600}} \cdot e^{-\frac{q_b C}{3600}} = e^{-\frac{q_p + q_b}{3600} C} \end{aligned} \,. \tag{4}$$

Therefore the probability of having at least one pedestrian or bicycle is determined by

$$1 - p_v = 1 - e^{-\frac{q_p + q_b}{3600} C} \,. \tag{5}$$

The movement capacity, $c_{i,2}$, is then derived as

$$
\begin{aligned}
c_{i,2} &= p_v c_{i,v} + (1 - p_v) c_{i,p} \\
&= p_v \frac{g_{i,v}}{C} s_i + (1 - p_v) \frac{g_{i,p}}{C} s_i \\
&= \left(e^{-\frac{q_p + q_b}{3600} C} \cdot \frac{g_{i,v}}{C} s_i \right) + \left(1 - e^{-\frac{q_p + q_b}{3600} C} \right) \cdot \frac{g_{i,p}}{C} s_i
\end{aligned} \quad . \qquad (6)
$$

<u>Capacity Model for Strategy #3</u>

Strategy #3 separates the bicycle phase from vehicle and pedestrian demand, so the activation of the bicycle and pedestrian phases depend independently on each of their arrival.

When no pedestrian and bicycles are present, the phase split is determined by vehicular demand and equals $g_{i,v}$. The probability of having no pedestrian and bicycle in a cycle can be calculated by Equation 4.

When no pedestrians are present and at least one bicycle call is placed, the phase split is determined by the greater of $g_{i,v}$, and $g_{i,b}$. The probability of having at least one bicycle and no pedestrians in a cycle can be calculated by

$$
\begin{aligned}
p_b &= \Pr(X = 0)\left[1 - \Pr(Y = 0)\right] \\
&= e^{-\frac{q_p C}{3600}} \cdot \left(1 - e^{-\frac{q_b C}{3600}} \right)
\end{aligned} \quad . \qquad (7)
$$

According to current signal timing standards for the crossing time derivation, the required pedestrian crossing time (WALK plus FDW) is greater than bicycle crossing time for the same location. Thus whenever a pedestrian call is placed, the split time will serve pedestrian crossing time, $g_{i,p}$, regardless of bicycle demand. The probability of having at least one pedestrian in a cycle can be calculated by

$$
\begin{aligned}
p_p &= 1 - \Pr(X = 0) \\
&= 1 - e^{-\frac{q_p C}{3600}}
\end{aligned} \quad . \qquad (8)
$$

The movement capacity, $c_{i,3}$, is then derived as

$$c_{i,3} = p_v c_{i,v} + p_b c_{i,b} + p_p c_{i,p} = \left(e^{-\frac{q_p+q_b}{3600}C} \cdot \frac{g_{i,v}}{C} s_i \right) + \left(e^{-\frac{q_p C}{3600}} \cdot \left(1 - e^{-\frac{q_b C}{3600}} \right) \right) \cdot \frac{g_{i,b}}{C} s_i + \left(1 - e^{-\frac{q_p C}{3600}} \right) \cdot \frac{g_{i,p}}{C} s_i \quad (9)$$

Delay Models

The delay models for each strategy can be derived similarly as the capacity models. The following parameters are defined.

$d_{i,v}$: average delay of movement i without pedestrians or bicycles,

$d_{i,p}$: average delay of movement i when pedestrian crossing time is accommodated,

$d_{i,b}$: average delay of movement i when bicycle crossing time is accommodated,

$d_{i,1}$, $d_{i,2}$, $d_{i,3}$: average delay of movement i for strategies #1, #2, and #3.

For each strategy, the average movement delay can be calculated by one of Equations 10-12 respectively.

$$d_{i,1} = d_{i,b} \quad (10)$$

$$d_{i,2} = p_v d_{i,v} + (1 - p_v) d_{i,p} = e^{-\frac{q_p+q_b}{3600}C} \cdot d_{i,v} + \left(1 - e^{-\frac{q_p+q_b}{3600}C} \right) \cdot d_{i,p} \quad (11)$$

$$d_{i,3} = p_v d_{i,v} + p_b d_{i,b} + p_p d_{i,p} = \left(e^{-\frac{q_p+q_b}{3600}C} \cdot d_{i,v} \right) + \left(e^{-\frac{q_p C}{3600}} \cdot \left(1 - e^{-\frac{q_b C}{3600}} \right) \right) \cdot d_{i,b} + \left(1 - e^{-\frac{q_p C}{3600}} \right) \cdot d_{i,p} \quad (12)$$

The HCM procedure or any software implementing the HCM procedure can be used to obtain $d_{i,v}$, $d_{i,p}$, and $d_{i,b}$.

The HCM procedure for calculating average delay in under-saturated scenarios is described as follows:

$$d = d_1 + d_2 + d_3 \tag{13}$$

where,

d = control delay $\left(\sec/_{veh}\right)$,

d_1 = uniform delay $\left(\sec/_{veh}\right)$,

where,

$$d_1 = \frac{C*[1-\frac{g}{C}]^2}{2*[1-\frac{g}{C}*\min(1,X)]}$$

(14)

d_2 = incremental delay $\left(\sec/_{veh}\right)$,

where,

$$d_2 = 900*T*\{(X-1)+\sqrt{(X-1)^2+\frac{8*k*I*X}{(s*\frac{g}{C})*T}}\}$$

(15)

and, d_3 = initial queue delay $\left(\sec/_{veh}\right)$.

CHAPTER 4: MODEL VALIDATION & DESIGN EVALUATION

This chapter discusses the methodologies and the results of the phasing strategies. The volumes of pedestrian and bicycle movements were varied to analyze the capacity and average delay of the right-turning movement adjacent to the bicycle and pedestrian path. Using the micro-simulation tool VISSIM, the results were obtained and used to determine which design strategy would work best at different pedestrian and bicycle volumes. The same bicycle and pedestrian volumes used in simulation are also used in the proposed analytical models discussed in the previous chapter. The results from the model were compared with the results from simulation for validation. The final part of this chapter discusses how effective in delay reduction each split design strategy would result using current case study P.M. peak volumes.

Simulation Setup

Since this study is based on improving a case study's intersection operation, the strategies developed had to be evaluated in a micro-simulation software where the model had to closely resemble the actual intersection. The software VISSIM was employed to handle this. It is critical that the results from simulation are similar to the results that would be yielded through implementation in the field.

Figure 10: Completed VISSIM Model of Strategies #2 and #3

There were six strategies developed. In order to save time, it was more efficient to first develop a base model in VISSIM where all strategies shared common parameters and inputs. The following VISSIM parameters held in common for all strategies included: base map of the case study intersection, road links and connectors, vehicle composition and class, vehicle inputs and routes, data collection points (for capacity results), vehicle travel times (for delay results), road link speeds, priority rules, speed reduction zones, and desired speed zones. Once this was done, the file is then duplicated so that modification may be done to reflect each individual strategy. The final inputs required for each strategy included: signal controller, signal timing parameters and the strategy itself, signal heads, and finally detectors. Figure 9 above shows a completed model of strategies #2 and #3 for both split and lead-lag configurations.

Split Timing Parameters

Please refer to chapter 2 on how the split strategies operate. Most of the signal timing parameters for each strategy used the existing timing from the case study intersection, this includes: splits, min green, passage time, yellow, all-red, walk, flashing don't walk and cycle length.

The only difference between strategies #2 and #3, is separate phase (ϕ 8) to accommodate the bicycle and pedestrian movements. In strategy #2, the pedestrian and bicycle movements are tied together, has its own phase (ϕ 8), and runs the same pedestrian timing as the case study. This will be activated when a detection of either bike, pedestrian, or both occur. Since the bicyclists can be crossing during the pedestrian phase, it is necessary to give enough crossing time for bicyclists when they are crossing the intersection at the end of green. The Bicycle Interim's Approval (Lindley, 2013), suggests that the yellow and all-red time be 4-6 seconds and 1-3 seconds respectively. When no detection occurs, the right-turn can proceed. Strategy #3 is similar to strategy #2, but the pedestrian and bicycle are timed separately. Bicycle calls ϕ 8, and pedestrian calls ped ϕ 8. The bicycle min green time is equal to the amount of time to allow a cyclist to cross the intersection based on the standard bicycle speed of 10mph (Federal Highway Administration , 2015). The timing parameters for the split configurations are summarized in Appendix C.

Lead-Lag Timing Parameters

Please refer to chapter 2 on how the lead-lag strategies operate. The goal for lead-lag strategies is to obtain similar results as the split strategies. This is to ensure that phasing scheme developed was consistent and worked in the same fashion as the split strategies in regards to the operation of the bicycle and pedestrian movements. And because of this, most timing parameters are the same as the split strategies. The only difference is that, there are now two more phases where the minor street left-turns are separated from the through movements. The major street movements will have the same assigned phase numbers as the split strategies, but the minor street will be different.

For all lead-lag strategies, the WBT is (ϕ 8), the EBT is (ϕ 4), the EBL (ϕ 7), and WBL is (ϕ 3). In order to be consistent with the split strategy results, the cycle length for lead-lag strategies is 150 seconds. ϕ 8 will be the lagging phase, just like ϕ 4 in the split configuration. And for the effective green to be the same, the case for lead-lag strategy #1, ϕ 8 will be tied to the bicycle movement, just like how ϕ 4 is tied to the bicycle in split strategy #1. In lead-lag strategies #2 and #3, ϕ 10 (bicycle movement) must start at the same time as ϕ 8. Since ϕ 3 in the split strategy is leading and has a 34 second split phase, ϕ 7 and ϕ 3 in lead-lag strategy will have the same split. ϕ 4 in lead-lag will have the same split as ϕ 8. The dummy phase before ϕ 10 will have the same timing parameters as ϕ 7. The detector for ϕ 7 is tied to the dummy phase also, so that ϕ 10 will start at the same time as ϕ 8. A summary of the lead-lag timing parameters are summarized in Appendix D.

Simulation Runs

Simulation runs were conducted for each varying pedestrian and bicycle volume. Each simulation run is set to have a 10-min seeding period and a 60-min simulation evaluation period. A total of 25 runs were conducted for each bicycle-pedestrian volume scenario to obtain stabilization and reduce error (Alexiadis, Dowling, & Skabardonis, 2007) (Wiegand & Yang, 2011) (Truong, Sarvi, Currie, & Garoni, 2015). The seed number is also increased by one for each run to ensure maximum randomness for both bicycle and pedestrian calls. For example, if the first seed is 51, then at the 25th run, the seed will be at 75. The final result is obtained by the average of 25 runs. The westbound right turn (WBR) movement was selected for the validation and comparison of capacity and average delay because the different alternatives have more significant impact on the green time.

For both split and lead-lag configurations for strategy #1, the simulation was set with no pedestrian or bicycle volumes because its volumes do not impact the signal timing. The results were used for comparisons under all bicycle and pedestrian scenarios.

Strategies #2 and #3 for both split and lead-lag configurations had the pedestrian and bicycle volumes varied from 0 to 50 in increments of 10. Thus for each strategy, the capacity and delay yielded 72 averaged results (36 for each capacity and delay). Table 1 shows where the averaged results were collected for the capacity of split strategy #3. The total of all averaged results for both strategies #2 and #3 for split and lead-lag is 288 averaged results. With 25 runs for each simulation, the total number of seeds used was 7200.

Solution #3 (Capacity)							
Average Seed # 901-1800		**Pedestrian**					
		0	10	20	30	40	50
Bike	0	871	718	628	567	509	479
	10	779	663	586	516	497	474
	20	703	617	553	509	480	464
	30	653	591	538	500	475	458
	40	635	569				
	50						

Table 1: Table Used to Record Split Strategy #3 Capacity's Averaged Results

Since the analysis was investigating how pedestrian and bicycle volumes will impact the operational efficiency of WBR movement, “max recall” was put on all vehicular phases for all strategies to minimize the impact of other factors such as vehicular traffic volume that might influence the signal operation. For the WBR movement volume, the volume will be saturated to obtain capacity values, and for delay, the volume was set to 200 vph.

Results of Design Strategies

This section discusses the results of the capacity and delay of both split and lead-lag design strategies #1 - #3 obtained from simulation and from the models developed. The two types of phasing strategies will be summarized and discussed together since results from both are very close. As mentioned in the previous section, the results are based on the variance of the bicycle and pedestrian volumes ranging from 0 - 50 with increments of 10. The results are plotted on a graph for both capacity and delay for all three strategies. The graphs are plotted in the following manner, the y-axis will either represent the capacity, in terms of vehicles per hour (all graphs hereinafter), or delay, in terms of seconds per vehicle. The x-axis for the bicycle volumes. There is a total of five graphs for each capacity and delay evaluation and are based on the varying pedestrian volume.

To calculate the capacity and delay for the westbound right-turn movement, the effective green time must be known. One set of results obtained from the models included the green time without clearance time (yellow and all-red). And other results which includes the clearance time. The green time without clearance time will yield lower capacity and higher delay, whereas if clearance time is included, the opposite would happen. This was done to check against the results from simulation and is discussed.

Capacity Results

According to capacity model, the calculated capacity of WBR movement for each alternative is listed below for both split and lead-lag phasing schemes.

The westbound right-turn capacity for strategies #1 is dependent on the green time based on its parent phase green time. The bicycle is tied to ϕ 4 in split, and ϕ 8 in lead-lag, once these phase terminates, ϕ 1 proceeds (refer to chapter 2 for strategies #1). The right-turn is controlled by southbound-left (ϕ 1). The phase split time for ϕ 1 is 22 seconds, and thus, with a yellow time of three seconds and one second all-red, the green time is 18 seconds. Equation 16 and 17 shows the capacity equation with lost time and without lost time respectively.

$$c_{`1,1} = \frac{\phi_{1,v}}{C} s_i \rightarrow c_{`1,1} = \frac{22}{C} s_i, \textit{ for } \text{Split \& Lead - Lag} \tag{16}$$

$$c_{`1,1} = \frac{g_{1,v}}{C} s_i \rightarrow c_{`1,1} = \frac{18}{C} s_i, \textit{ for } \text{Split \& Lead - Lag} \tag{17}$$

For strategies #2, ϕ 4 and ϕ 8 represent the westbound through movement, and ϕ 8 and ϕ 10 are the bicycle and pedestrian movement for split and lead-lag phasing respectively. The green time with and without lost time will vary based on the pedestrian and bicycle calls. Equations 18 and 19 show the capacity equation for split, and equations 20 and 21 show the capacity equation for lead-lag with lost time and then without lost time respectively.

$$c_{14,2} = e^{-\frac{q_p+q_b}{3600}C} \frac{\phi_{14,v}}{C} s_i + (1 - e^{-\frac{q_p+q_b}{3600}C}) \frac{\phi_{14,p}}{C} s_i \tag{18}$$

where $\phi_{14,v} = \phi_{1,v} + \phi_{4,v} \rightarrow$ 22 + 46 = 68 , and $\phi_{14,p} = \phi_{1,v} + (\phi_{4,v,} - \phi_{8,p}) \rightarrow$ 22 + (46 - 34) = 34.

$$c_{14,2} = e^{-\frac{q_p+q_b}{3600}C} \frac{g_{14,v}}{C} s_i + (1 - e^{-\frac{q_p+q_b}{3600}C}) \frac{g_{14,p}}{C} s_i \tag{19}$$

where $g_{14,v} = g_{1,v} + g_{4,v} \rightarrow$ 18 + 46 = 64 , and $g_{14,p} = g_{1,v} + (g_{4,v,} - g_{8,p}) \rightarrow$ 18 + (46 - 34) = 30.

$$c_{18,2} = e^{-\frac{q_p+q_b}{3600}C} \frac{\phi_{18,v}}{C} s_i + (1 - e^{-\frac{q_p+q_b}{3600}C}) \frac{\phi_{18,p}}{C} s_i \tag{20}$$

where $\phi_{18,v} = \phi_{1,v} + \phi_{8,v} \rightarrow$ 22 + 46 = 68 , and $\phi_{18,p} = \phi_{1,v} + (\phi_{8,v,} - \phi_{10,p}) \rightarrow$ 22 + (46 - 34) = 34.

$$c_{18,2} = e^{-\frac{q_p+q_b}{3600}C} \frac{g_{18,v}}{C} s_i + (1 - e^{-\frac{q_p+q_b}{3600}C}) \frac{g_{18,p}}{C} s_i \tag{21}$$

where $g_{18,v} = g_{1,v} + g_{8,v} \rightarrow$ 18 + 46 = 64 , and $g_{18,p} = g_{1,v} + (g_{8,v,} - g_{10,p}) \rightarrow$ 18 + (46 - 34) = 30.

For strategies #3, the phase assignment are the same as strategies #2. The only difference is that the bicycle and pedestrian timing are separated. Equations 22 and 23 show the capacity equation for split, and equations 24 and 25 show the capacity equation for lead-lag. With lost time and then without lost time respectively.

$$c_{14,3} = \left(e^{-\frac{q_p+q_b}{3600}C} \cdot \frac{\phi_{14,v}}{C} s_i \right) + \left(e^{-\frac{q_pC}{3600}} \cdot \left(1 - e^{-\frac{q_bC}{3600}} \right) \right) \cdot \frac{\phi_{14,b}}{C} s_i + \left(1 - e^{-\frac{q_pC}{3600}} \right) \cdot \frac{\phi_{14,p}}{C} s_i \tag{22}$$

where, $\phi_{14,v} = \phi_{1,v} + \phi_{4,v} \rightarrow$ 22 + 46 = 68, $\phi_{14,b} = \phi_{1,v} + (\phi_{4,v} - \phi_{8,b}) \rightarrow$ 18 + (46 - 22) = 46, and $\phi_{14,p} = \phi_{1,v} + (\phi_{4,v} - \phi_{8,p}) \rightarrow$ 18 + (46 - 34) = 34.

$$c_{14,3} = \left(e^{-\frac{q_p+q_b}{3600}C} \cdot \frac{g_{14,v}}{C} s_i \right) + \left(e^{-\frac{q_pC}{3600}} \cdot \left(1 - e^{-\frac{q_bC}{3600}} \right) \right) \cdot \frac{g_{14,b}}{C} s_i + \left(1 - e^{-\frac{q_pC}{3600}} \right) \cdot \frac{g_{14,p}}{C} s_i \tag{23}$$

where, $g_{14,v} = g_{1,v} + g_{4,v} \rightarrow$ 18 + 46 = 64, $g_{14,b} = g_{1,v} + (g_{4,v} - g_{8,b}) \rightarrow$ 18 + (46 - 22) = 42, and $g_{14,p} = g_{1,v} + (g_{4,v} - g_{8,p}) \rightarrow$ 18 + (46 - 34) = 30.

$$c_{18,3} = \left(e^{-\frac{q_p+q_b}{3600}C} \cdot \frac{\phi_{18,v}}{C} s_i \right) + \left(e^{-\frac{q_pC}{3600}} \cdot \left(1 - e^{-\frac{q_bC}{3600}} \right) \right) \cdot \frac{\phi_{18,b}}{C} s_i + \left(1 - e^{-\frac{q_pC}{3600}} \right) \cdot \frac{\phi_{18,p}}{C} s_i \tag{24}$$

where, $\phi_{18,v} = \phi_{1,v} + \phi_{8,v} \rightarrow$ 22 + 46 = 68, $\phi_{18,b} = \phi_{1,v} + (\phi_{8,v} - \phi_{10,b}) \rightarrow$ 18 + (46 - 22) = 46, and $\phi_{18,p} = \phi_{1,v} + (\phi_{8,v} - \phi_{10,p}) \rightarrow$ 18 + (46 - 34) = 34.

$$c_{18,3} = \left(e^{-\frac{q_p + q_b}{3600}C} \cdot \frac{g_{14,v}}{C} s_i \right) + \left(e^{-\frac{q_p C}{3600}} \cdot \left(1 - e^{-\frac{q_b C}{3600}} \right) \right) \cdot \frac{g_{18,b}}{C} s_i + \left(1 - e^{-\frac{q_p C}{3600}} \right) \cdot \frac{g_{18,p}}{C} s_i \quad (25)$$

where, $g_{18,v} = g_{1,v} + g_{8,v} \rightarrow$ 18 + 46 = 64, $g_{18,b} = g_{1,v} + (g_{8,v} - g_{10,b}) \rightarrow$ 18 + (46 - 22) = 42, and $g_{18,p} = g_{1,v} + (g_{8,v} - g_{10,p}) \rightarrow$ 18 + (46 - 34) = 30.

The saturation flow rate of the westbound right-turn was assumed at 1900 vph for model calculation. Figure 10 illustrates the split capacity results of strategies #2 and #3 from simulation and the proposed model under various bicycle and pedestrian volume scenarios. Strategy #1 was not included in the figure because its capacity is constant regardless of the pedestrian and bicycle volume. See Appendix F and H for strategy #1 graphs. It can been seen that with the graphs without the clearance time (i.e. green time only) the model charts are slightly off. Whereas the graphs that included the clearance time, the model almost matches perfectly up with the results from simulation.

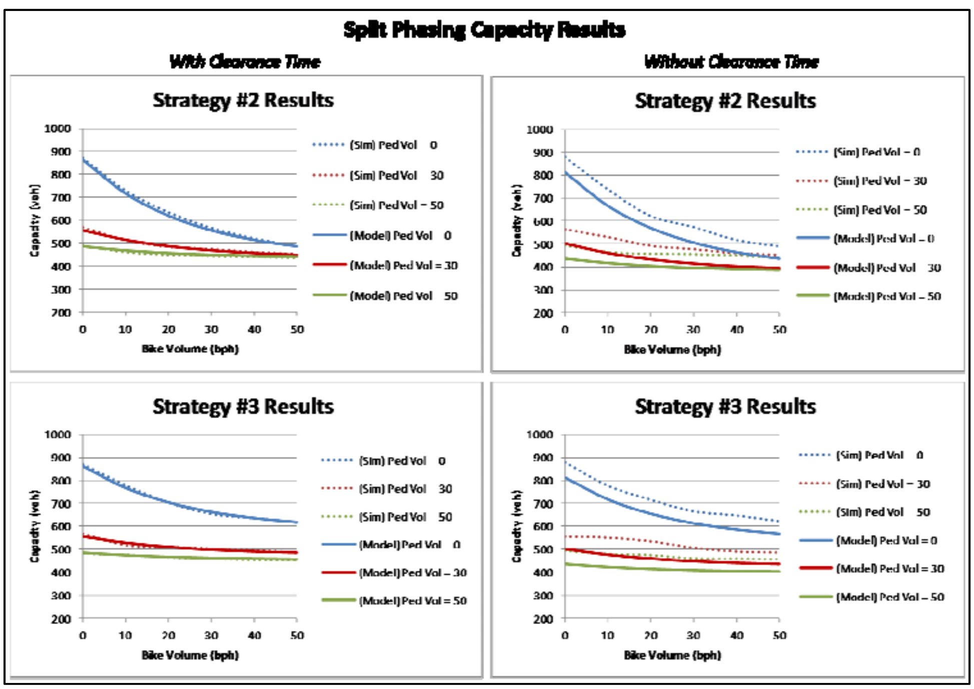


Figure 11: Split Phasing Capacity Results for Strategies #2 and #3

The equation for capacity does not consider the potential of vehicles proceeding during the clearance time, only vehicles within the green time. In simulation and real-world, not all vehicles will stop on green, which is why by including the clearance time the models match up with simulation results. And because of this, it can be concluded that the model proposed for capacity is validated.

Strategy #1 has the lowest movement capacity of westbound right-turn among all the plans, and it does not change regardless of the bicycle and pedestrian volume (See Appendix F and H). Strategies #2 and #3 significantly increase westbound right-turn capacity compared to strategy #1, with a difference that #3 has a slightly higher capacity than #2 does. With the increase of bicycle and pedestrian volumes, the capacity of westbound right-turn under strategies #2 and #3 decreases, and the difference between # 2 and #3 becomes minimal.

The goal of the lead-lag phasing strategies is to ensure that its operation runs exactly like the split phasing schemes, with the exception of two more phases and a dummy phase. Since in both the split and lead-lag designs, the westbound through movement, the bicycle and pedestrian movements all are running the same phase splits, and are lagging in the ring-barrier structure, the model proposed can be used to validate the lead-lag operation. The results of lead-lag phasing scheme is shown in Figure 11.

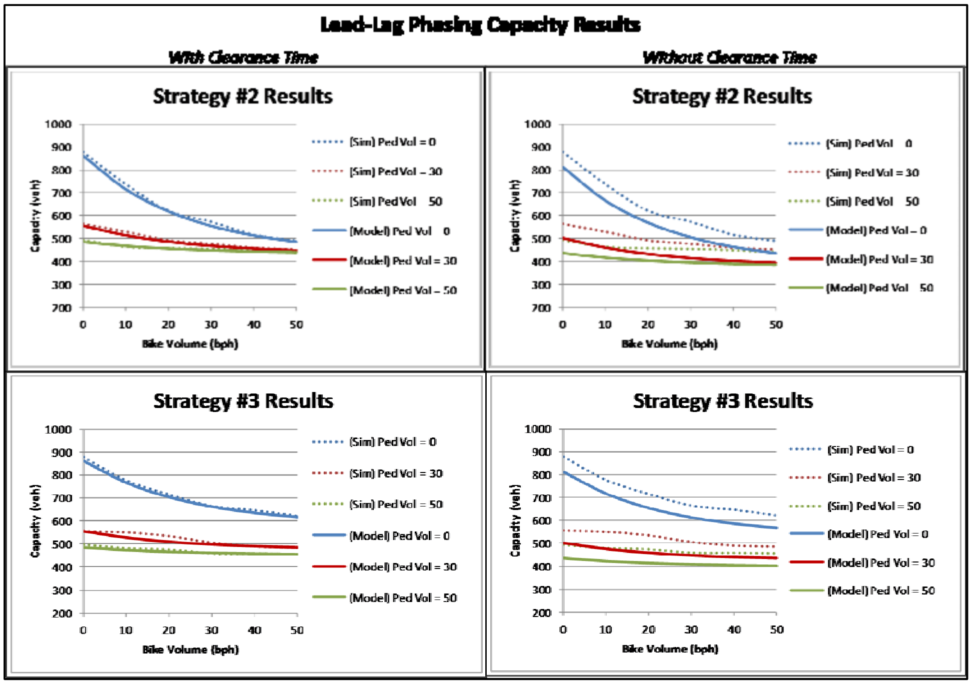


Figure 12: Lead-Lag Phasing Capacity Results for Strategies #2 and #3

It can be seen that the results from simulation of both strategies #2 and #3 are close to the results of the split designs. Strategy #1's results are almost the same as split strategy #1 results, and are not shown (See Appendix J and L). The with clearance time and without clearance time graphs from figure 10, it can be seen that the analytical model and simulation results of the lead-lag strategies almost matches with those. With this, it can be concluded that the lead-lag strategies do work since results are identical to split strategies and can be used as an alternative treatment for bicycle and pedestrian movements, and the behavior of the capacity for each design are the same.

Delay Results

The delay for the westbound right-turn was evaluated for all strategies using under-saturated conditions only. The hourly WBR volume was set at 200 vph for all simulation runs, which is below the hourly capacity of all scenarios. And therefore, the incremental delay and initial queue delay was not calculated. Uniform delay was calculated by the model and compared with the average vehicle delay obtained from the simulation software in the following analysis. The delay was also evaluated with and without the clearance time. According to HCM procedure, the uniform delay is represented as

$$d_1 = \frac{0.5C(1-\frac{g}{C})^2}{1-[\min(1,X)\frac{g}{C}]} \tag{26}$$

For strategies #1, both split and lead-lag phasing will have the same green time as did the capacity evaluation. Based on the saturation rate of 1900vph, and a cycle length of 150 seconds, the capacity is 278.7 vehicles for green and clearance time, and 228 vehicles for green without clearance time. Equations 27 and 28 shows the average vehicle delay for both clearance and without clearance times respectively.

$$d_{1,1} = \frac{0.5C(1-\frac{\phi_{1,v}}{C})^2}{1-[\min(1,\frac{v_1}{c_{1,1}})\frac{\phi_{1,v}}{C}]} \rightarrow \frac{0.5C(1-\frac{22}{C})^2}{1-[\min(1,\frac{200}{278.7})\frac{22}{C}]}, \text{for Split and Lead - Lag} \tag{27}$$

$$d_{1,1} = \frac{0.5C(1-\frac{g_{1,v}}{C})^2}{1-[\min(1,\frac{v_1}{c_{1,1}})\frac{g_{1,v}}{C}]} \rightarrow \frac{0.5C(1-\frac{18}{C})^2}{1-[\min(1,\frac{200}{278.7})\frac{18}{C}]}, \text{for Split and Lead - Lag} \tag{28}$$

Equation 29 below show the model used to evaluate strategies #2. Since the delay for both split and lead-lag phasing will be the same, the delay will be denoted as $d_{14\,\text{or}\,18,2}$ where "14" is representing phases 1 and 4 in split phasing, and "18" represent phases 1 and 8 in lead-lag. The capacity for both split and lead-lag phasing with clearance time is 861.3 vehicles when no bicycle or pedestrians are called, and 430.6 vehicles when there is a call for either. And the capacity without clearance time is 810.7 when there are only vehicles, and 380 vehicles with a bicycle and/or pedestrian call.

$$d_{14\text{ or }18,2} = e^{-\frac{q_p+q_b}{3600}C} d_{14\text{ or }18,\text{v}} + (1-e^{-\frac{q_p+q_b}{3600}C}) d_{14\text{ or }18,\text{p}} \quad (29)$$

where $d_{14\text{ or }18,\text{v}} = \dfrac{0.5C(1-\frac{68}{C})^2}{1-[\min(1,\frac{200}{861.3})\frac{68}{C}]}$ and $d_{14\text{ or }18,\text{p}} = \dfrac{0.5C(1-\frac{34}{C})^2}{1-[\min(1,\frac{200}{430.7})\frac{34}{C}]}$ for green with clearance time.

And where, $d_{14\text{ or }18,\text{v}} = \dfrac{0.5C(1-\frac{64}{C})^2}{1-[\min(1,\frac{200}{810.7})\frac{64}{C}]}$ and $d_{14\text{ or }18,\text{p}} = \dfrac{0.5C(1-\frac{30}{C})^2}{1-[\min(1,\frac{200}{380})\frac{30}{C}]}$ for green without clearance time.

Equation 30 below shows the model used to evaluate strategies #3. The same denotation $d_{14\text{ or }18,2}$ is used and described in the previous paragraph. The capacity for both split and lead-lag phasing with clearance time is 861.3 vehicles when no bicycle or pedestrians are called, 582.7 vehicles when there is a call for bicycle, and 430.6 vehicles when there is a call for pedestrians. And the capacity without clearance time is 810.7 when there are only vehicles, 532 vehicles with a bicycle call, and 380 vehicles with only a pedestrian call.

$$d_{i,3} = e^{-\frac{q_p+q_b}{3600}C} d_{i,v} + e^{-\frac{q_pC}{3600}}(1-e^{-\frac{q_bC}{3600}}) d_{i,b} + (1-e^{-\frac{q_pC}{3600}}) d_{i,p} \quad (30)$$

where $d_{14\text{ or }18,\text{v}} = \dfrac{0.5C(1-\frac{68}{C})^2}{1-[\min(1,\frac{200}{861.3})\frac{68}{C}]}$, $d_{14\text{ or }18,\text{b}} = \dfrac{0.5C(1-\frac{46}{C})^2}{1-[\min(1,\frac{200}{582.7})\frac{46}{C}]}$ and

$d_{14\text{ or }18,\text{p}} = \dfrac{0.5C(1-\frac{34}{C})^2}{1-[\min(1,\frac{200}{430.6})\frac{34}{C}]}$ for green with clearance time.

And where $d_{14\text{ or }18,\text{v}} = \dfrac{0.5C(1-\frac{64}{C})^2}{1-[\min(1,\frac{200}{810.7})\frac{64}{C}]}$, $d_{14\text{ or }18,\text{b}} = \dfrac{0.5C(1-\frac{42}{C})^2}{1-[\min(1,\frac{200}{532})\frac{42}{C}]}$ and

$d_{14\text{ or }18,\text{p}} = \dfrac{0.5C(1-\frac{30}{C})^2}{1-[\min(1,\frac{200}{380})\frac{30}{C}]}$ for green without clearance time.

Figure 12 illustrates the average delay results from simulation and the proposed model. The graph for strategy #1 is not shown because the westbound right-turn movement green time is the same for every cycle regardless if there is a bicyclist present. The delay for split phasing strategy #1 from simulation resulted in 71.56 sec/veh. As for the models, a delay of 64.91 sec/veh and 61.04 sec/veh resulted for one with the clearance and without clearance time respectively.

As it can be seen in the graphs for strategy #2 and #3, the delay increases when the bicycle volume increases. The graphs converge and the results are close as the bicycle volume reaches 50. In strategy #2, the blue line (Ped Vol = 0) when the bicycle volume is at zero, the right-turn movement has the minimal amount of delay. But as the bicycle volume increases to 50, the rate of its delay increases rapidly and almost converges to the red and green graph lines. The reason for that is the bicycle phase is tied to the pedestrian phase. When there is a bicycle detection, the pedestrian time will be given. Essentially the bicyclist can be considered as a pedestrian. Essentially, as the bike volume reaches 50, the number of calls can be considered as 50 pedestrian calls. From the red line (Ped Vol = 30) it can be seen that when the bicycle volume is 20, and when the blue line at a bike volume of 50, the delay is the same. The green and red line's delay increase is not as rapid as the blue line is because the chances of multiple bicyclist and pedestrians getting accommodated are higher. In strategy #3, there is a slight difference in the rate at which delay is increasing. This is due to the bicycle phase being separated from the pedestrian phase. The timing for the bicycle phase is less.

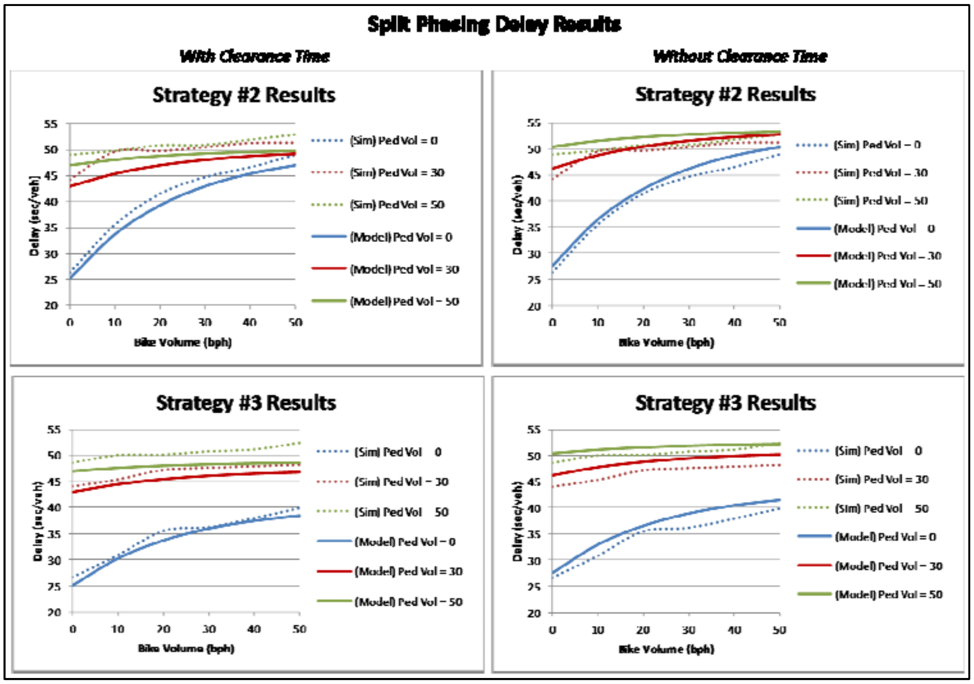


Figure 13: Split Phasing Delay Results for Strategies #2 and #3

In figure 12, the analytical model results, and the simulation results indicate the same trend. The analytical model graphs that included clearance time yield a lower delay than ones without the clearance time, which is expected. The authors believe the difference resulted from the accountability of acceleration and deceleration analysis. The proposed model was designed to estimate control delay, so it was unable to account for the delay caused by acceleration and deceleration as the simulation software does. The results for the delays in split phasing can be seen in Appendix E and G.

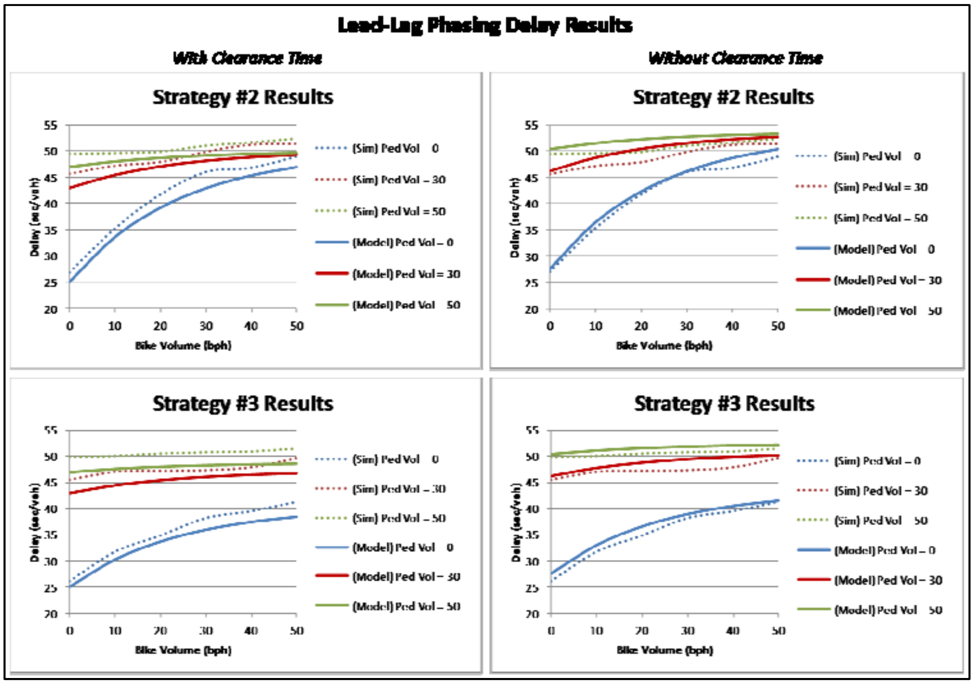


Figure 14: Lead-Lag Phasing Delay Results for Strategies #2 and #3

The results from simulation for lead-lag phasing is almost identical with split phasing. As mentioned in the capacity results, the lead-lag design was developed and is to be checked if its operation can run like the split phasing. Comparing the results from figure 13 to figure 12, it can be seen that the lines are almost identical. The simulation results from figure 13 also follow the trends lines from the results of the proposed model. From this, it can be concluded that the lead-lag operation works.

Case Study Evaluation

As explained in Chapter 2, the topic investigated in this paper is based on a real-case intersection located in Sparks, Nevada at E. McCarran Blvd. and Nichols Blvd. To compare how efficient each of the proposed design strategies would operate at this intersection, the author used VISSIM simulations for testing. This intersection is operating under split phasing, and thus only the split phasing strategies will be applied to the intersection.

A 2-hour vehicular volume count was conducted during PM peak hours at the intersection. The peak 15-min flow rate was used in the simulation analysis (Table 2). The bicycle and pedestrian column values are the volume for both approaches, east and westbound. Each simulation was set to have 25 runs of a 10-min seeding period and a 60-min simulation period. Figure 14 shows the average delay of WBR movement.

Signal Group (Sol #1)	SB L	SBT/SB R	NB L	NBT/NB R	E B	WBL/WB T	WB R	EB/WB Bike	EB/WB Ped
Peak 15-min flow rate (vph)	19	220	18	507	55	73	21	-	-
Signal Group (Sol #2)	SB L	SBT/SB R	NB L	NBT/NB R	E B	WBL/WB T	WB R	EB/WB Bike	EB/WB Ped
Peak 15-min flow rate (vph)	19	220	18	507	55	73	21	5	7
Signal Group (Sol #3)	SB L	SBT/SB R	NB L	NBT/NB R	E B	WBL/WB T	WB R	EB/WB Bike	EB/WB Ped
Peak 15-min flow rate (vph)	19	220	18	507	55	73	21	5	7

Table 2: Peak P.M. Volumes Used for Each Design Strategies.

Figure 14 shows the average delay results from simulation. It can be seen that the current operation westbound right-turn suffers from high delay. Strategies #2 and #3 offer the best solution for this case as there is about 12 seconds in delay reduction. Strategy #3 has a lower delay result than strategy #2 because the bicycle and pedestrian phasing are not tied together and each has their own separate timing. Bicycle crossing time is less than pedestrian crossing time which when there is only a bicycle call, the westbound right-turn can proceed sooner and experience lower delay.

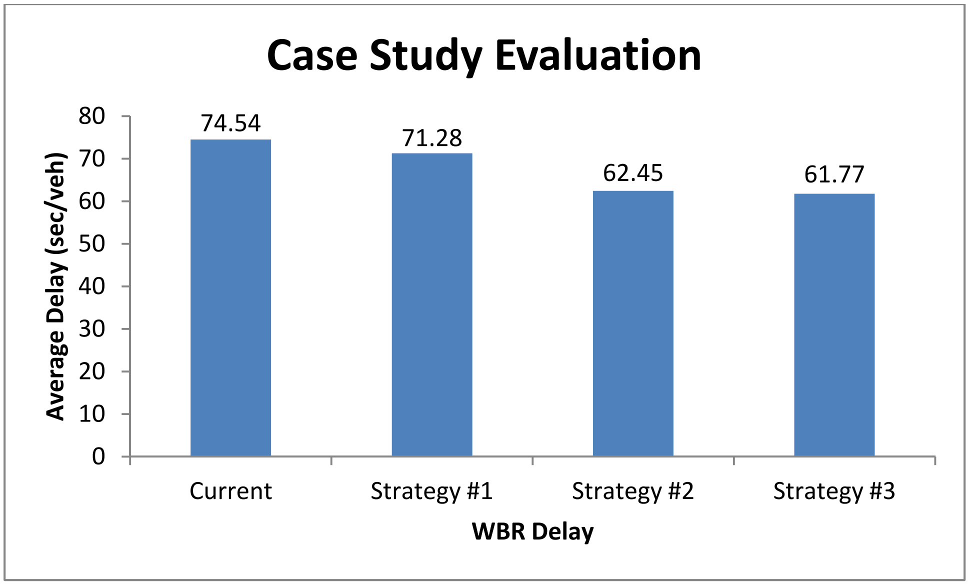


Figure 15: Westbound Right-Turn Delay Results

It can be concluded from the simulation results that, with the current traffic demand, the operational efficiency of the study intersection can be improved with the implementation of strategies #2 or #3.

Implementation to Intersection

The results from simulation provide a good overall observation of what an actual intersection may experience, however, observations from the field may differ. For this case study, strategies #2 or #3 were not implemented in the field. The City of Sparks uses an Eagle controller (model PIM-177) for this particular intersection. The version of this model is older than 10 years and does not offer many programming options that modern controllers have. To implement strategies #2 or #3, a phase modifier function is needed to suppress the westbound right-turn overlap when there is a bicycle or pedestrian call, which the Eagle controller offers no programmable options to accommodate. Based on a discussion with the city engineer, a modern controller will replace the current controller in the future. It is then when these strategies should be implemented for testing and to see whether improvements can be seen in the field.

Use of the current controller's omit feature has been thought of as an idea by the city's traffic engineer. This solution uses two overlaps and a tied bicycle and pedestrian phase. One overlap (westbound right) is controlled by the southbound left (φ1) and φ4. The other (westbound through) is controlled by φ4 and the bicycle and pedestrian phase (φ8). If there are no bicycle and/or pedestrians present, φ4 is activated. If there is a bicycle or pedestrian call, φ4 is omitted and φ8 is activated. At this time, westbound through, bicycle and pedestrians can proceed while westbound right is off. This idea has yet to be implemented and/or tested. There is speculation whether this idea would work in coordination.

CHAPTER 5: RECOMMENDATIONS & CONCLUSIONS

The aim of this research was to develop suitable and efficient phasing strategies that accommodate exclusive bicycle traffic signals at intersections. Six strategies, three of each in split and lead-lag phasing schemes, were tested in simulation. Specifically to evaluate the right-turn lane that is adjacent to a two-way bicycle path in terms of its capacity and delay. Considering the randomness of bicycle and pedestrian arrivals, analytical models were also developed and validated with the results from simulation. The strategies were also implemented in the case study's current operation and tested in simulation. Major findings and conclusions reached in this research are as follows.

- The proposed analytical model, analyzed the right-turn lane capacity and delay, accounts for the stochastic nature of pedestrian and bicycle arrivals, produced results that are consistent with VISSIM micro-simulations. It can be seen that under the results for capacity, the model resulted in a lower capacity when using the effective green time. However, in simulation and in real life, not all vehicles will stop prior to the clearance interval. When the actual split time was used, the results from the model matches up with the results from simulation. As for delay, when the effective green time is used, model resulted in a slightly higher delay than simulations. When split time is used, the delay models resulted in a slightly lower delay than simulation. However, the results from delay are still consistent with the delay models. If half the clearance time is added to the effective green time, the model will match up with simulation.
- On the basis of sample calculation in this study, design strategies with actuated bicycle phases would significantly improve traffic efficiency compared with pre-timed bicycle phase operation under various scenarios. The design strategies to tie bicycle phase with adjacent through-vehicle movement are recommended when pedestrian or bicycle demand is high and the adjacent vehicle traffic is not heavy, typically when there is a demand bicycle and

pedestrians for every cycle. This will reduce the capacity and increase the delay of the adjacent right-turn lane since it will only proceed after the adjacent through and bicycle movement is terminated. However, since the right-turn operates as an overlap, increasing the concurrent southbound left-turn lane split can improve its performance.

- The strategies (#2) to tie bicycle phase with pedestrian movement are recommended when the difference between pedestrian and bicycle crossing time is small. This can be applied when all ranges of bicycle and pedestrian volume are low, medium and high, and when the intersection crossing width is small. The efficiency of this solution is lower than that of #3 strategies, however, installation of a bicycle detector can be wired to the pedestrian detector and there are less timing parameters to be set.
- The strategies (#3) to separate bicycle and pedestrian activation would have the most efficient impact on traffic operation when the intersection geometry resulted in longer pedestrian crossing time than bicycle crossing time and both bicycle and pedestrian demands are at a low or medium level. This strategy can be used for high bicycle and pedestrian demands as well, however, the chances of a pedestrian call at every cycle is certain, and pedestrian timing will be activated regardless, when this occurs the effectiveness of this strategy becomes similar to strategies #2.
- In terms of the impact on the adjacent right-turn lane operations, based on the case study results, the three proposed split strategies do not show a lot of difference when the right-turn traffic is low. However, under heavier right-turn vehicular demand, actuated bicycle phase designs (Strategies #2 and #3) will be more efficient than the pre-timed design to increase vehicle mobility and reduce delay.
- Split phasing strategies should be used based on the geometric configuration of the road (i.e. shared through and left turn lane). Lead-Lag strategies should be used at intersections that are under coordination.

<u>Future Research</u>

- During this research, each of the strategies was not tested with different controllers and implemented in the field. Strategies should be tested with different scenarios ranging from: Intersection coordination, bicycle path along the major street, and different lane configurations such as two-lane right-turn adjacent to bicycle path.
- In both split and phasing strategies (#2 and #3), the author did not test the bicycle movement as the leading phase. Different options in the controller would have to be set and some existing options would have to be changed in order for this to work. The issue with this option is that the through movement adjacent to the bicycle path may terminate early and then allow a conflicting left-turn movement to proceed while the bicycle and pedestrian movement is on.

References

(1) Alexiadis, V., Dowling, R., & Skabardonis, A. (2007). Traffic Analysis Toolbox Volume III. Guidelines for Applying Traffic Microsimulation Modeling Sofeware.

(2) American Association of State Highway and Transporation Officials . (2012). Guide for the Development of Bicycle Facilities (4th ed.). Washington D.C.

(3) California Department of Transportation . (2012). California Manual on Uniform Traffic Control Devices (CA MUTCD). Sacramento, CA.

(4) Cheng, D., Tian, Z., & Liu, H. (2008). Implementian actuated signal-controlled intersection capacity analysis with pedestrians. Transportation Research Record: Journal of the Transportation Research Board. 2071, 125-30.

(5) Dill, J., & Carr, T. (2003). Bicycle Commuting and Facilities in Major U.S. Cities: If You Build Them, Commuters Will Use Them. Transportation Research Record, 1828, 116-123.

(6) Federal Highway Administration . (2015, May). Separated Bike Lane Planning and Design Guide. Task Order: DTFH61-11-D-00035-T-13001.

(7) FHWA. (2004, August). Signalized Intersections: Informational Guide: Contract No. DTFH61-98-C-00075.

(8) Golgowski, N. (2012, December 3). More bicycle traffic signals getting green light in cites across U.S. Retrieved from Daily Mail Web Site: http://www.dailymail.co.uk/news/article-2242412/Bicycle-traffic-signals-green-light-U-S-motorists-beware-green-mean-go.html

(9) Lindley, J. A. (2013, December). Interim Approval for Optional Use of a Bicycle Signal Face (IA-16): FHWA. Retrieved from http://mutcd.fhwa.dot.gov/resources/interim_approval/ia16/index.htm

(10) Monsere, C., Figliozzi, M., Thompson, S., & Paulsen, K. (2013, October). Operational Guidance For Bicycle-Specific Traffic Signals in the United States. Contract No.: OTREC 2102FG.

(11) NACTO. (2011, April). Urban Bikeway Design Guide.

(12) TAC. (2004, March). Traffic Signal Guidelines for Bicycles.

(13) Thompson, S. R., Monsere, C. M., Figliozzi, M. A., Koonce, P., & Obery, G. (2013, May). Bicycle-Specific Traffic Signals: Results from State-of-the-Practice Review. Retrieved from http://pdxscholar.library.pdx.edu/cgi/viewcontent.cgi?article=1007&context=studentsymposium

(14) Transportation Research Board. (2010). Highway Capacity Manual. Washington D.C.: Transporatation Research Board, National Research Council.

(15) Transportation Research Board. (2015). Signal Timing Manual (2nd Ed.). NCHRP Report 812. Washington, D.C.: National Cooperative Highway Research Program.

(16) Truong, L. T., Sarvi, M., Currie, G., & Garoni, T. M. (2015). Required traffic micro-simulation runs for reliable multivariate performance estimates. Journal of Advanced Transporation.

(17) Wei, D., Kumfer, W., Tian, Z., & Yuan, C. (2013). An analytical delay model to yielding vehicles at unsignalized pedestrian crossings. In Transportation Research Board 92nd Annual Meeting (No. 13-2881).

(18) Wei, D., Liu, H., & Tian, Z. (2015). Vehicle delay estimation at unsignalised pedestrian crosswalks with probablistic yielding behavior. Transporatmetriac A: Transport Science, 11(2), 103-118.

(19) Wiegand, J. D., & Yang, C. Y. (2011). Traffic Simulation Runs: How Many Needed?. Public Roads, 74(4).

APPENDIX A: Case Study's Signal Database

E. McCarran Blvd / Nichols Blvd Timing Database								
Phase	**1 SBLT**	**2 NB**	**3 WB**	**4 EB**	**5 NBLT**	**6 SB**	**7 N/A**	**8 N/A**
Min Green	4	10	4	4	4	10	0	0
Passage	1	2	1	1	1	2	0	0
Max 1	20	40	20	20	20	40	25	35
Max 2	25	100	17	28	20	100	30	50
Yellow Change	3	3.9	3	3	3	3.9	4	4
Red Clearance	1	2.3	3.7	3.7	4	2.3	1	1
Added Init	0	0	0	0	0	0	0	0
Max Init	0	0	0	0	0	0	0	0
TBR	0	16	0	0	0	16	0	0
CBR	0	0	0	0	0	0	0	0
TTR	0	16	0	0	0	16	0	0
Min Gap	0	1	0	0	0	1	0	0
Walk	0	6	6	6	0	6	0	0
Pedestrian Clear	0	19	20	22	0	20	0	0

Timing Plan								
Time	0600 - 0830							
Cycle Length	140							
Phase Time	18	43	34	45	16	45	0	0
Phase Mode	Actuated	Coord Ph	Actuated	Actuated	Actuated	Coord Ph	Actuated	Actuated
Offset	109							
Pattern Mode	Perm Omit							
Alternate Sequence	0							
Time	0830 - 1100	1300 - 1500	1830 - 1930					
Cycle Length	140							
Phase Time	24	46	34	36	28	42	0	0
Phase Mode	0 -Actuated	Coord Ph	Actuated	Actuated	Actuated	Coord Ph	Actuated	Actuated
Offset	103							
Pattern Mode	Normal							
Alternate Sequence	0							

Time	1500 - 1830							
Cycle Length	150							
Phase Time	22	48	34	46	22	48	0	0
Phase Mode	Actuated	Coord Ph	Actuated	Actuated	Actuated	Coord Ph	Actuated	Actuated
Offset	80							
Pattern Mode	Normal							
Alternate Sequence	0							
Time	1100 - 1300							
Cycle Length	150							
Phase Time	22	48	34	46	22	48	0	0
Phase Mode	Actuated	Coord Ph	Actuated	Actuated	Actuated	Coord Ph	Actuated	Actuated
Offset	108							
Pattern Mode	Perm Omit							
Alternate Sequence	2							

APPENDIX B: Counted Peak P.M. Volumes

Site:	E. McCarran Blvd. / Nichols Blvd.
Time:	4:30p.m. - 6:00p.m. (May 2015)

Time Interval	NB L	NBT	NB R	SB L	SBT	SB R	EB L	EB T	EB R	WBL (T/B)	WBT (T/B)
4:30p.m. - 4:45p.m.	18	388	68	14	186	20	20	12	6	8	0
4:45p.m. - 5:00p.m.	14	361	40	13	179	11	20	14	9	8	1
5:00p.m. - 5:15p.m.	6	409	42	19	200	13	23	16	5	16	0
5:15p.m. - 5:30p.m.	16	439	58	15	184	11	17	13	5	6	1
5:30p.m. - 5:45p.m.	13	386	46	9	127	14	10	16	6	7	0
5:45p.m. - 6:00p.m.	10	390	47	10	161	18	30	10	3	7	1
Totals	77	2373	301	80	1037	87	120	81	34	52	3

WBR (T/B)	WBL	WBT	WBR	Bike (N)	Bike (S)	Ped (N)	Ped (S)	Totals (Veh)
0	37	9	21	1	2	3	3	807
0	47	9	14	5	0	7	5	740
0	31	5	16	0	2	0	2	805
0	33	8	12	1	1	4	8	832
0	38	5	13	1	0	1	5	697
0	31	8	9	0	0	2	4	741
0	217	44	85	8	5	17	27	

APPENDIX C: Split Design Strategy Timing Parameters

Phase #	Strategy #1					
	φ1 - SBL	φ2 - NBT	φ3 - EBT	φ4 - WBT	φ5 - NBL	φ6 - SBT
Split	22	48	34	46	22	48
Min. Green	4	10	4	16	4	10
Passage	1	2	1	1	1	2
Yellow	3	3.9	3	5	3	3.9
All-Red	1	2.3	3.7	1	4	2.3
Walk	0	6	6	6	0	6
FDW	0	19	20	22	0	20
Cycle	150					

Phase #	Strategy #2						
	φ1 - SBL	φ2 - NBT	φ3 - EBT	φ4 - WBT	φ5 - NBL	φ6 - SBT	φ8 - Ped & Bicycle
Split	22	48	34	46	22	48	34
Min. Green	4	10	4	4	4	10	-
Passage	1	2	1	1	1	2	-
Yellow	3	3.9	3	3	3	3.9	5
All-Red	1	2.3	3.7	3.7	4	2.3	1
Walk	0	6	6	6	0	6	6
FDW	0	19	20	22	0	20	22
Cycle	150						

Phase #	Strategy #3							
	φ1 - SBL	φ2 - NBT	φ3 - EBT	φ4 - WBT	φ5 - NBL	φ6 - SBT	φ8 - Ped & Bicycle	φ8 - Bicycle Only
Split	22	48	34	46	22	48	34	22
Min. Green	4	10	4	4	4	10	-	16
Passage	1	2	1	1	1	2	-	-
Yellow	3	3.9	3	3	3	3.9	5	5
All-Red	1	2.3	3.7	3.7	4	2.3	1	1
Walk	0	6	6	6	0	6	6	-
FDW	0	19	20	22	0	20	22	-
Cycle	150							

APPENDIX D: Lead-Lag Design Strategy Timing Parameters

Phase #	Strategy #1							
	φ1 - SBL	φ2 - NBT	φ3 - WBL	φ4 - EBT	φ5 - NBL	φ6 - SBT	φ7 - EBL	φ8 - WBT
Split	22	48	34	46	22	48	34	46
Min. Green	4	10	4	4	4	10	4	16
Passage	1	2	3	1	1	2	1	3
Yellow	3	3.9	3	3	3	3.9	3	5
All-Red	1	2.3	3.7	3.7	4	2.3	3.7	1
Walk	0	6	0	6	0	6	0	6
FDW	0	19	0	22	0	22	0	22
Cycle	150							

Phase #	Strategy #2								
	φ1 - SBL	φ2 - NBT	φ3 - WBL	φ4 - EBT	φ5 - NBL	φ6 - SBT	φ7 - EBL	φ8 - WBT	φ10 - Ped & Bicycle
Split	22	48	34	46	22	48	34	46	34
Min. Green	4	10	4	4	4	10	4	4	-
Passage	1	2	3	1	1	2	1	1	-
Yellow	3	3.9	3	3	3	3.9	3	3	5
All-Red	1	2.3	3.7	3.7	4	2.3	3.7	3.7	1
Walk	0	6	0	6	0	6	0	6	6
FDW	0	19	0	22	0	22	0	22	22
Cycle	150								

Phase #	Strategy #3									
	φ1 - SBL	φ2 - NBT	φ3 - WBL	φ4 - EBT	φ5 - NBL	φ6 - SBT	φ7 - EBL	φ8 - WBT	φ10 - Ped & Bicycle	φ10 - Bicycle Only
Split	22	48	34	46	22	48	34	46	34	22
Min. Green	4	10	4	4	4	10	4	4	-	16
Passage	1	2	3	1	1	2	1	1	-	-
Yellow	3	3.9	3	3	3	3.9	3	3	5	5
All-Red	1	2.3	3.7	3.7	4	2.3	3.7	3.7	1	1
Walk	0	6	0	6	0	6	0	6	6	-
FDW	0	19	0	22	0	22	0	22	22	-
Cycle	150									

APPENDIX E: Split Design Capacity and Delay Results (W/ Clearance Time)

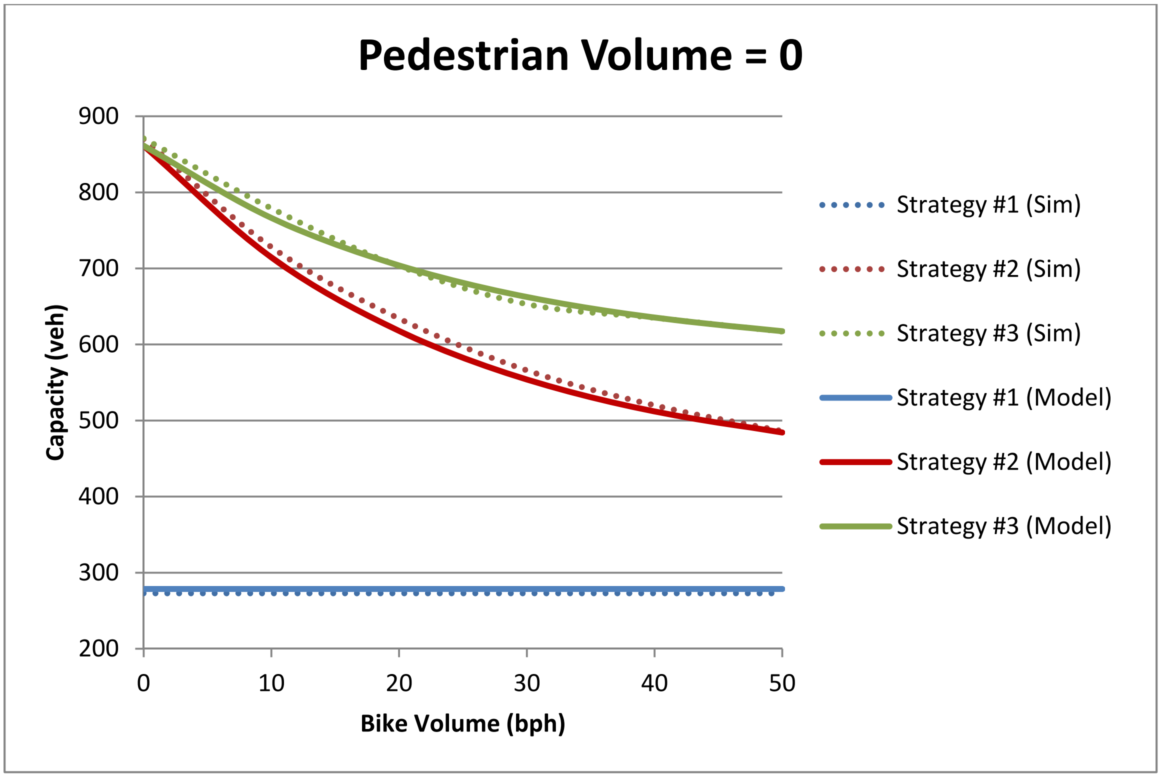
Split Capacity Results							
Simulation				Model			
Pedestrian Volume =	0			Pedestrian Volume =	0		
Bicycle Volume	Strategy #1	Strategy #2	Strategy #3	Bicycle Volume	Strategy #1	Strategy #2	Strategy #3
0	273	870	871	0	278.6666667	861.3333333	861.3333333
10	273	728	779	10	278.6666667	714.5796314	766.3750556
20	273	634	703	20	278.6666667	617.8336285	703.7747008
30	273	566	653	30	278.6666667	554.0547325	662.5060034
40	273	520	635	40	278.6666667	512.009093	635.3000013
50	273	486	617	50	278.6666667	484.290899	617.3646994
Pedestrian Volume =	10			Pedestrian Volume =	10		
Bicycle Volume	Strategy #1	Strategy #2	Strategy #3	Bicycle Volume	Strategy #1	Strategy #2	Strategy #3
0	273	725	718	0	278.6666667	714.5796314	714.5796314
10	273	613	663	10	278.6666667	617.8336285	651.9792766
20	273	568	617	20	278.6666667	554.0547325	610.7105792
30	273	510	591	30	278.6666667	512.009093	583.5045771
40	273	489	569	40	278.6666667	484.290899	565.5692752
50	273	467	554	50	278.6666667	466.0179394	553.7455954
Pedestrian Volume =	20			Pedestrian Volume =	20		
Bicycle Volume	Strategy #1	Strategy #2	Strategy #3	Bicycle Volume	Strategy #1	Strategy #2	Strategy #3
0	273	633	628	0	278.6666667	617.8336285	617.8336285
10	273	563	586	10	278.6666667	554.0547325	576.5649311
20	273	516	553	20	278.6666667	512.009093	549.358929
30	273	487	538	30	278.6666667	484.290899	531.4236271
40	273	461	527	40	278.6666667	466.0179394	519.5999473
50	273	445	517	50	278.6666667	453.971662	511.8052972
Pedestrian Volume =	30			Pedestrian Volume =	30		
Bicycle Volume	Strategy #1	Strategy #2	Strategy #3	Bicycle Volume	Strategy #1	Strategy #2	Strategy #3
0	273	569	567	0	278.6666667	554.0547325	554.0547325
10	273	512	516	10	278.6666667	512.009093	526.8487304
20	273	482	509	20	278.6666667	484.290899	508.9134285
30	273	472	500	30	278.6666667	466.0179394	497.0897487
40	273	458	493	40	278.6666667	453.971662	489.2950986
50	273	450	483	50	278.6666667	446.0302665	484.1565486
Pedestrian Volume =	40			Pedestrian Volume =	40		

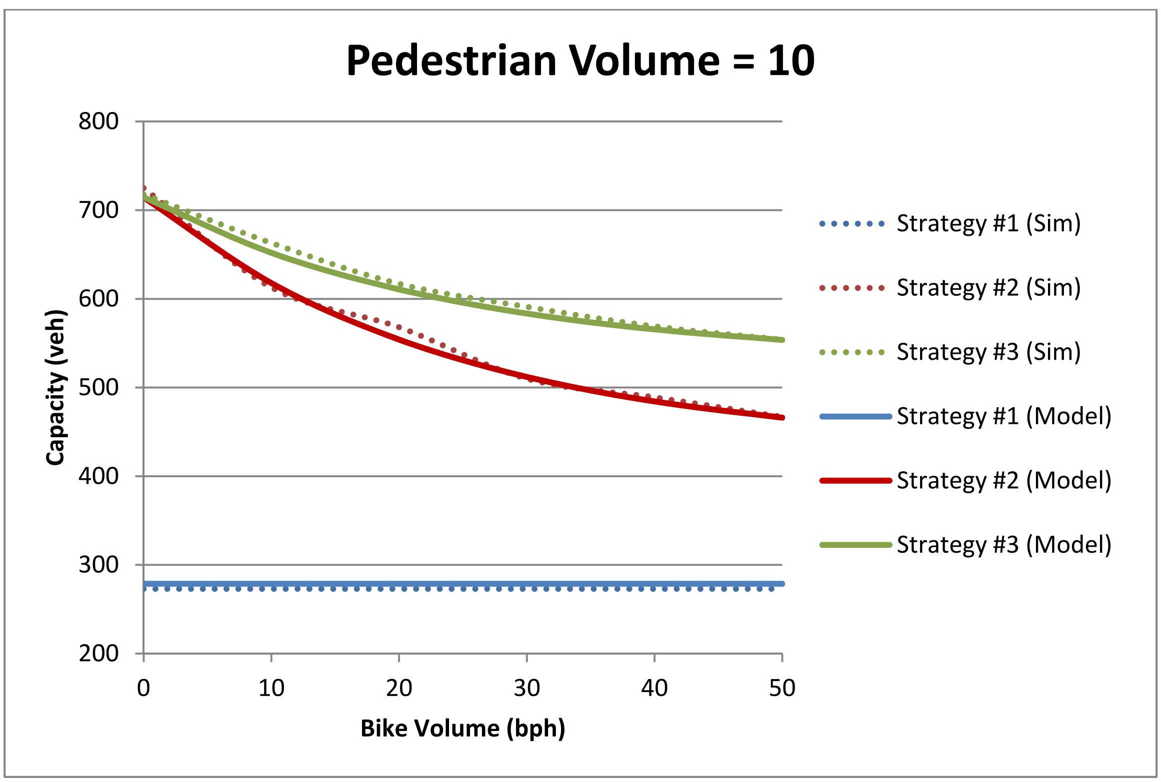
Bicycle Volume	Strategy #1	Strategy #2	Strategy #3	Bicycle Volume	Strategy #1	Strategy #2	Strategy #3
0	273	510	509	0	278.6666667	512.009093	512.009093
10	273	476	497	10	278.6666667	484.290899	494.073791
20	273	464	480	20	278.6666667	466.0179394	482.2501112
30	273	453	475	30	278.6666667	453.971662	474.4554612
40	273	443	471	40	278.6666667	446.0302665	469.3169111
50	273	442	467	50	278.6666667	440.7949759	465.9293701
Pedestrian Volume =		50		Pedestrian Volume =		50	
Bicycle Volume	Strategy #1	Strategy #2	Strategy #3	Bicycle Volume	Strategy #1	Strategy #2	Strategy #3
0	273	488	479	0	278.6666667	484.290899	484.290899
10	273	459	474	10	278.6666667	466.0179394	472.4672193
20	273	448	464	20	278.6666667	453.971662	464.6725692
30	273	442	458	30	278.6666667	446.0302665	459.5340191
40	273	439	454	40	278.6666667	440.7949759	456.1464782
50	273	435	452	50	278.6666667	437.3436596	453.9132735
Strategy #1 Simulation Seed =				#10001 - 10025			
Strategy #2 Simulation Seed =				#1 - 900			
Strategy #3 Simulation Seed =				#901 - 1800			

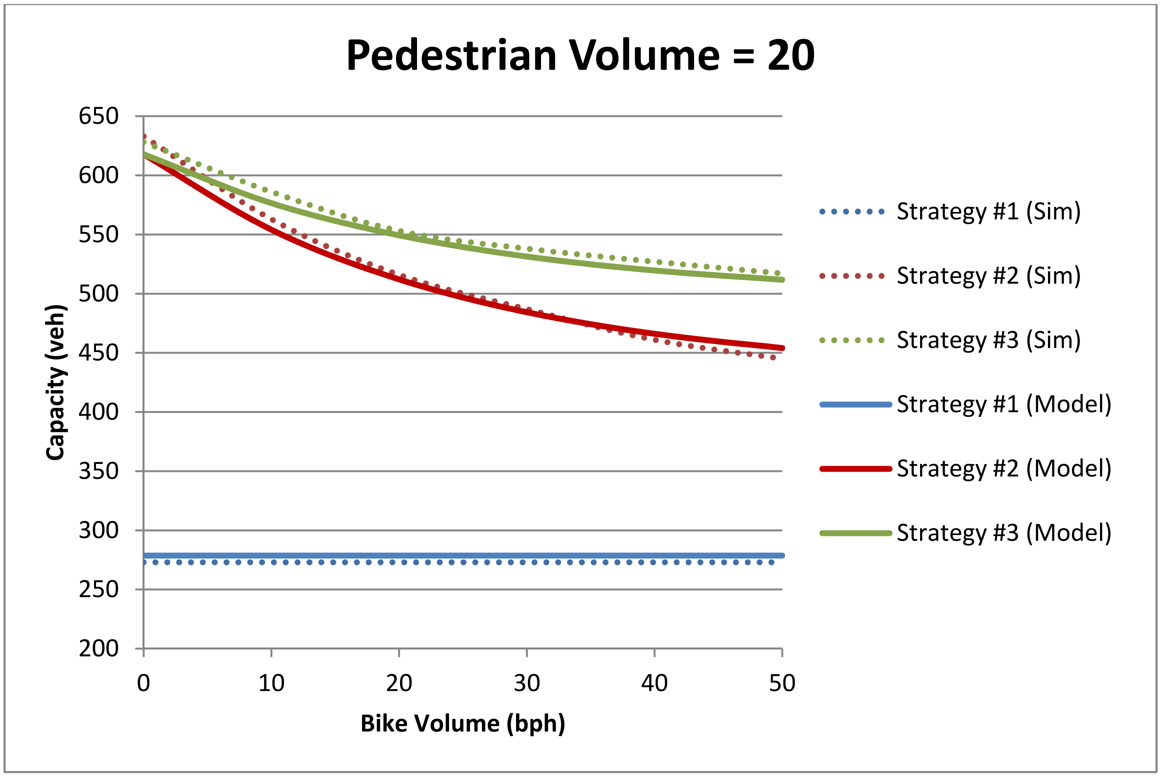
Split Delay Results (Veh = 200)							
Simulation				Model			
Pedestrian Volume =		0		Pedestrian Volume =		0	
Bicycle Volume	Strategy #1	Strategy #2	Strategy #3	Bicycle Volume	Strategy #1	Strategy #2	Strategy #3
0	71.56	26.3	26.72	0	61.03843137	25.05019608	25.05019608
10	71.56	35.53	30.9	10	61.03843137	33.59644107	30.24497245
20	71.56	41.5	35.54	20	61.03843137	39.23047301	33.6695801
30	71.56	44.72	36.22	30	61.03843137	42.94465577	35.9272206
40	71.56	46.6	37.96	40	61.03843137	45.39319596	37.41554895
50	71.56	49.03	39.87	50	61.03843137	47.00737313	38.39671547
Pedestrian Volume =		10		Pedestrian Volume =		10	
Bicycle Volume	Strategy #1	Strategy #2	Strategy #3	Bicycle Volume	Strategy #1	Strategy #2	Strategy #3
0	71.56	37.01	36.2	0	61.03843137	33.59644107	33.59644107
10	71.56	40.72	38.57	10	61.03843137	39.23047301	37.02104872
20	71.56	45.5	41.03	20	61.03843137	42.94465577	39.27868922
30	71.56	48.07	42.44	30	61.03843137	45.39319596	40.76701757
40	71.56	48.56	43.82	40	61.03843137	47.00737313	41.74818409

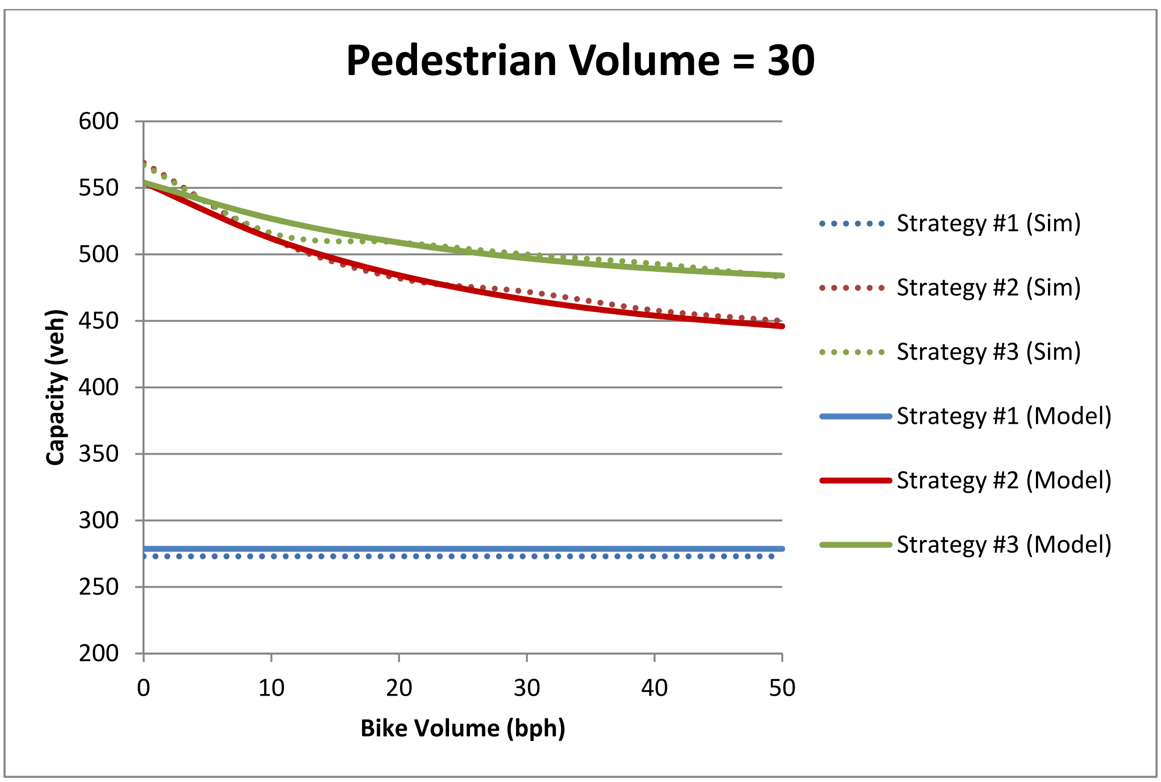
50	71.56	50.48	45.08	50	61.03843137	48.07150431	42.39500892
Pedestrian Volume =		20		Pedestrian Volume =		20	
Bicycle Volume	Strategy #1	Strategy #2	Strategy #3	Bicycle Volume	Strategy #1	Strategy #2	Strategy #3
0	71.56	40.93	41.62	0	61.03843137	39.23047301	39.23047301
10	71.56	44.77	44.03	10	61.03843137	42.94465577	41.48811351
20	71.56	47.42	44.84	20	61.03843137	45.39319596	42.97644186
30	71.56	49.59	46.21	30	61.03843137	47.00737313	43.95760838
40	71.56	49.7	45.95	40	61.03843137	48.07150431	44.60443321
50	71.56	51.69	47.22	50	61.03843137	48.77302282	45.03084642
Pedestrian Volume =		30		Pedestrian Volume =		30	
Bicycle Volume	Strategy #1	Strategy #2	Strategy #3	Bicycle Volume	Strategy #1	Strategy #2	Strategy #3
0	71.56	44.21	43.97	0	61.03843137	42.94465577	42.94465577
10	71.56	49.6	45.29	10	61.03843137	45.39319596	44.43298412
20	71.56	49.7	47.15	20	61.03843137	47.00737313	45.41415064
30	71.56	50.44	47.57	30	61.03843137	48.07150431	46.06097547
40	71.56	51.23	47.88	40	61.03843137	48.77302282	46.48738868
50	71.56	51.3	48.2	50	61.03843137	49.23549233	46.7684976
Pedestrian Volume =		40		Pedestrian Volume =		40	
Bicycle Volume	Strategy #1	Strategy #2	Strategy #3	Bicycle Volume	Strategy #1	Strategy #2	Strategy #3
0	71.56	48.25	47.6	0	61.03843137	45.39319596	45.39319596
10	71.56	49.43	48.29	10	61.03843137	47.00737313	46.37436248
20	71.56	50.44	48.83	20	61.03843137	48.07150431	47.02118731
30	71.56	51.23	49.12	30	61.03843137	48.77302282	47.44760052
40	71.56	51.49	49.64	40	61.03843137	49.23549233	47.72870944
50	71.56	51.57	50.81	50	61.03843137	49.54037101	47.91402785
Pedestrian Volume =		50		Pedestrian Volume =		50	
Bicycle Volume	Strategy #1	Strategy #2	Strategy #3	Bicycle Volume	Strategy #1	Strategy #2	Strategy #3
0	71.56	48.93	48.51	0	61.03843137	47.00737313	47.00737313
10	71.56	49.67	50.01	10	61.03843137	48.07150431	47.65419797
20	71.56	50.75	50.11	20	61.03843137	48.77302282	48.08061118
30	71.56	50.81	50.75	30	61.03843137	49.23549233	48.36172009
40	71.56	51.82	51.14	40	61.03843137	49.54037101	48.54703851
50	71.56	52.82	52.46	50	61.03843137	49.74135943	48.66920794
Strategy #1 Simulation Seed =				#10026 - 10050			
Strategy #2 Simulation Seed =				#1801 - 2700			
Strategy #3 Simulation Seed =				#2701 - 3600			

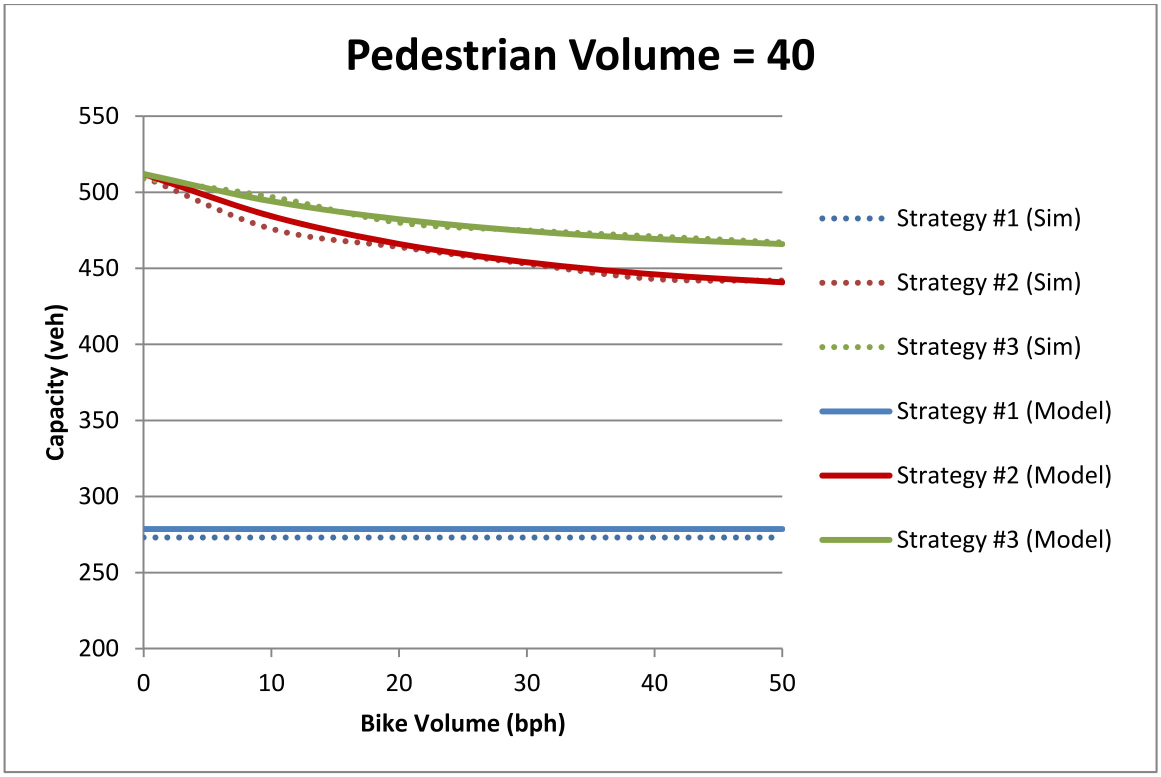
APPENDIX F: Split Design Capacity and Delay Result Charts (W/ Clearance Time)



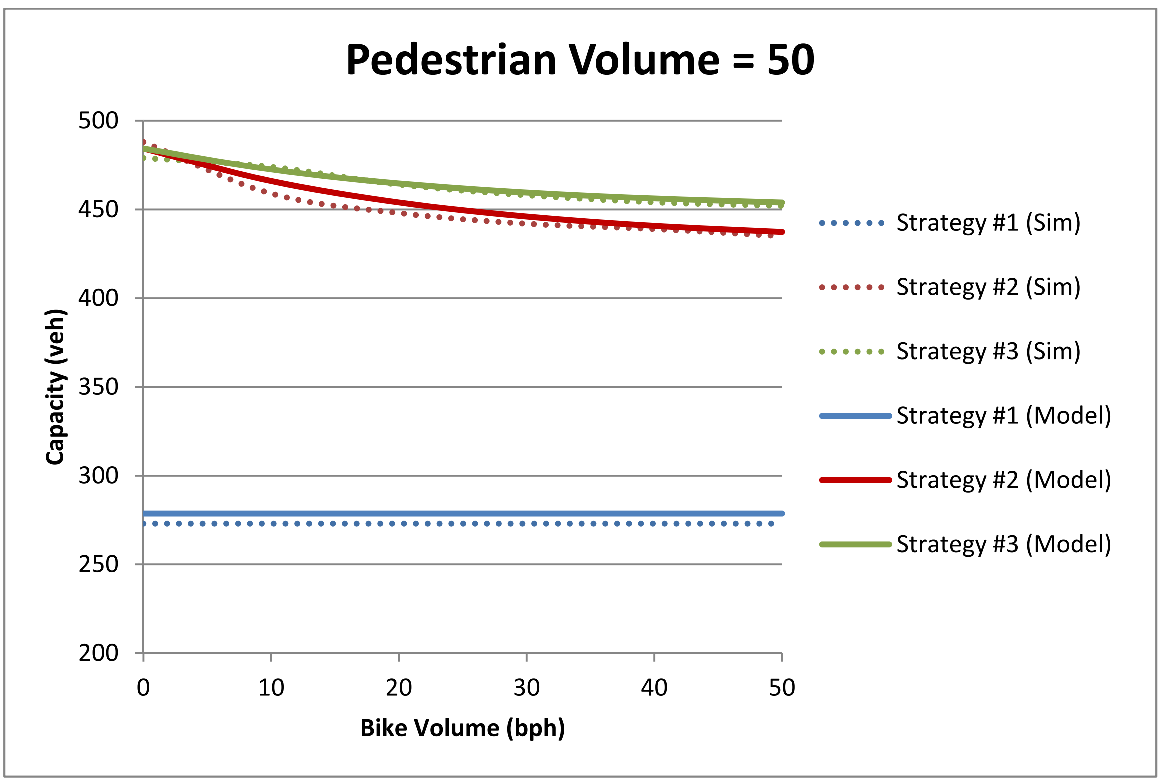



Pedestrian Volume = 20
650
600
550
500
450
400
350
300
250
200
Capacity (veh)
0
10
20
30
40
50
Bike Volume (bph)
Strategy #1 (Sim)
Strategy #2 (Sim)
Strategy #3 (Sim)
Strategy #1 (Model)
Strategy #2 (Model)
Strategy #3 (Model)


Pedestrian Volume = 30
600
550
500
450
400
350
300
250
200
Capacity (veh)
0
10
20
30
40
50
Bike Volume (bph)
Strategy #1 (Sim)
Strategy #2 (Sim)
Strategy #3 (Sim)
Strategy #1 (Model)
Strategy #2 (Model)
Strategy #3 (Model)

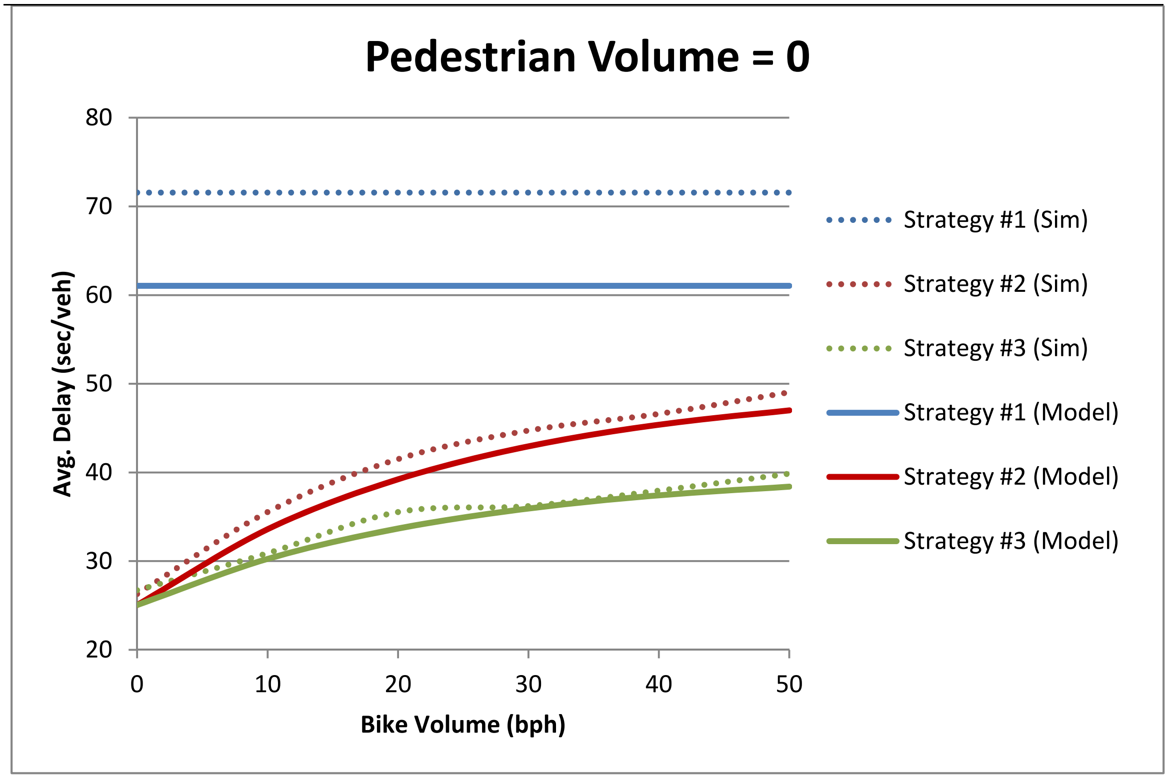


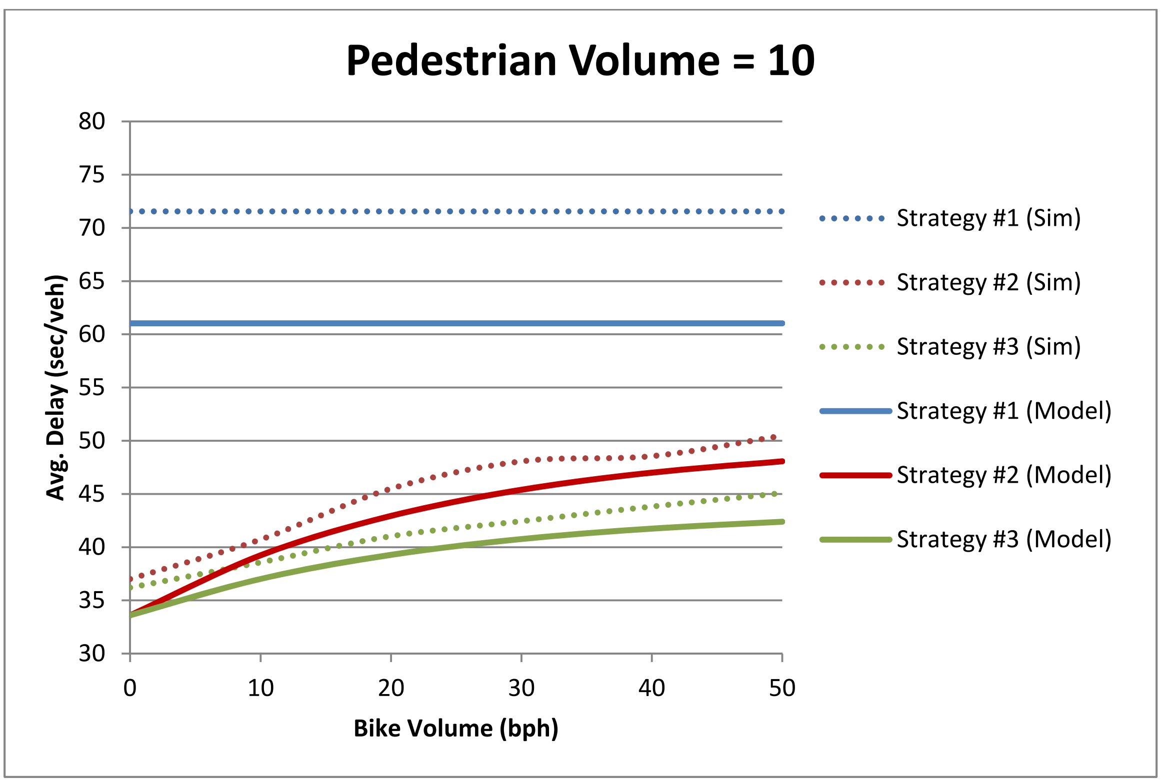
Pedestrian Volume = 40
Capacity (veh)
550
500
450
400
350
300
250
200
0
10
20
30
40
50
Bike Volume (bph)
Strategy #1 (Sim)
Strategy #2 (Sim)
Strategy #3 (Sim)
Strategy #1 (Model)
Strategy #2 (Model)
Strategy #3 (Model)

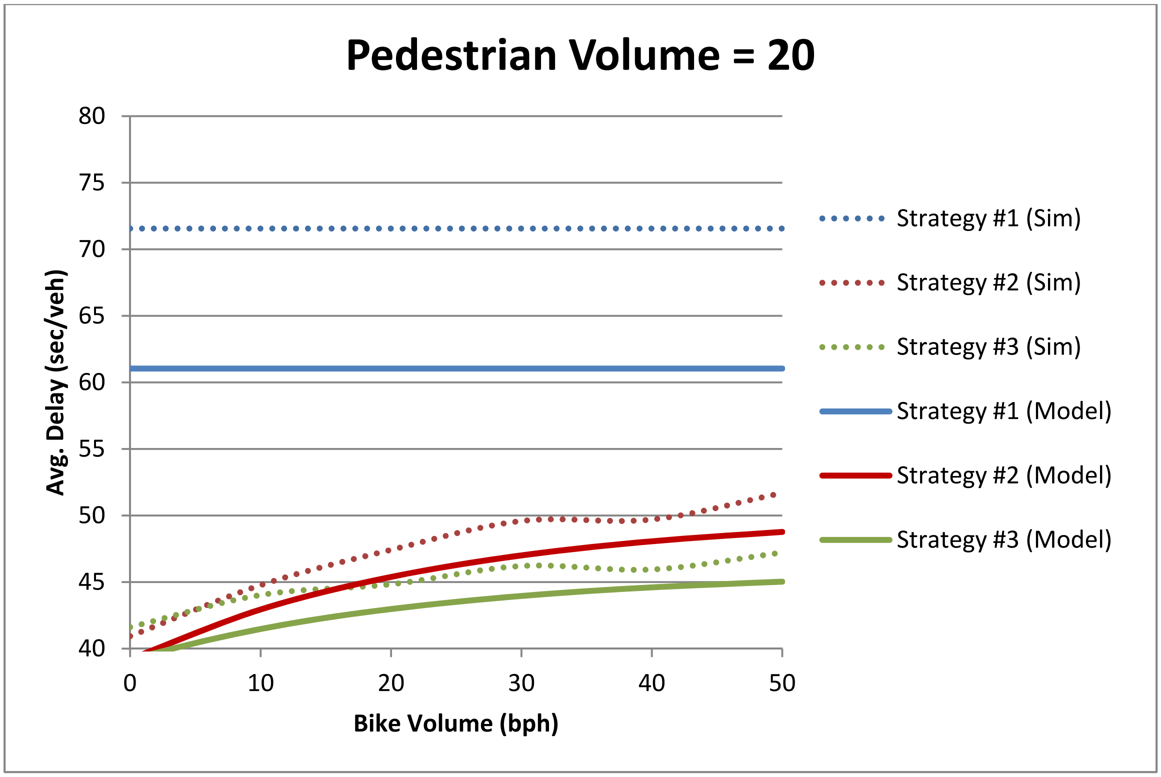


Pedestrian Volume = 50
Capacity (veh)
500
450
400
350
300
250
200
0
10
20
30
40
50
Bike Volume (bph)
Strategy #1 (Sim)
Strategy #2 (Sim)
Strategy #3 (Sim)
Strategy #1 (Model)
Strategy #2 (Model)
Strategy #3 (Model)

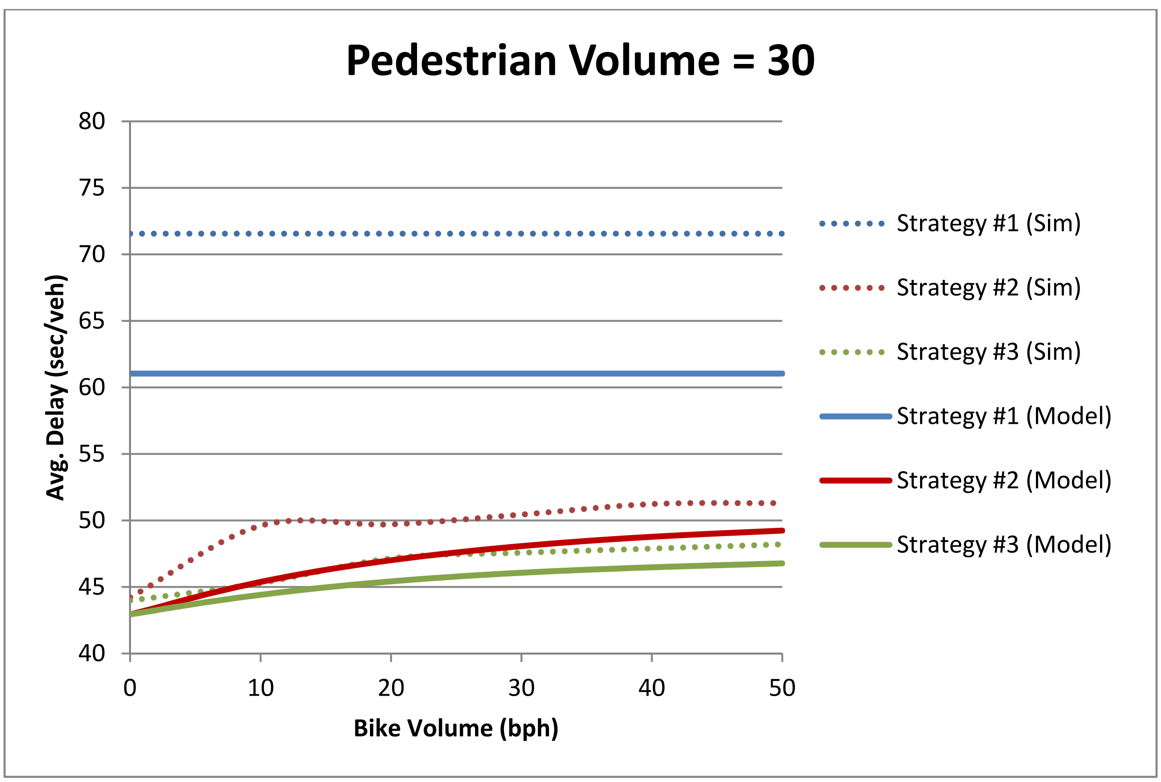
Delay Charts



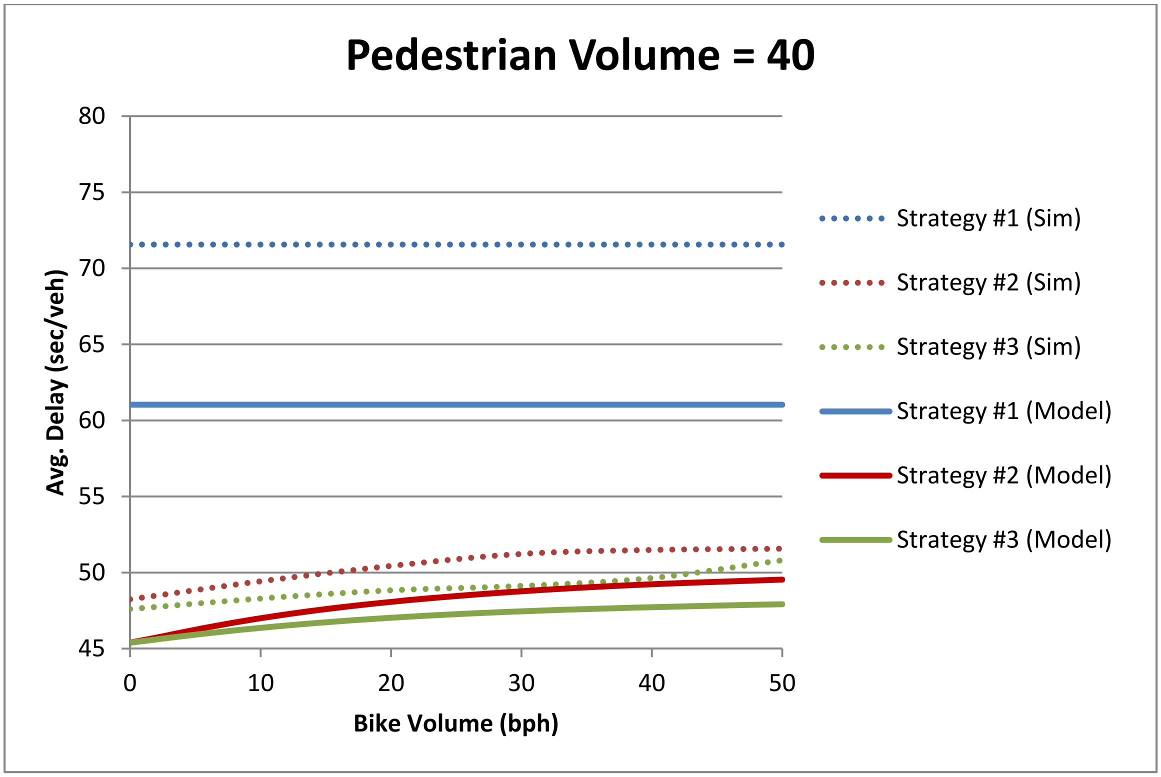


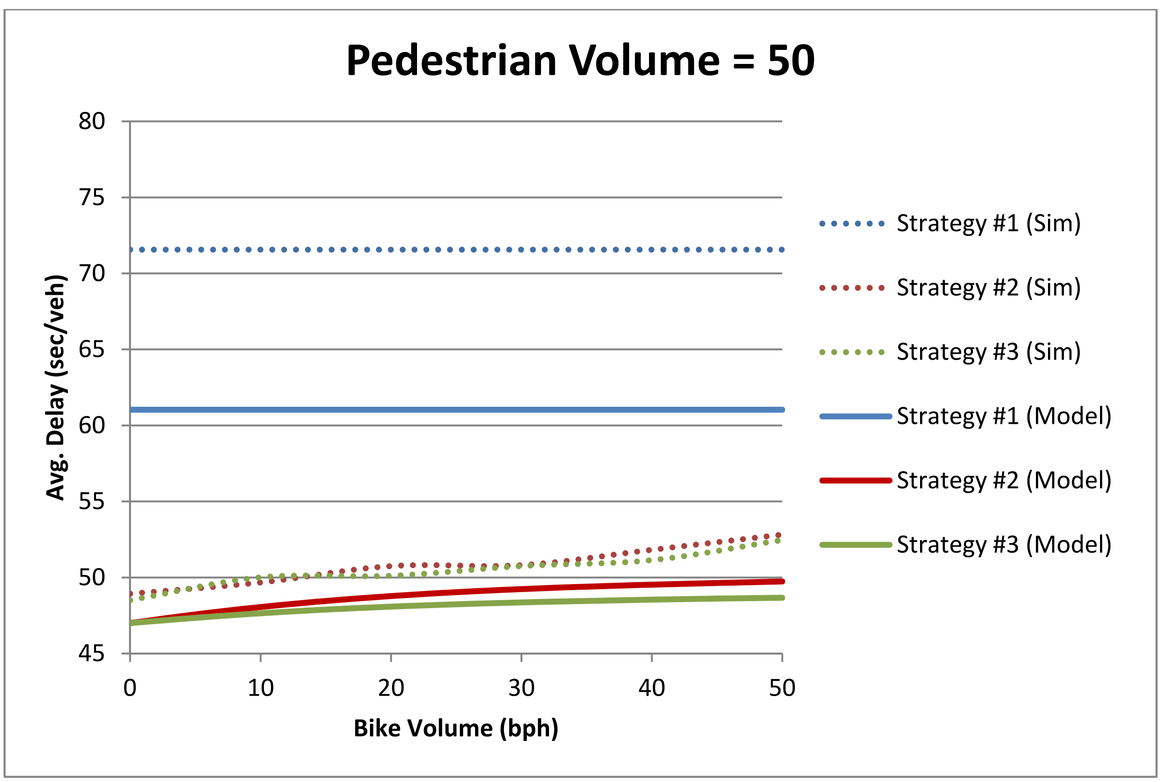


Pedestrian Volume = 20
Avg. Delay (sec/veh)
80
75
70
65
60
55
50
45
40
0
10
20
30
40
50
Bike Volume (bph)
Strategy #1 (Sim)
Strategy #2 (Sim)
Strategy #3 (Sim)
Strategy #1 (Model)
Strategy #2 (Model)
Strategy #3 (Model)



Pedestrian Volume = 30
Avg. Delay (sec/veh)
80
75
70
65
60
55
50
45
40
0
10
20
30
40
50
Bike Volume (bph)
Strategy #1 (Sim)
Strategy #2 (Sim)
Strategy #3 (Sim)
Strategy #1 (Model)
Strategy #2 (Model)
Strategy #3 (Model)


Pedestrian Volume = 40
Avg. Delay (sec/veh)
80
75
70
65
60
55
50
45
0
10
20
30
40
50
Bike Volume (bph)
Strategy #1 (Sim)
Strategy #2 (Sim)
Strategy #3 (Sim)
Strategy #1 (Model)
Strategy #2 (Model)
Strategy #3 (Model)


Pedestrian Volume = 50
Avg. Delay (sec/veh)
80
75
70
65
60
55
50
45
0
10
20
30
40
50
Bike Volume (bph)
Strategy #1 (Sim)
Strategy #2 (Sim)
Strategy #3 (Sim)
Strategy #1 (Model)
Strategy #2 (Model)
Strategy #3 (Model)

APPENDIX G: Split Design Capacity and Delay Results (W/O Clearance Time)

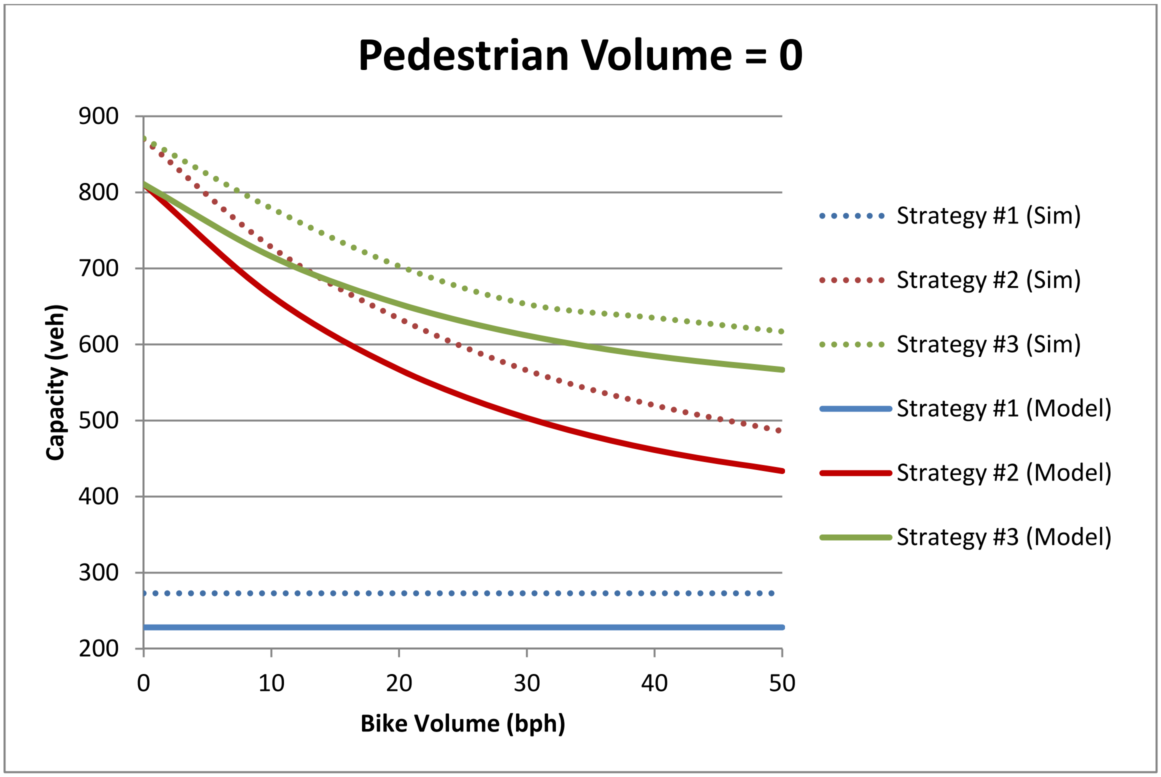
Split Capacity Results							
Simulation				Model			
Pedestrian Volume =	0			Pedestrian Volume =	0		
Bicycle Volume	Strategy #1	Strategy #2	Strategy #3	Bicycle Volume	Strategy #1	Strategy #2	Strategy #3
0	273	870	871	0	228	810.6666667	810.6666667
10	273	728	779	10	228	663.9129647	715.7083889
20	273	634	703	20	228	567.1669618	653.1080341
30	273	566	653	30	228	503.3880658	611.8393367
40	273	520	635	40	228	461.3424263	584.6333347
50	273	486	617	50	228	433.6242324	566.6980327
Pedestrian Volume =	10			Pedestrian Volume =	10		
Bicycle Volume	Strategy #1	Strategy #2	Strategy #3	Bicycle Volume	Strategy #1	Strategy #2	Strategy #3
0	273	725	718	0	228	663.9129647	663.9129647
10	273	613	663	10	228	567.1669618	601.3126099
20	273	568	617	20	228	503.3880658	560.0439125
30	273	510	591	30	228	461.3424263	532.8379104
40	273	489	569	40	228	433.6242324	514.9026085
50	273	467	554	50	228	415.3512727	503.0789287
Pedestrian Volume =	20			Pedestrian Volume =	20		
Bicycle Volume	Strategy #1	Strategy #2	Strategy #3	Bicycle Volume	Strategy #1	Strategy #2	Strategy #3
0	273	633	628	0	228	567.1669618	567.1669618
10	273	563	586	10	228	503.3880658	525.8982644
20	273	516	553	20	228	461.3424263	498.6922624
30	273	487	538	30	228	433.6242324	480.7569604
40	273	461	527	40	228	415.3512727	468.9332806
50	273	445	517	50	228	403.3049953	461.1386305
Pedestrian Volume =	30			Pedestrian Volume =	30		
Bicycle Volume	Strategy #1	Strategy #2	Strategy #3	Bicycle Volume	Strategy #1	Strategy #2	Strategy #3
0	273	569	567	0	228	503.3880658	503.3880658
10	273	512	516	10	228	461.3424263	476.1820638
20	273	482	509	20	228	433.6242324	458.2467618
30	273	472	500	30	228	415.3512727	446.4230821
40	273	458	493	40	228	403.3049953	438.628432
50	273	450	483	50	228	395.3635998	433.4898819
Pedestrian Volume =	40			Pedestrian Volume =	40		

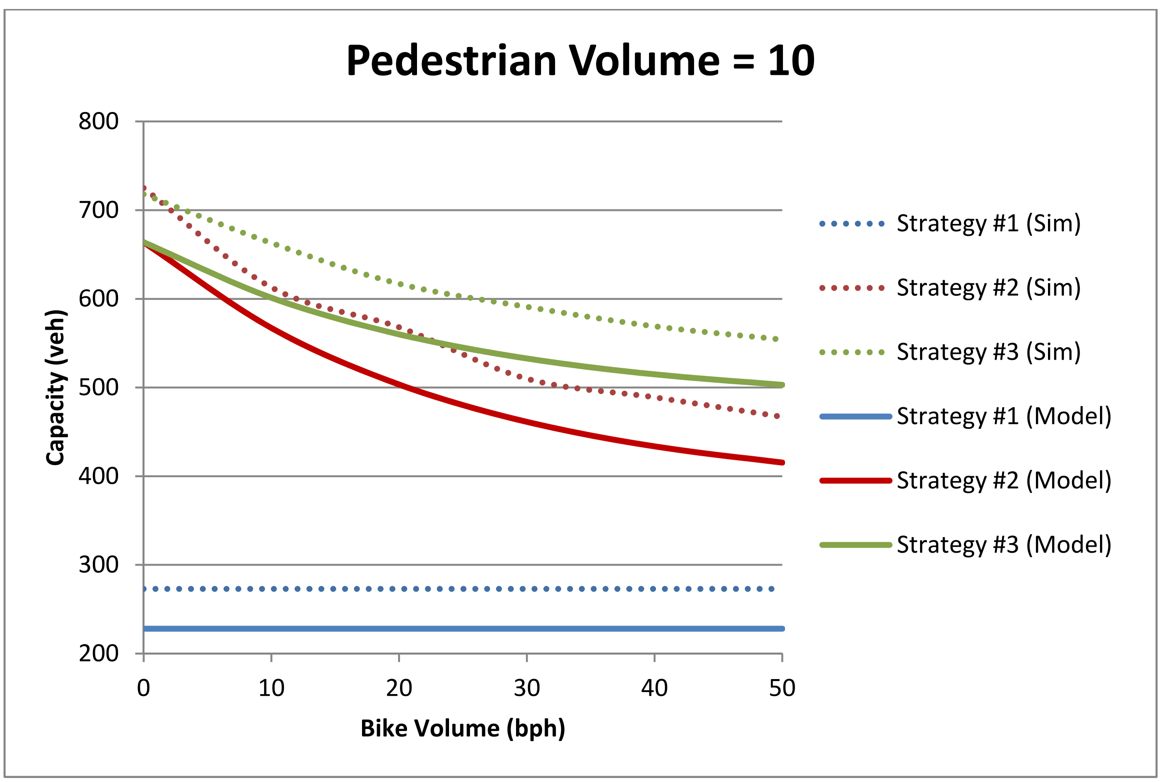
Bicycle Volume	Strategy #1	Strategy #2	Strategy #3	Bicycle Volume	Strategy #1	Strategy #2	Strategy #3
0	273	510	509	0	228	461.3424263	461.3424263
10	273	476	497	10	228	433.6242324	443.4071243
20	273	464	480	20	228	415.3512727	431.5834446
30	273	453	475	30	228	403.3049953	423.7887945
40	273	443	471	40	228	395.3635998	418.6502444
50	273	442	467	50	228	390.1283092	415.2627035
Pedestrian Volume =		50		Pedestrian Volume =		50	
Bicycle Volume	Strategy #1	Strategy #2	Strategy #3	Bicycle Volume	Strategy #1	Strategy #2	Strategy #3
0	273	488	479	0	228	433.6242324	433.6242324
10	273	459	474	10	228	415.3512727	421.8005526
20	273	448	464	20	228	403.3049953	414.0059025
30	273	442	458	30	228	395.3635998	408.8673525
40	273	439	454	40	228	390.1283092	405.4798115
50	273	435	452	50	228	386.6769929	403.2466069
Strategy #1 Simulation Seed =				#10001 - 10025			
Strategy #2 Simulation Seed =				#1 - 900			
Strategy #3 Simulation Seed =				#901 - 1800			

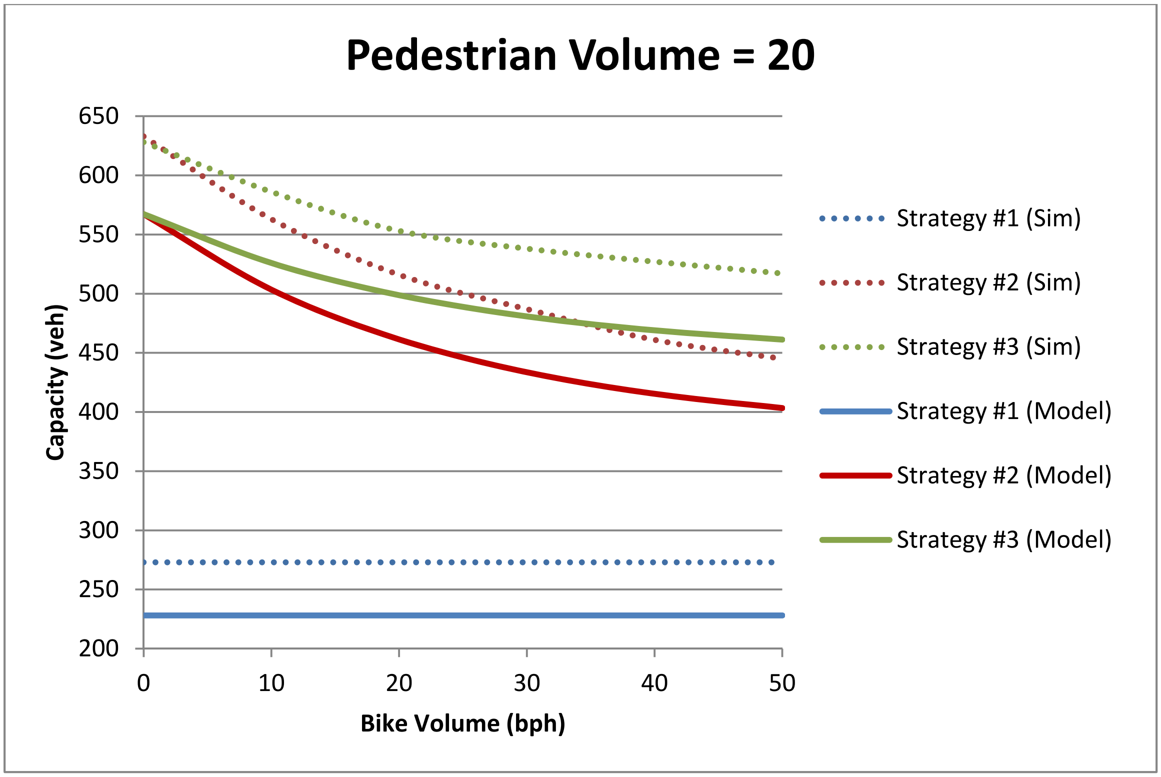
Split Delay Results (Veh = 200)							
Simulation				Model			
Pedestrian Volume =		0		Pedestrian Volume =		0	
Bicycle Volume	Strategy #1	Strategy #2	Strategy #3	Bicycle Volume	Strategy #1	Strategy #2	Strategy #3
0	71.56	26.3	26.72	0	64.91294118	27.55372549	27.55372549
10	71.56	35.53	30.9	10	64.91294118	36.44527331	32.9719331
20	71.56	41.5	35.54	20	64.91294118	42.3069429	36.5438357
30	71.56	44.72	36.22	30	64.91294118	46.17119366	38.89857902
40	71.56	46.6	37.96	40	64.91294118	48.71866476	40.45092149
50	71.56	49.03	39.87	50	64.91294118	50.39806122	41.47428872
Pedestrian Volume =		10		Pedestrian Volume =		10	
Bicycle Volume	Strategy #1	Strategy #2	Strategy #3	Bicycle Volume	Strategy #1	Strategy #2	Strategy #3
0	71.56	37.01	36.2	0	64.91294118	36.44527331	36.44527331
10	71.56	40.72	38.57	10	64.91294118	42.3069429	40.01717591
20	71.56	45.5	41.03	20	64.91294118	46.17119366	42.37191923
30	71.56	48.07	42.44	30	64.91294118	48.71866476	43.9242617
40	71.56	48.56	43.82	40	64.91294118	50.39806122	44.94762893

50	71.56	50.48	45.08	50	64.91294118	51.50518759	45.62227419
Pedestrian Volume =		20		Pedestrian Volume =		20	
Bicycle Volume	Strategy #1	Strategy #2	Strategy #3	Bicycle Volume	Strategy #1	Strategy #2	Strategy #3
0	71.56	40.93	41.62	0	64.91294118	42.3069429	42.3069429
10	71.56	44.77	44.03	10	64.91294118	46.17119366	44.66168622
20	71.56	47.42	44.84	20	64.91294118	48.71866476	46.21402869
30	71.56	49.59	46.21	30	64.91294118	50.39806122	47.23739592
40	71.56	49.7	45.95	40	64.91294118	51.50518759	47.91204118
50	71.56	51.69	47.22	50	64.91294118	52.23505028	48.35679474
Pedestrian Volume =		30		Pedestrian Volume =		30	
Bicycle Volume	Strategy #1	Strategy #2	Strategy #3	Bicycle Volume	Strategy #1	Strategy #2	Strategy #3
0	71.56	44.21	43.97	0	64.91294118	46.17119366	46.17119366
10	71.56	49.6	45.29	10	64.91294118	48.71866476	47.72353613
20	71.56	49.7	47.15	20	64.91294118	50.39806122	48.74690336
30	71.56	50.44	47.57	30	64.91294118	51.50518759	49.42154861
40	71.56	51.23	47.88	40	64.91294118	52.23505028	49.86630218
50	71.56	51.3	48.2	50	64.91294118	52.71620542	50.1595018
Pedestrian Volume =		40		Pedestrian Volume =		40	
Bicycle Volume	Strategy #1	Strategy #2	Strategy #3	Bicycle Volume	Strategy #1	Strategy #2	Strategy #3
0	71.56	48.25	47.6	0	64.91294118	48.71866476	48.71866476
10	71.56	49.43	48.29	10	64.91294118	50.39806122	49.74203199
20	71.56	50.44	48.83	20	64.91294118	51.50518759	50.41667725
30	71.56	51.23	49.12	30	64.91294118	52.23505028	50.86143081
40	71.56	51.49	49.64	40	64.91294118	52.71620542	51.15463043
50	71.56	51.57	50.81	50	64.91294118	53.03340244	51.34791953
Pedestrian Volume =		50		Pedestrian Volume =		50	
Bicycle Volume	Strategy #1	Strategy #2	Strategy #3	Bicycle Volume	Strategy #1	Strategy #2	Strategy #3
0	71.56	48.93	48.51	0	64.91294118	50.39806122	50.39806122
10	71.56	49.67	50.01	10	64.91294118	51.50518759	51.07270647
20	71.56	50.75	50.11	20	64.91294118	52.23505028	51.51746004
30	71.56	50.81	50.75	30	64.91294118	52.71620542	51.81065966
40	71.56	51.82	51.14	40	64.91294118	53.03340244	52.00394876
50	71.56	52.82	52.46	50	64.91294118	53.2425116	52.13137279
Strategy #1 Simulation Seed =				#10026 - 10050			
Strategy #2 Simulation Seed =				#1801 - 2700			
Strategy #3 Simulation Seed =				#2701 - 3600			

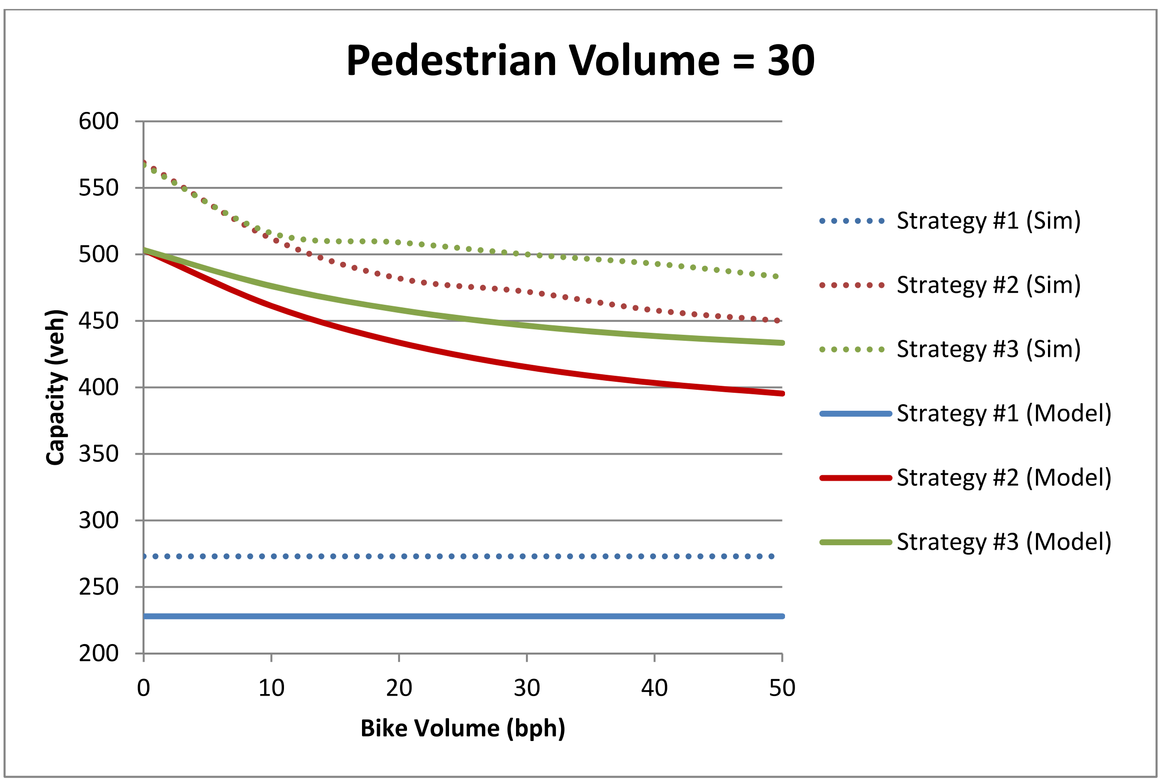
APPENDIX H: Split Design Capacity and Delay Result Charts (W/O Clearance Time)



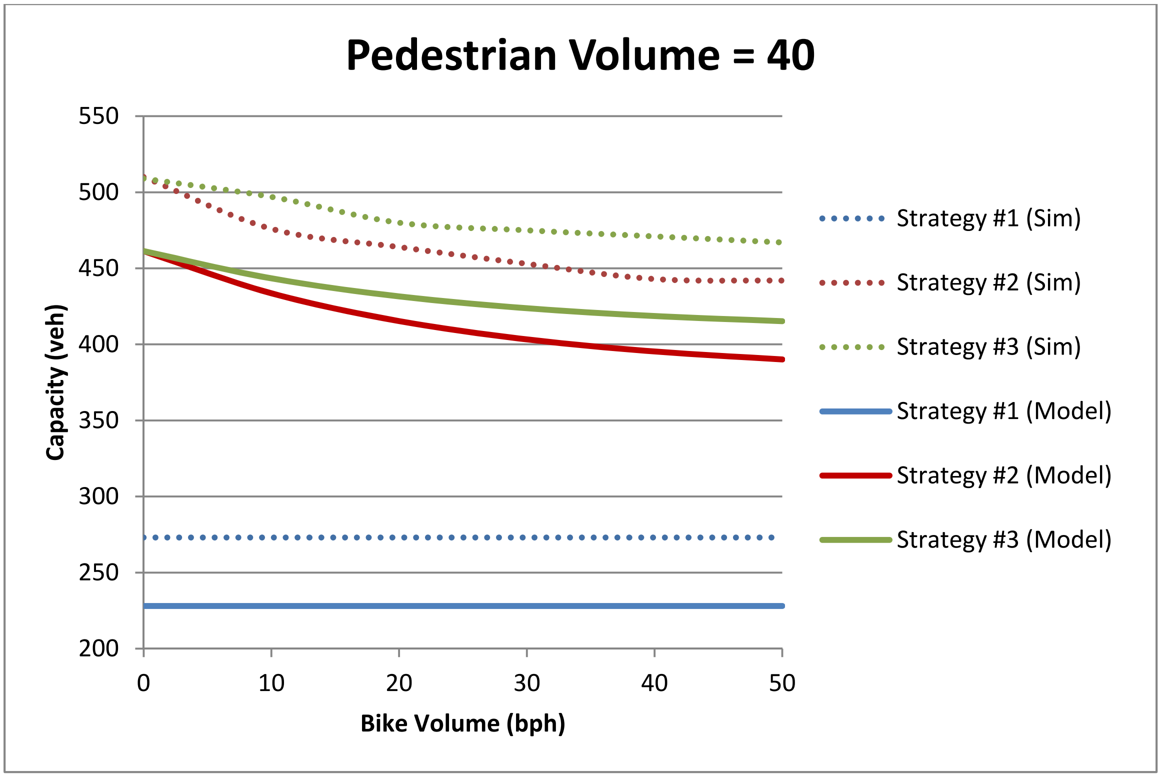


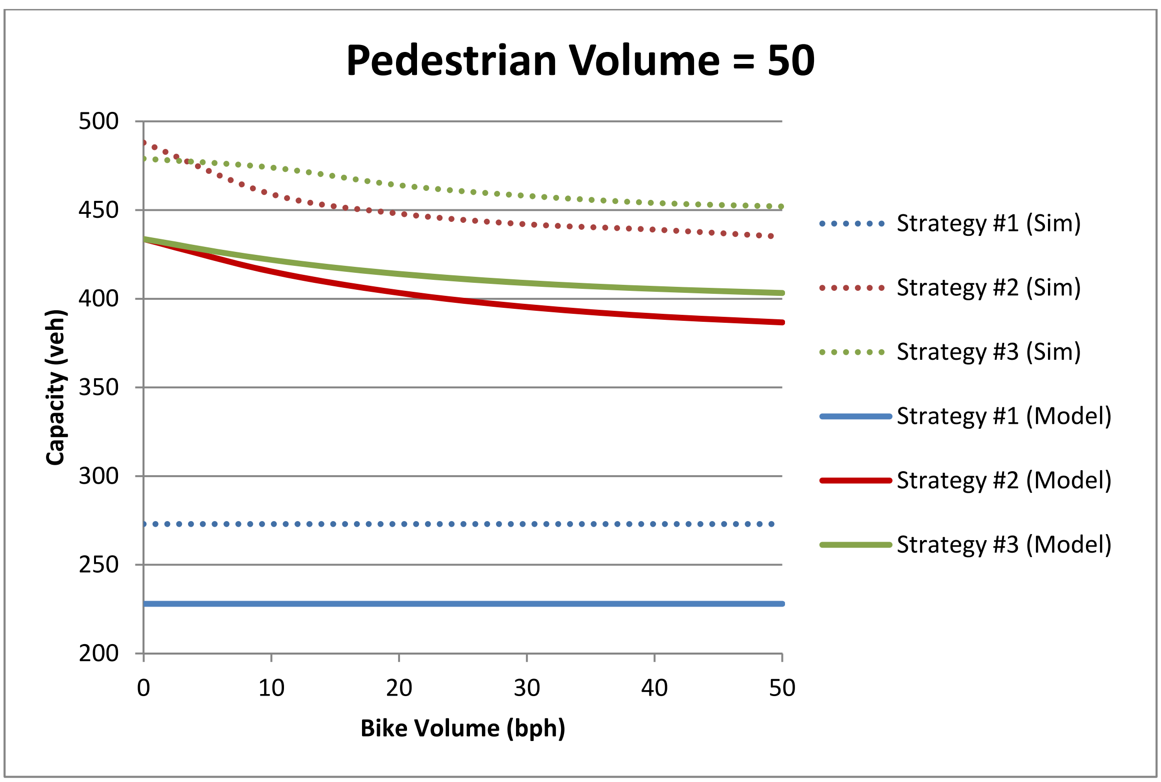


Pedestrian Volume = 20
Capacity (veh)
650
600
550
500
450
400
350
300
250
200
0
10
20
30
40
50
Bike Volume (bph)
Strategy #1 (Sim)
Strategy #2 (Sim)
Strategy #3 (Sim)
Strategy #1 (Model)
Strategy #2 (Model)
Strategy #3 (Model)

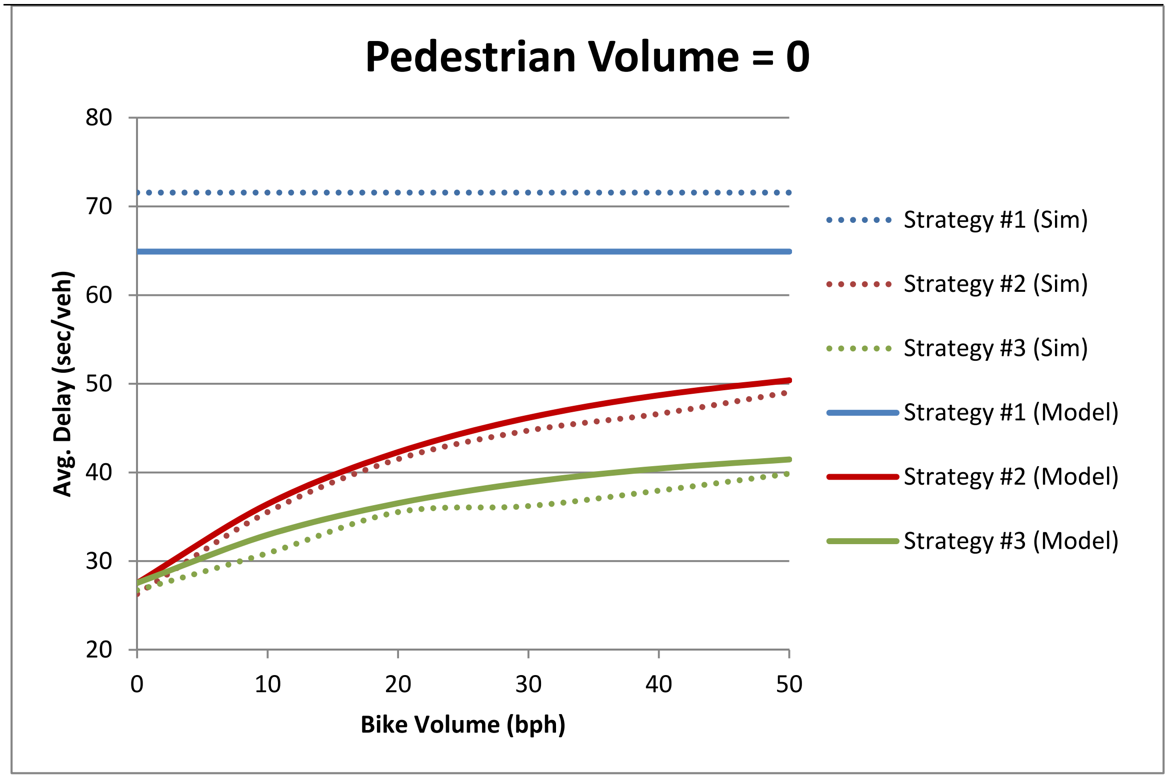


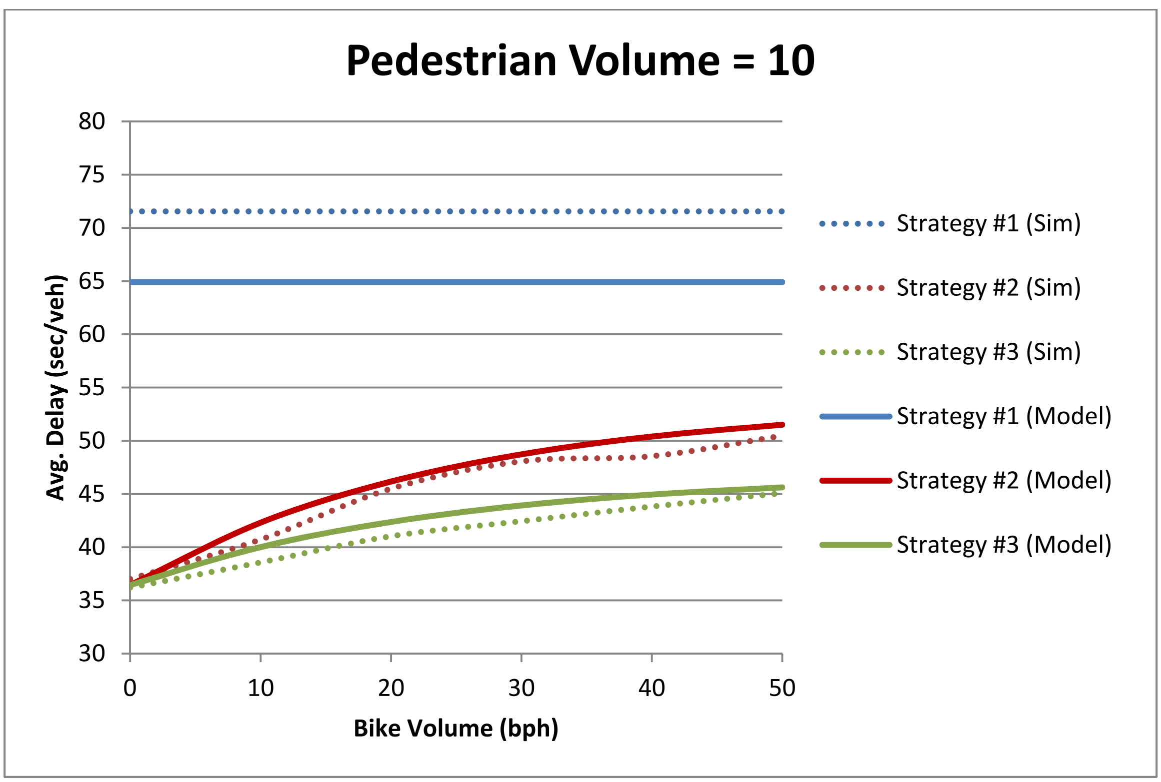
Pedestrian Volume = 30
Capacity (veh)
600
550
500
450
400
350
300
250
200
0
10
20
30
40
50
Bike Volume (bph)
Strategy #1 (Sim)
Strategy #2 (Sim)
Strategy #3 (Sim)
Strategy #1 (Model)
Strategy #2 (Model)
Strategy #3 (Model)

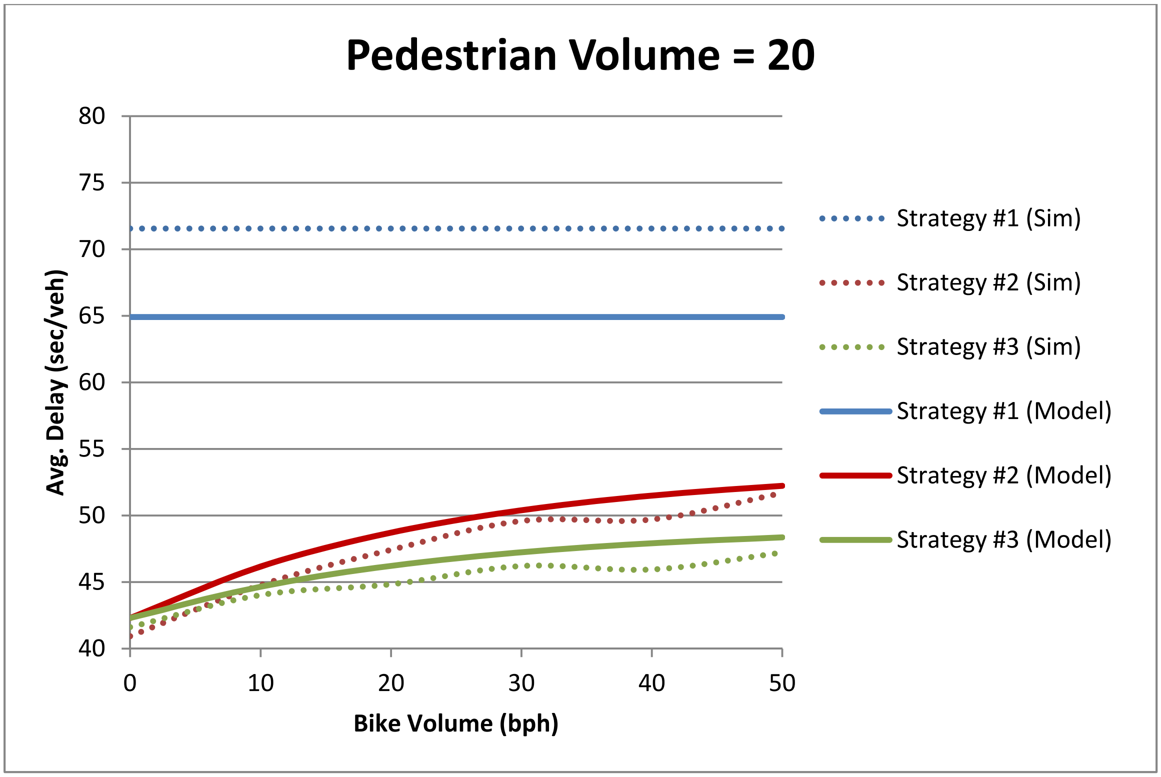

Pedestrian Volume = 40
550
500
450
400
350
300
250
200
Capacity (veh)
0
10
20
30
40
50
Bike Volume (bph)
Strategy #1 (Sim)
Strategy #2 (Sim)
Strategy #3 (Sim)
Strategy #1 (Model)
Strategy #2 (Model)
Strategy #3 (Model)

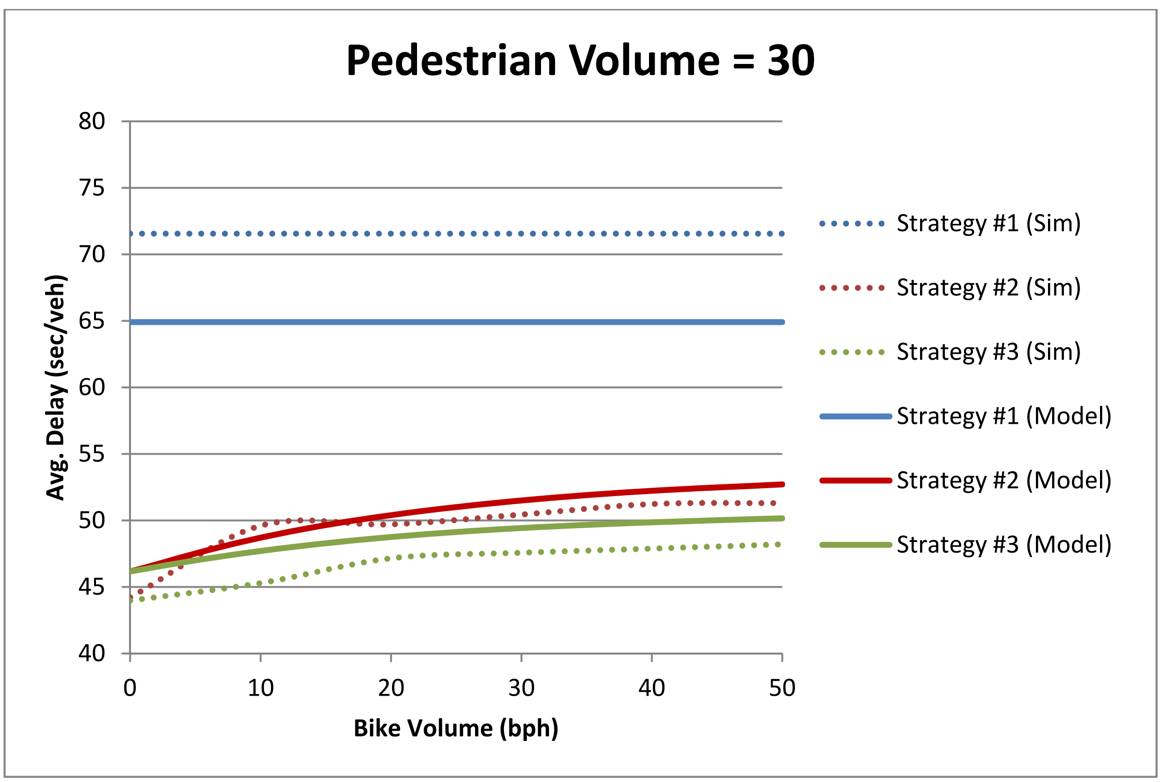

Pedestrian Volume = 50
500
450
400
350
300
250
200
Capacity (veh)
0
10
20
30
40
50
Bike Volume (bph)
Strategy #1 (Sim)
Strategy #2 (Sim)
Strategy #3 (Sim)
Strategy #1 (Model)
Strategy #2 (Model)
Strategy #3 (Model)

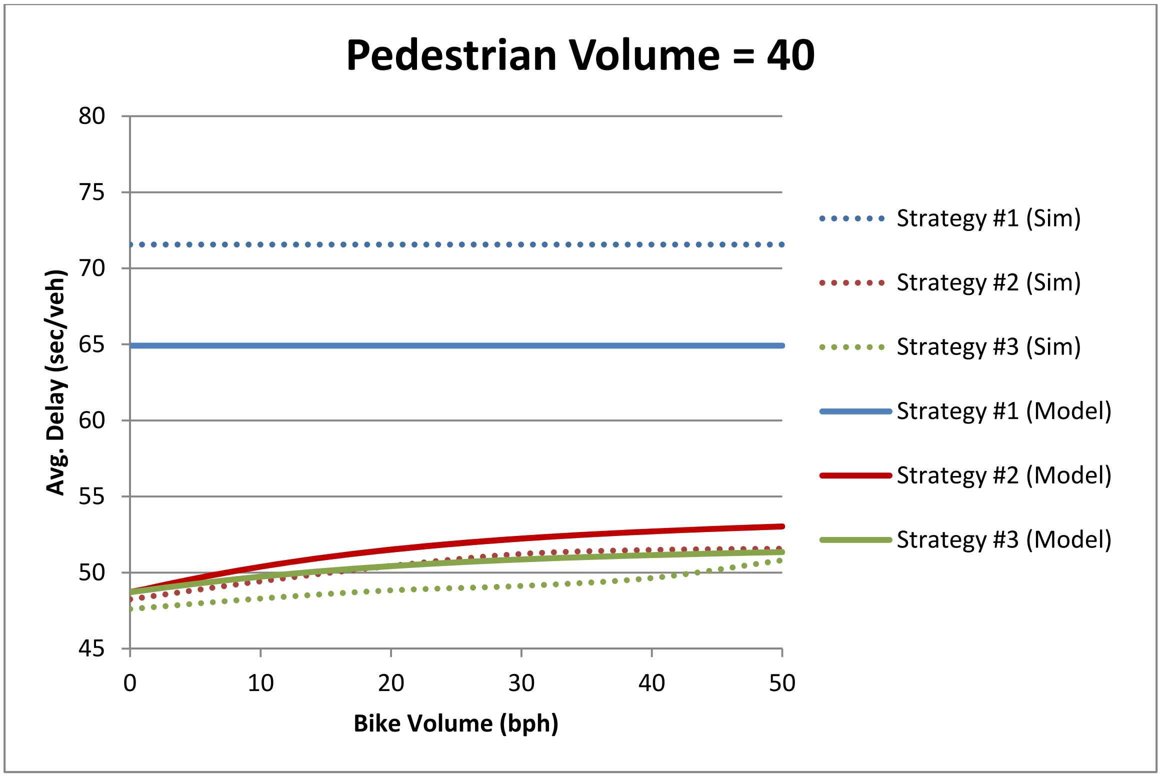
Delay Charts



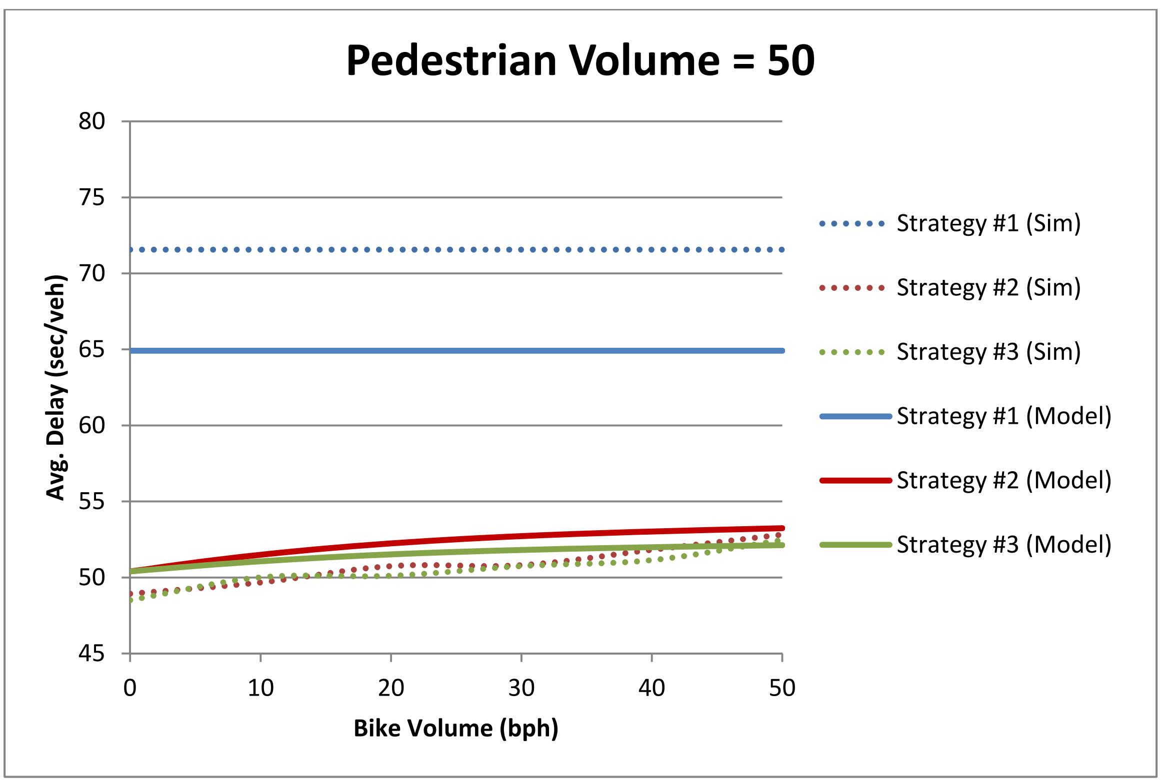



Pedestrian Volume = 20
Avg. Delay (sec/veh)
80
75
70
65
60
55
50
45
40
0
10
20
30
40
50
Bike Volume (bph)
Strategy #1 (Sim)
Strategy #2 (Sim)
Strategy #3 (Sim)
Strategy #1 (Model)
Strategy #2 (Model)
Strategy #3 (Model)


Pedestrian Volume = 30
Avg. Delay (sec/veh)
80
75
70
65
60
55
50
45
40
0
10
20
30
40
50
Bike Volume (bph)
Strategy #1 (Sim)
Strategy #2 (Sim)
Strategy #3 (Sim)
Strategy #1 (Model)
Strategy #2 (Model)
Strategy #3 (Model)



Pedestrian Volume = 40
80
75
70
65
60
55
50
45
0
10
20
30
40
50
Avg. Delay (sec/veh)
Bike Volume (bph)
Strategy #1 (Sim)
Strategy #2 (Sim)
Strategy #3 (Sim)
Strategy #1 (Model)
Strategy #2 (Model)
Strategy #3 (Model)



Pedestrian Volume = 50
80
75
70
65
60
55
50
45
0
10
20
30
40
50
Avg. Delay (sec/veh)
Bike Volume (bph)
Strategy #1 (Sim)
Strategy #2 (Sim)
Strategy #3 (Sim)
Strategy #1 (Model)
Strategy #2 (Model)
Strategy #3 (Model)

APPENDIX I: Lead-Lag Design Capacity and Delay Results (W/ Clearance Time)

Lead-Lag Capacity Results							
Simulation				Model			
Pedestrian Volume =	0			Pedestrian Volume =	0		
Bicycle Volume	Strategy #1	Strategy #2	Strategy #3	Bicycle Volume	Strategy #1	Strategy #2	Strategy #3
0	271	878	878	0	278.6666667	861.3333333	861.3333333
10	271	737	777	10	278.6666667	714.5796314	766.3750556
20	271	620	716	20	278.6666667	617.8336285	703.7747008
30	271	572	666	30	278.6666667	554.0547325	662.5060034
40	271	515	648	40	278.6666667	512.009093	635.3000013
50	271	488	623	50	278.6666667	484.290899	617.3646994
Pedestrian Volume =	10			Pedestrian Volume =	10		
Bicycle Volume	Strategy #1	Strategy #2	Strategy #3	Bicycle Volume	Strategy #1	Strategy #2	Strategy #3
0	271	705	715	0	278.6666667	714.5796314	714.5796314
10	271	626	665	10	278.6666667	617.8336285	651.9792766
20	271	574	620	20	278.6666667	554.0547325	610.7105792
30	271	521	604	30	278.6666667	512.009093	583.5045771
40	271	503	581	40	278.6666667	484.290899	565.5692752
50	271	474	555	50	278.6666667	466.0179394	553.7455954
Pedestrian Volume =	20			Pedestrian Volume =	20		
Bicycle Volume	Strategy #1	Strategy #2	Strategy #3	Bicycle Volume	Strategy #1	Strategy #2	Strategy #3
0	271	663	625	0	278.6666667	617.8336285	617.8336285
10	271	561	579	10	278.6666667	554.0547325	576.5649311
20	271	516	560	20	278.6666667	512.009093	549.358929
30	271	491	538	30	278.6666667	484.290899	531.4236271
40	271	469	523	40	278.6666667	466.0179394	519.5999473
50	271	455	509	50	278.6666667	453.971662	511.8052972
Pedestrian Volume =	30			Pedestrian Volume =	30		
Bicycle Volume	Strategy #1	Strategy #2	Strategy #3	Bicycle Volume	Strategy #1	Strategy #2	Strategy #3
0	271	563	555	0	278.6666667	554.0547325	554.0547325
10	271	528	550	10	278.6666667	512.009093	526.8487304
20	271	490	534	20	278.6666667	484.290899	508.9134285
30	271	475	505	30	278.6666667	466.0179394	497.0897487
40	271	457	489	40	278.6666667	453.971662	489.2950986
50	271	450	484	50	278.6666667	446.0302665	484.1565486
Pedestrian Volume =	40			Pedestrian Volume =	40		

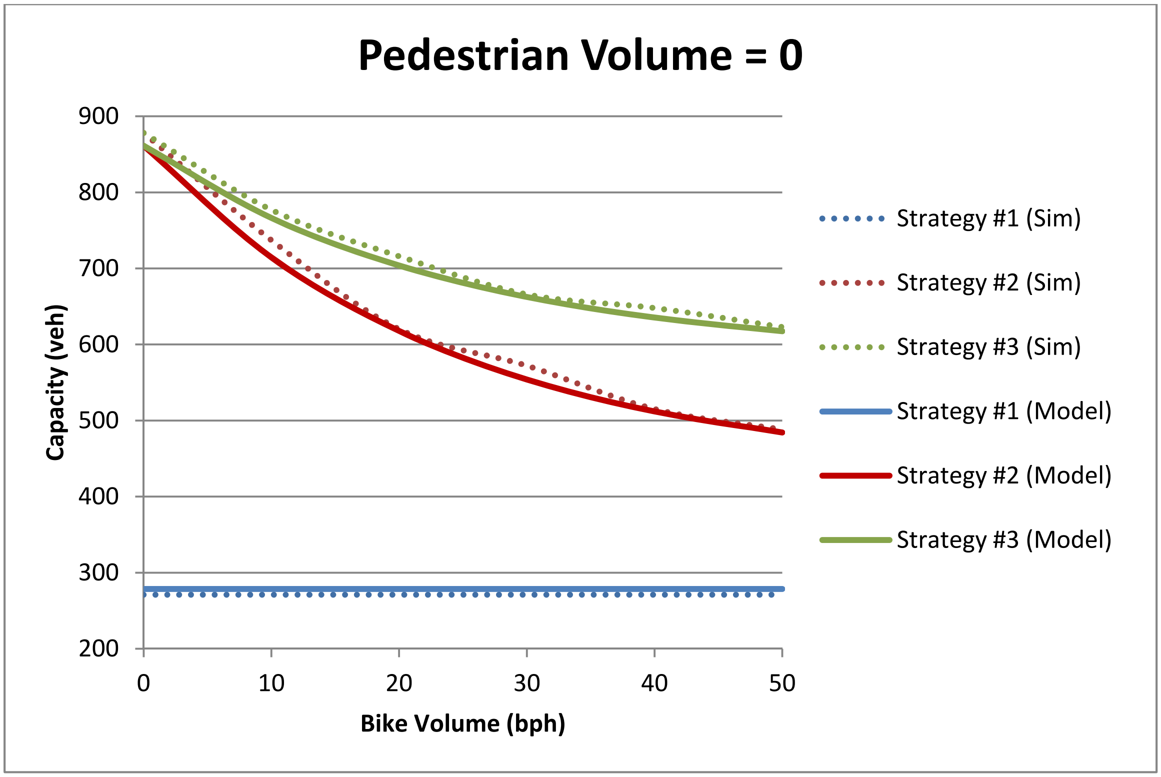
Bicycle Volume	Strategy #1	Strategy #2	Strategy #3	Bicycle Volume	Strategy #1	Strategy #2	Strategy #3
0	271	518	518	0	278.6666667	512.009093	512.009093
10	271	485	506	10	278.6666667	484.290899	494.073791
20	271	474	482	20	278.6666667	466.0179394	482.2501112
30	271	453	481	30	278.6666667	453.971662	474.4554612
40	271	450	478	40	278.6666667	446.0302665	469.3169111
50	271	443	457	50	278.6666667	440.7949759	465.9293701
Pedestrian Volume =		50		Pedestrian Volume =		50	
Bicycle Volume	Strategy #1	Strategy #2	Strategy #3	Bicycle Volume	Strategy #1	Strategy #2	Strategy #3
0	271	494	495	0	278.6666667	484.290899	484.290899
10	271	464	480	10	278.6666667	466.0179394	472.4672193
20	271	457	475	20	278.6666667	453.971662	464.6725692
30	271	455	459	30	278.6666667	446.0302665	459.5340191
40	271	449	458	40	278.6666667	440.7949759	456.1464782
50	271	440	456	50	278.6666667	437.3436596	453.9132735
Strategy #1 Simulation Seed =				#15001 - 15025			
Strategy #2 Simulation Seed =				#3601 - 4500			
Strategy #3 Simulation Seed =				#5401 - 6300			

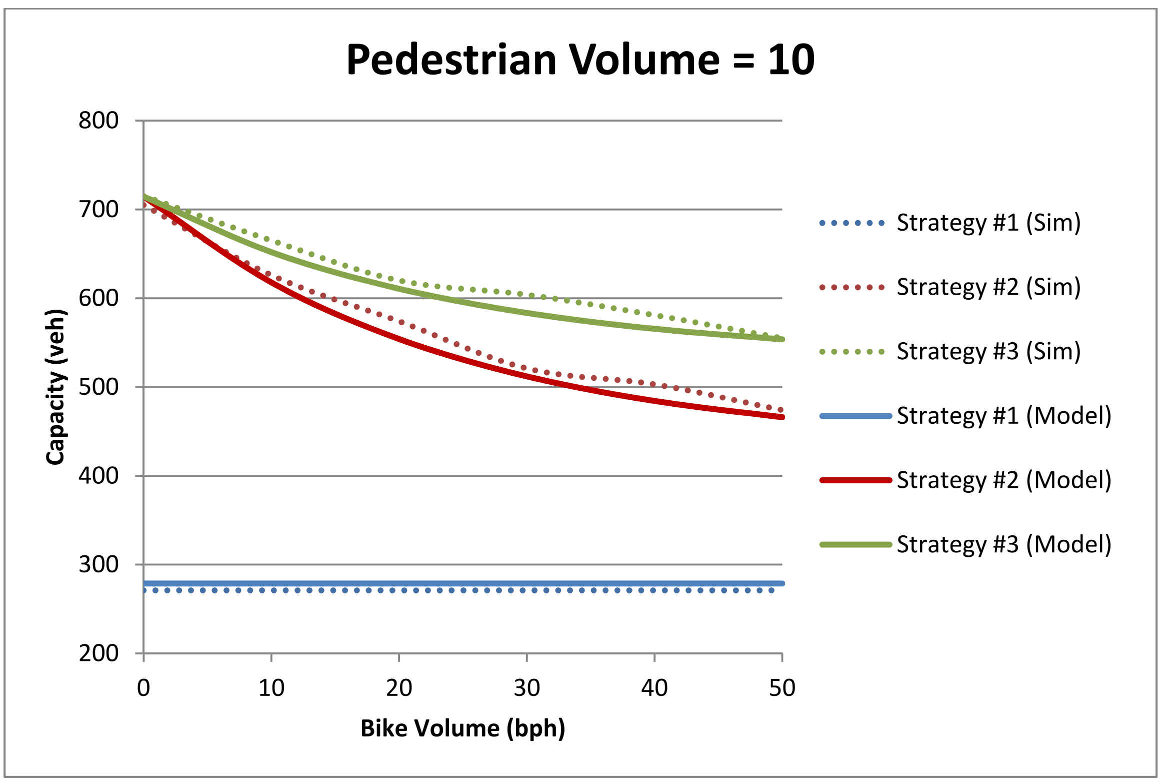
Lead-Lag Delay Results (Veh = 200)

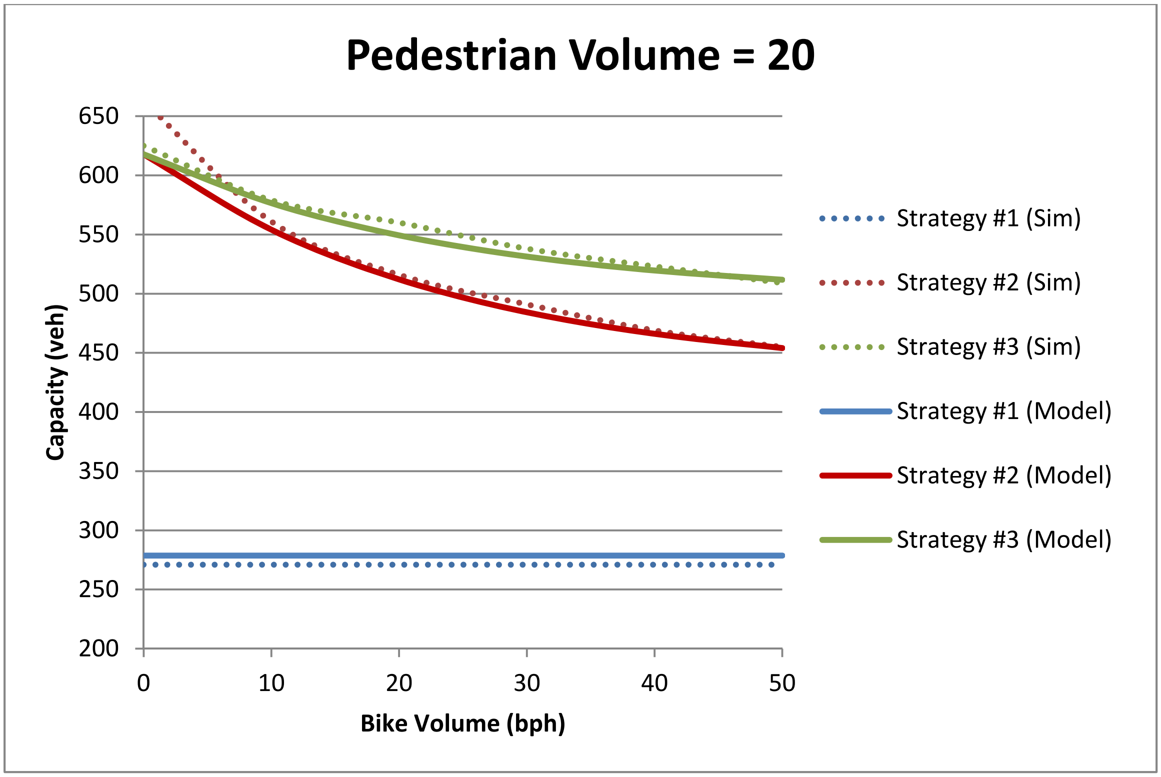
Simulation				Model			
Pedestrian Volume =		0		Pedestrian Volume =		0	
Bicycle Volume	Strategy #1	Strategy #2	Strategy #3	Bicycle Volume	Strategy #1	Strategy #2	Strategy #3
0	72.12	26.92	26.17	0	61.03843137	25.05019608	25.05019608
10	72.12	35.26	31.8	10	61.03843137	33.59644107	30.24497245
20	72.12	41.74	34.89	20	61.03843137	39.23047301	33.6695801
30	72.12	45.98	38.23	30	61.03843137	42.94465577	35.9272206
40	72.12	46.8	39.54	40	61.03843137	45.39319596	37.41554895
50	72.12	48.92	41.36	50	61.03843137	47.00737313	38.39671547
Pedestrian Volume =		10		Pedestrian Volume =		10	
Bicycle Volume	Strategy #1	Strategy #2	Strategy #3	Bicycle Volume	Strategy #1	Strategy #2	Strategy #3
0	72.12	35.89	35.16	0	61.03843137	33.59644107	33.59644107
10	72.12	40.52	39.2	10	61.03843137	39.23047301	37.02104872
20	72.12	45.71	41.27	20	61.03843137	42.94465577	39.27868922
30	72.12	48.38	43.01	30	61.03843137	45.39319596	40.76701757
40	72.12	49.43	44	40	61.03843137	47.00737313	41.74818409

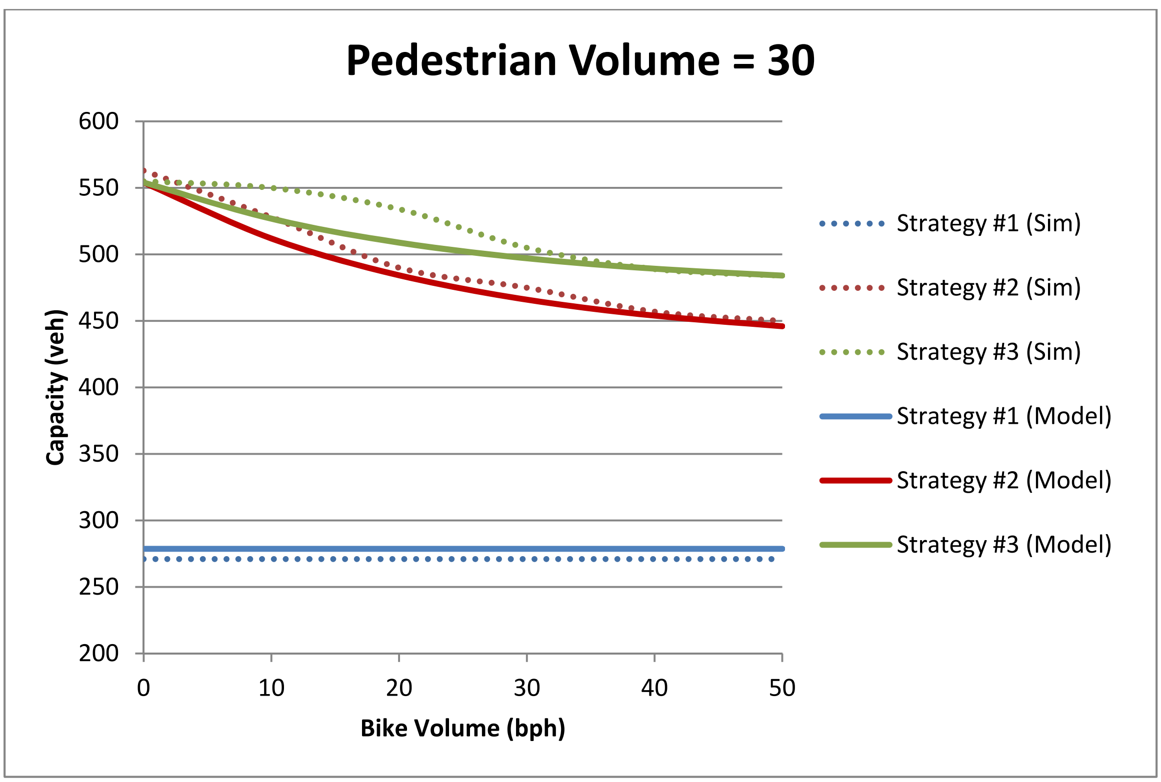
50	72.12	50.34	45.33	50	61.03843137	48.07150431	42.39500892
Pedestrian Volume =		20		Pedestrian Volume =		20	
Bicycle Volume	Strategy #1	Strategy #2	Strategy #3	Bicycle Volume	Strategy #1	Strategy #2	Strategy #3
0	72.12	40.46	40.89	0	61.03843137	39.23047301	39.23047301
10	72.12	45.01	43.82	10	61.03843137	42.94465577	41.48811351
20	72.12	469	44.26	20	61.03843137	45.39319596	42.97644186
30	72.12	48.54	46.21	30	61.03843137	47.00737313	43.95760838
40	72.12	49.99	46.75	40	61.03843137	48.07150431	44.60443321
50	72.12	50.4	48.14	50	61.03843137	48.77302282	45.03084642
Pedestrian Volume =		30		Pedestrian Volume =		30	
Bicycle Volume	Strategy #1	Strategy #2	Strategy #3	Bicycle Volume	Strategy #1	Strategy #2	Strategy #3
0	72.12	45.75	45.46	0	61.03843137	42.94465577	42.94465577
10	72.12	47.26	44.99	10	61.03843137	45.39319596	44.43298412
20	72.12	47.99	47.68	20	61.03843137	47.00737313	45.41415064
30	72.12	49.94	47.31	30	61.03843137	48.07150431	46.06097547
40	72.12	51.31	47.84	40	61.03843137	48.77302282	46.48738868
50	72.12	51.49	49.59	50	61.03843137	49.23549233	46.7684976
Pedestrian Volume =		40		Pedestrian Volume =		40	
Bicycle Volume	Strategy #1	Strategy #2	Strategy #3	Bicycle Volume	Strategy #1	Strategy #2	Strategy #3
0	72.12	46.88	48.11	0	61.03843137	45.39319596	45.39319596
10	72.12	48.93	48.52	10	61.03843137	47.00737313	46.37436248
20	72.12	49.76	49.34	20	61.03843137	48.07150431	47.02118731
30	72.12	51.33	50.29	30	61.03843137	48.77302282	47.44760052
40	72.12	51.71	50.62	40	61.03843137	49.23549233	47.72870944
50	72.12	51.88	51.75	50	61.03843137	49.54037101	47.91402785
Pedestrian Volume =		50		Pedestrian Volume =		50	
Bicycle Volume	Strategy #1	Strategy #2	Strategy #3	Bicycle Volume	Strategy #1	Strategy #2	Strategy #3
0	72.12	49.51	49.87	0	61.03843137	47.00737313	47.00737313
10	72.12	49.65	50.1	10	61.03843137	48.07150431	47.65419797
20	72.12	49.89	50.57	20	61.03843137	48.77302282	48.08061118
30	72.12	51.06	50.83	30	61.03843137	49.23549233	48.36172009
40	72.12	51.68	50.98	40	61.03843137	49.54037101	48.54703851
50	72.12	52.44	51.56	50	61.03843137	49.74135943	48.66920794
Strategy #1 Simulation Seed =				#15026 - 15050			
Strategy #2 Simulation Seed =				#4501 - 5400			
Strategy #3 Simulation Seed =				#6301 - 7200			

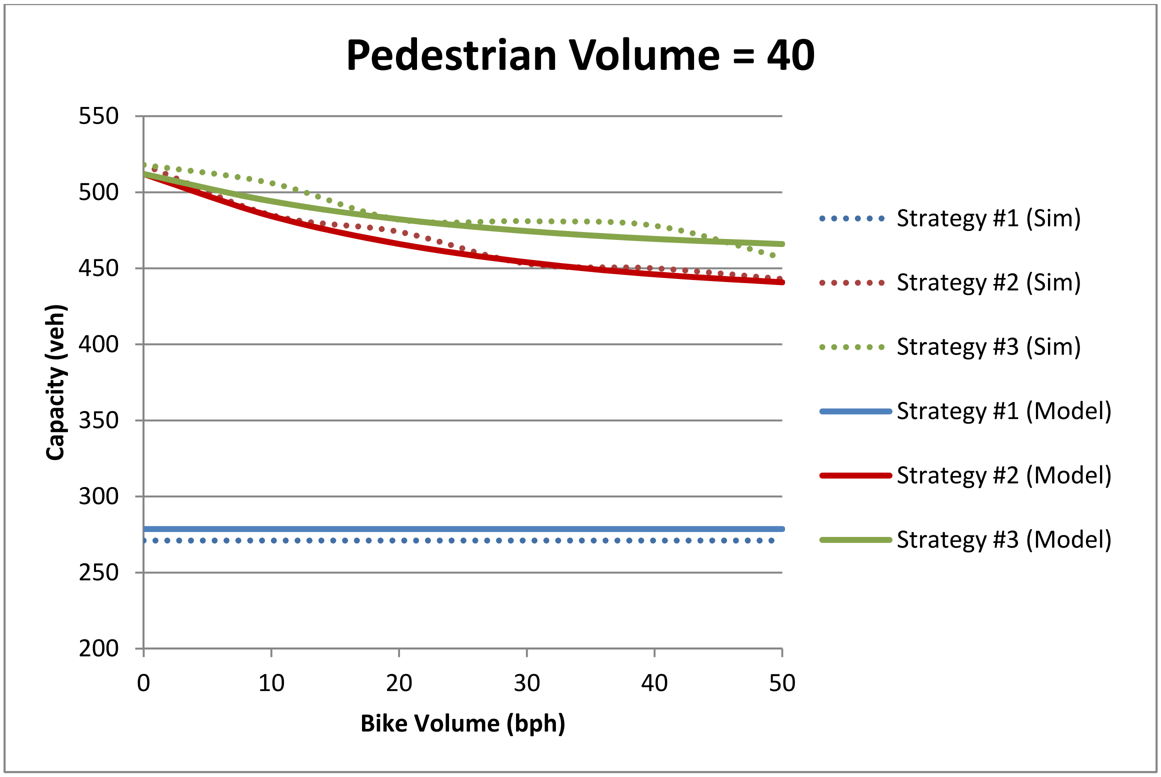
APPENDIX J: Lead-Lag Design Capacity and Delay Result Charts (W/ Clearance Time)

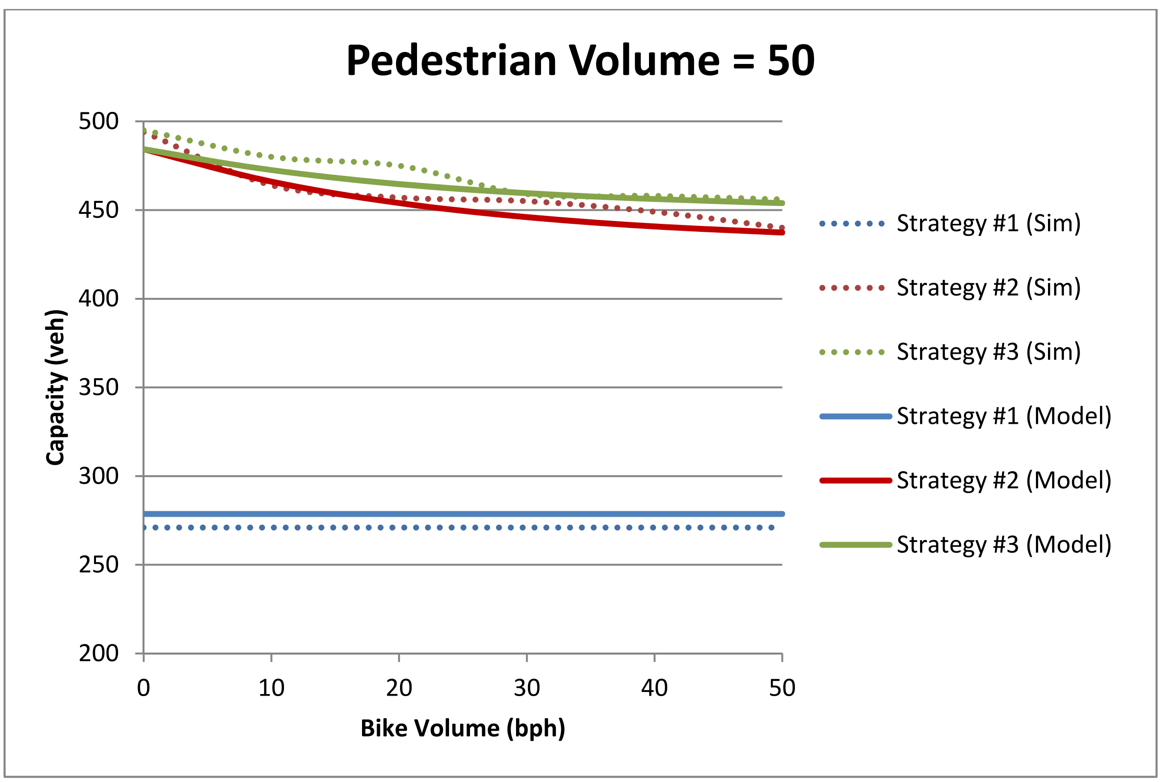




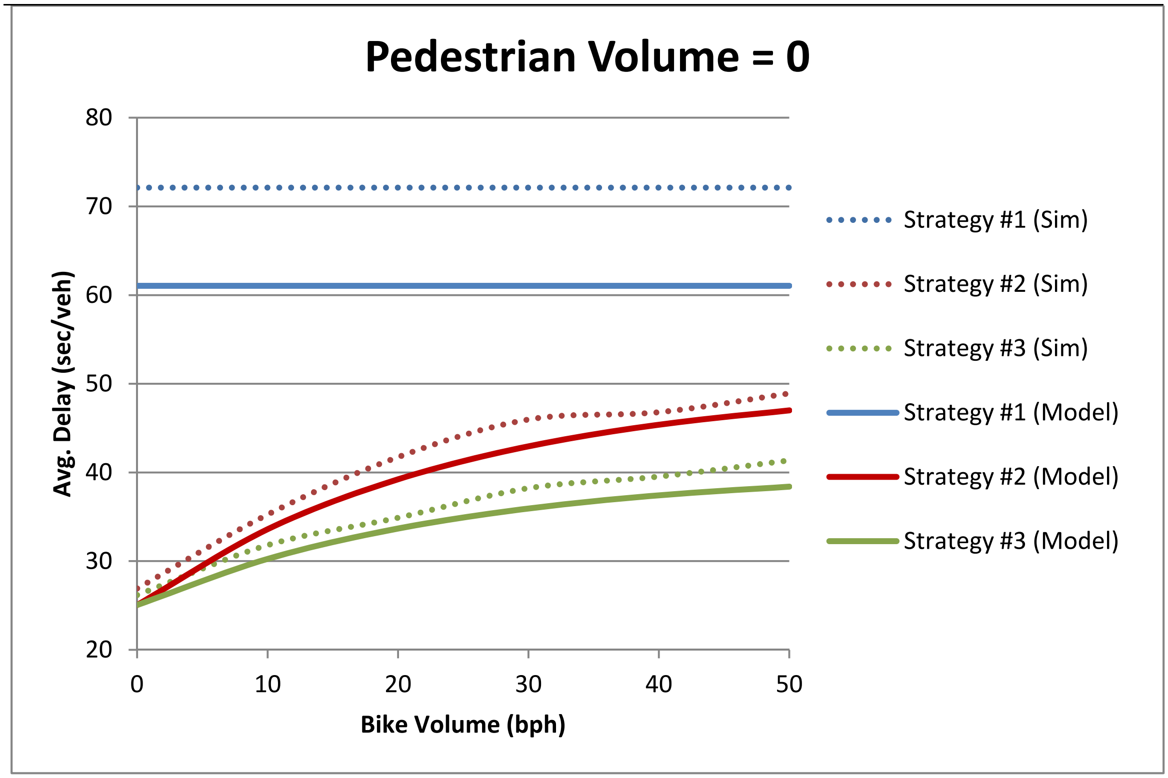

Pedestrian Volume = 20
650
600
550
500
450
400
350
300
250
200
Capacity (veh)
0
10
20
30
40
50
Bike Volume (bph)
Strategy #1 (Sim)
Strategy #2 (Sim)
Strategy #3 (Sim)
Strategy #1 (Model)
Strategy #2 (Model)
Strategy #3 (Model)

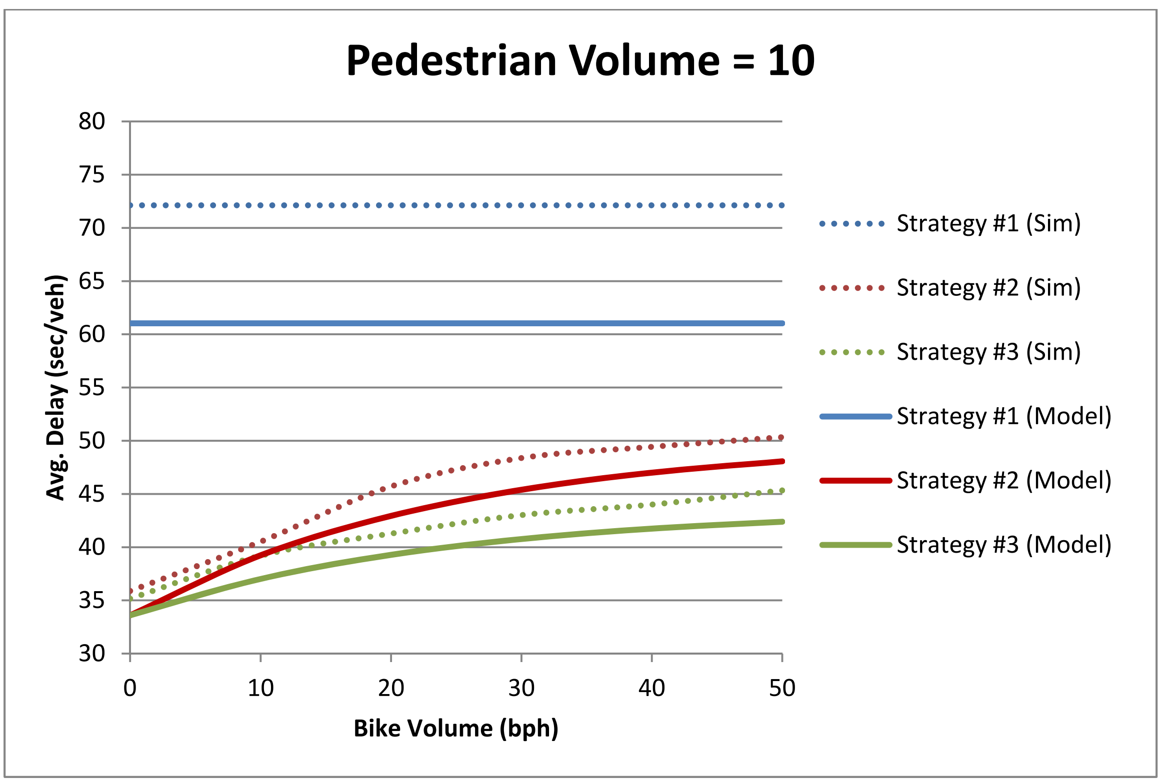

Pedestrian Volume = 30
600
550
500
450
400
350
300
250
200
Capacity (veh)
0
10
20
30
40
50
Bike Volume (bph)
Strategy #1 (Sim)
Strategy #2 (Sim)
Strategy #3 (Sim)
Strategy #1 (Model)
Strategy #2 (Model)
Strategy #3 (Model)

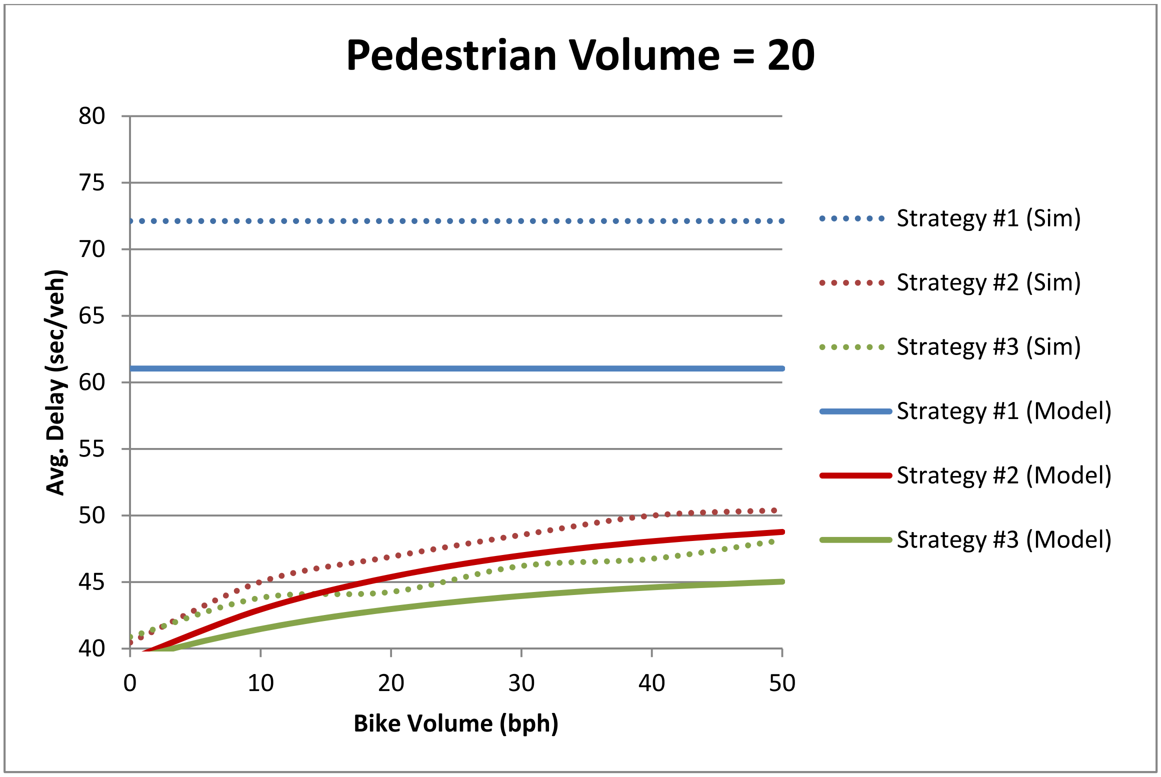

Pedestrian Volume = 40
550
500
450
400
350
300
250
200
Capacity (veh)
0
10
20
30
40
50
Bike Volume (bph)
Strategy #1 (Sim)
Strategy #2 (Sim)
Strategy #3 (Sim)
Strategy #1 (Model)
Strategy #2 (Model)
Strategy #3 (Model)


Pedestrian Volume = 50
500
450
400
350
300
250
200
Capacity (veh)
0
10
20
30
40
50
Bike Volume (bph)
Strategy #1 (Sim)
Strategy #2 (Sim)
Strategy #3 (Sim)
Strategy #1 (Model)
Strategy #2 (Model)
Strategy #3 (Model)

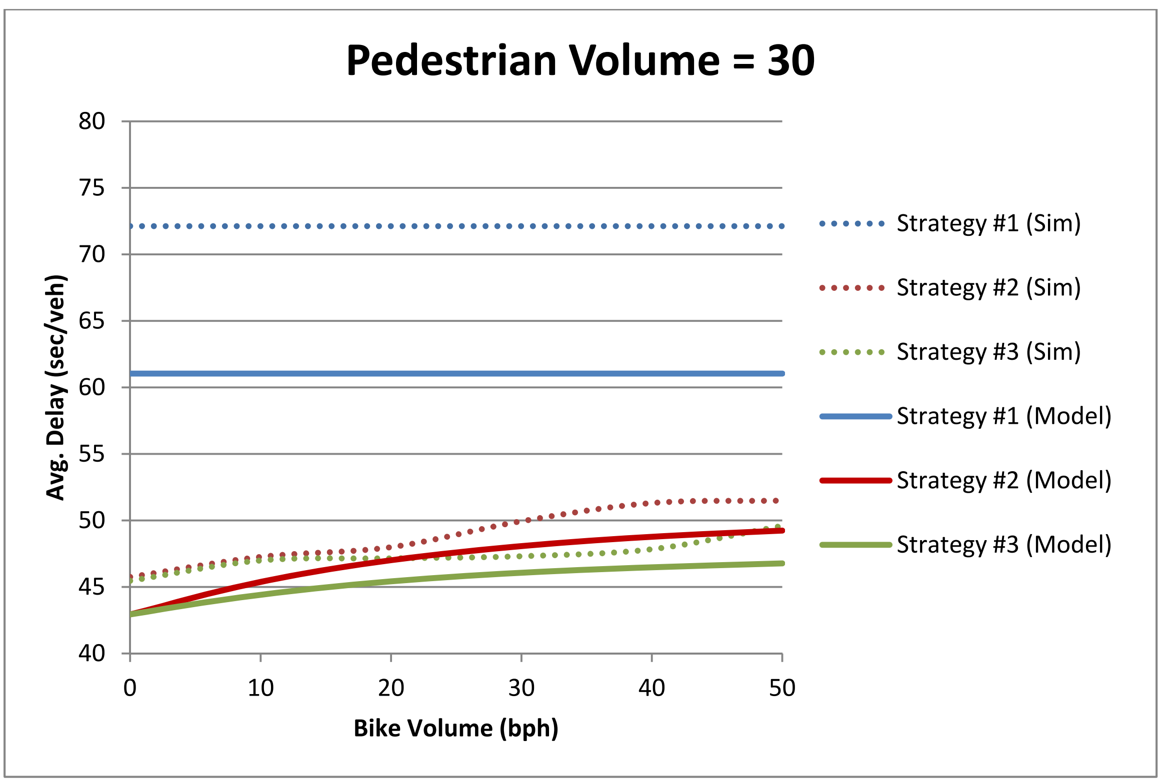
Delay Charts



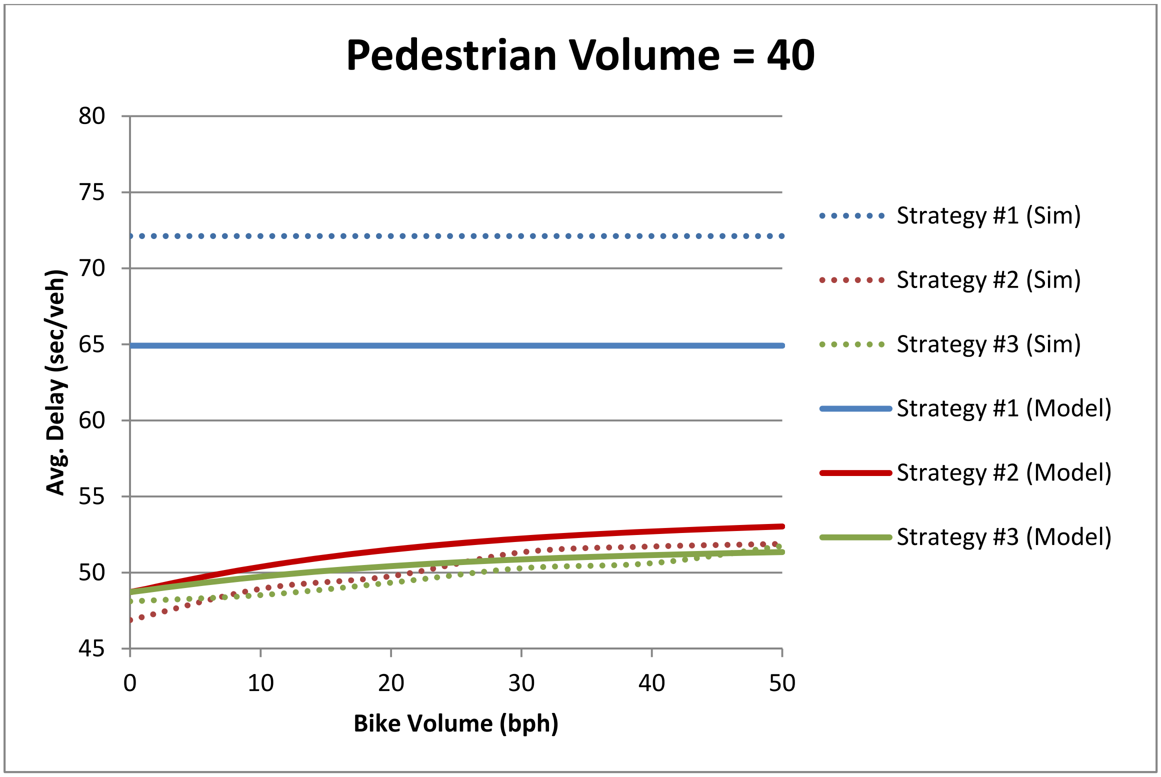


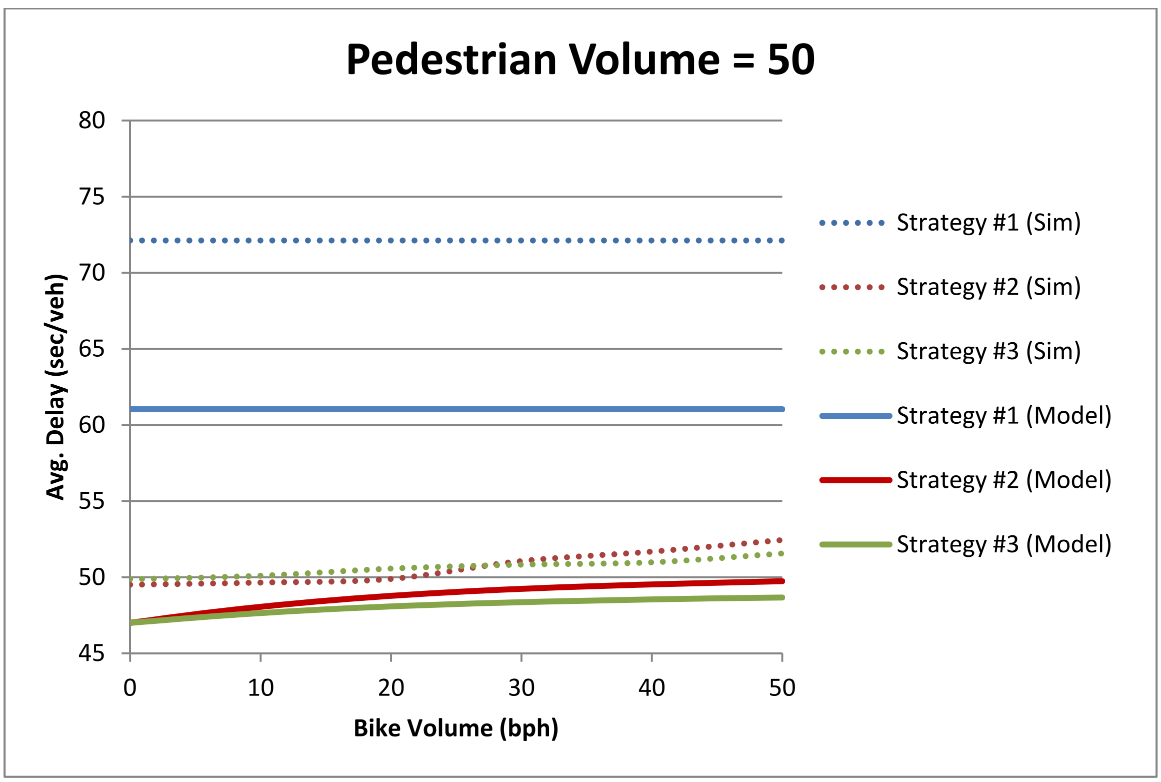


Pedestrian Volume = 20
80
75
70
65
60
55
50
45
40
Avg. Delay (sec/veh)
0
10
20
30
40
50
Bike Volume (bph)
Strategy #1 (Sim)
Strategy #2 (Sim)
Strategy #3 (Sim)
Strategy #1 (Model)
Strategy #2 (Model)
Strategy #3 (Model)



Pedestrian Volume = 30
80
75
70
65
60
55
50
45
40
Avg. Delay (sec/veh)
0
10
20
30
40
50
Bike Volume (bph)
Strategy #1 (Sim)
Strategy #2 (Sim)
Strategy #3 (Sim)
Strategy #1 (Model)
Strategy #2 (Model)
Strategy #3 (Model)


Pedestrian Volume = 40
Avg. Delay (sec/veh)
80
75
70
65
60
55
50
45
0
10
20
30
40
50
Bike Volume (bph)
Strategy #1 (Sim)
Strategy #2 (Sim)
Strategy #3 (Sim)
Strategy #1 (Model)
Strategy #2 (Model)
Strategy #3 (Model)


Pedestrian Volume = 50
Avg. Delay (sec/veh)
80
75
70
65
60
55
50
45
0
10
20
30
40
50
Bike Volume (bph)
Strategy #1 (Sim)
Strategy #2 (Sim)
Strategy #3 (Sim)
Strategy #1 (Model)
Strategy #2 (Model)
Strategy #3 (Model)

APPENDIX K: Lead-Lag Design Capacity and Delay Results (W/O Clearance Time)

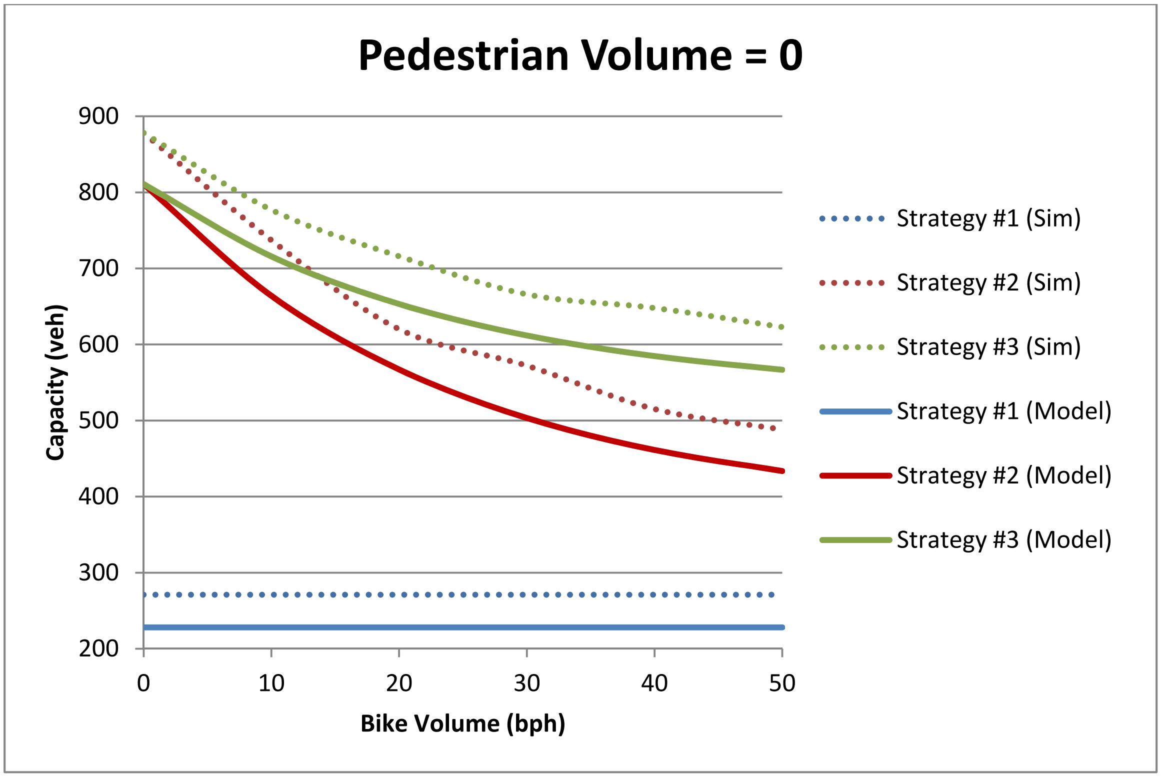
Lead-Lag Capacity Results							
Simulation				Model			
Pedestrian Volume =	0			Pedestrian Volume =	0		
Bicycle Volume	Strategy #1	Strategy #2	Strategy #3	Bicycle Volume	Strategy #1	Strategy #2	Strategy #3
0	271	878	878	0	228	810.6666667	810.6666667
10	271	737	777	10	228	663.9129647	715.7083889
20	271	620	716	20	228	567.1669618	653.1080341
30	271	572	666	30	228	503.3880658	611.8393367
40	271	515	648	40	228	461.3424263	584.6333347
50	271	488	623	50	228	433.6242324	566.6980327
Pedestrian Volume =	10			Pedestrian Volume =	10		
Bicycle Volume	Strategy #1	Strategy #2	Strategy #3	Bicycle Volume	Strategy #1	Strategy #2	Strategy #3
0	271	705	715	0	228	663.9129647	663.9129647
10	271	626	665	10	228	567.1669618	601.3126099
20	271	574	620	20	228	503.3880658	560.0439125
30	271	521	604	30	228	461.3424263	532.8379104
40	271	503	581	40	228	433.6242324	514.9026085
50	271	474	555	50	228	415.3512727	503.0789287
Pedestrian Volume =	20			Pedestrian Volume =	20		
Bicycle Volume	Strategy #1	Strategy #2	Strategy #3	Bicycle Volume	Strategy #1	Strategy #2	Strategy #3
0	271	663	625	0	228	567.1669618	567.1669618
10	271	561	579	10	228	503.3880658	525.8982644
20	271	516	560	20	228	461.3424263	498.6922624
30	271	491	538	30	228	433.6242324	480.7569604
40	271	469	523	40	228	415.3512727	468.9332806
50	271	455	509	50	228	403.3049953	461.1386305
Pedestrian Volume =	30			Pedestrian Volume =	30		
Bicycle Volume	Strategy #1	Strategy #2	Strategy #3	Bicycle Volume	Strategy #1	Strategy #2	Strategy #3
0	271	563	555	0	228	503.3880658	503.3880658
10	271	528	550	10	228	461.3424263	476.1820638
20	271	490	534	20	228	433.6242324	458.2467618
30	271	475	505	30	228	415.3512727	446.4230821
40	271	457	489	40	228	403.3049953	438.628432
50	271	450	484	50	228	395.3635998	433.4898819
Pedestrian Volume =	40			Pedestrian Volume =	40		

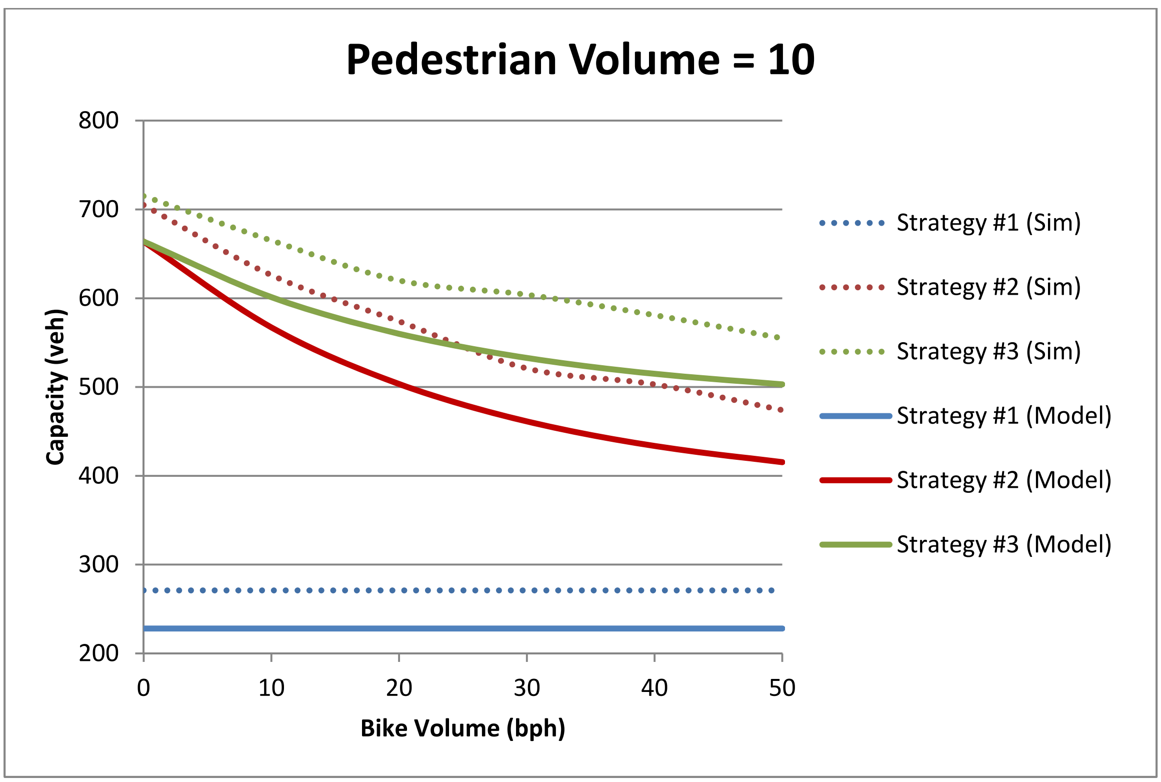
Bicycle Volume	Strategy #1	Strategy #2	Strategy #3	Bicycle Volume	Strategy #1	Strategy #2	Strategy #3
0	271	518	518	0	228	461.3424263	461.3424263
10	271	485	506	10	228	433.6242324	443.4071243
20	271	474	482	20	228	415.3512727	431.5834446
30	271	453	481	30	228	403.3049953	423.7887945
40	271	450	478	40	228	395.3635998	418.6502444
50	271	443	457	50	228	390.1283092	415.2627035
Pedestrian Volume =	50			Pedestrian Volume =		50	
Bicycle Volume	Strategy #1	Strategy #2	Strategy #3	Bicycle Volume	Strategy #1	Strategy #2	Strategy #3
0	271	494	495	0	228	433.6242324	433.6242324
10	271	464	480	10	228	415.3512727	421.8005526
20	271	457	475	20	228	403.3049953	414.0059025
30	271	455	459	30	228	395.3635998	408.8673525
40	271	449	458	40	228	390.1283092	405.4798115
50	271	440	456	50	228	386.6769929	403.2466069
Strategy #1 Simulation Seed =				#15001 - 15025			
Strategy #2 Simulation Seed =				#3601 - 4500			
Strategy #3 Simulation Seed =				#5401 - 6300			

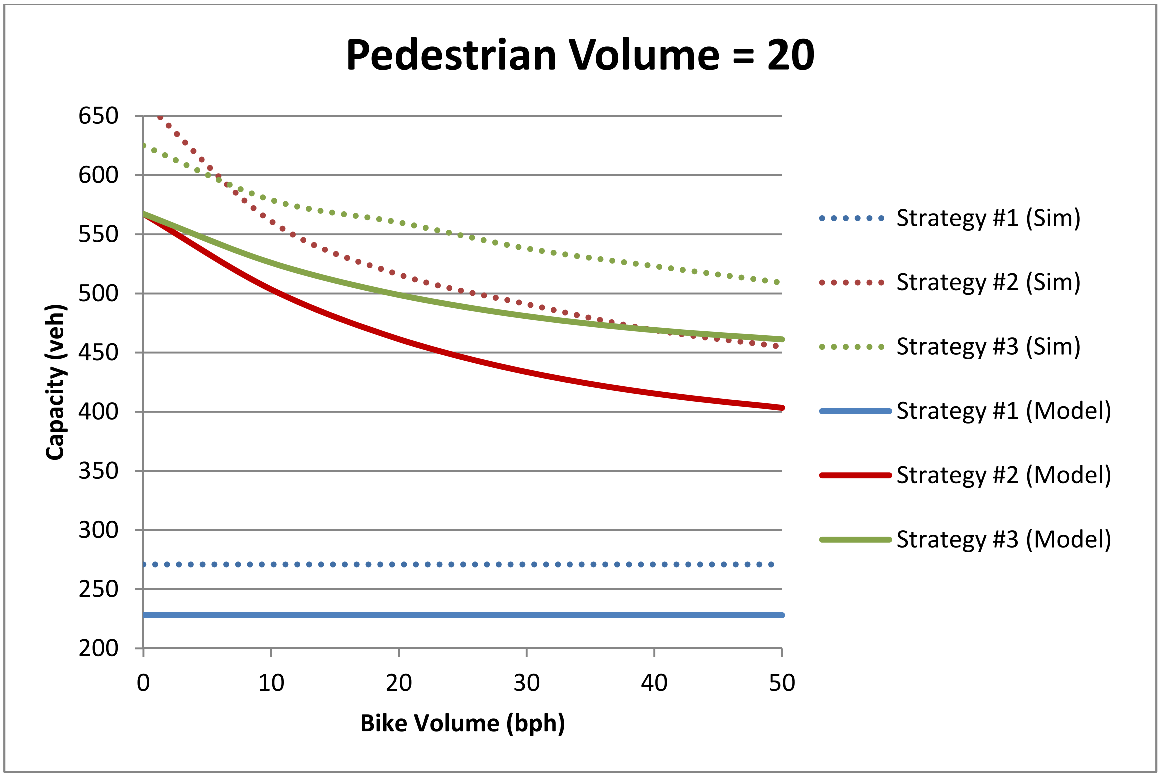
Lead-Lag Delay Results (Veh = 200)							
Simulation				Model			
Pedestrian Volume =	0			Pedestrian Volume =		0	
Bicycle Volume	Strategy #1	Strategy #2	Strategy #3	Bicycle Volume	Strategy #1	Strategy #2	Strategy #3
0	72.12	26.92	26.17	0	64.91294118	27.55372549	27.55372549
10	72.12	35.26	31.8	10	64.91294118	36.44527331	32.9719331
20	72.12	41.74	34.89	20	64.91294118	42.3069429	36.5438357
30	72.12	45.98	38.23	30	64.91294118	46.17119366	38.89857902
40	72.12	46.8	39.54	40	64.91294118	48.71866476	40.45092149
50	72.12	48.92	41.36	50	64.91294118	50.39806122	41.47428872
Pedestrian Volume =	10			Pedestrian Volume =		10	
Bicycle Volume	Strategy #1	Strategy #2	Strategy #3	Bicycle Volume	Strategy #1	Strategy #2	Strategy #3
0	72.12	35.89	35.16	0	64.91294118	36.44527331	36.44527331
10	72.12	40.52	39.2	10	64.91294118	42.3069429	40.01717591
20	72.12	45.71	41.27	20	64.91294118	46.17119366	42.37191923
30	72.12	48.38	43.01	30	64.91294118	48.71866476	43.9242617
40	72.12	49.43	44	40	64.91294118	50.39806122	44.94762893

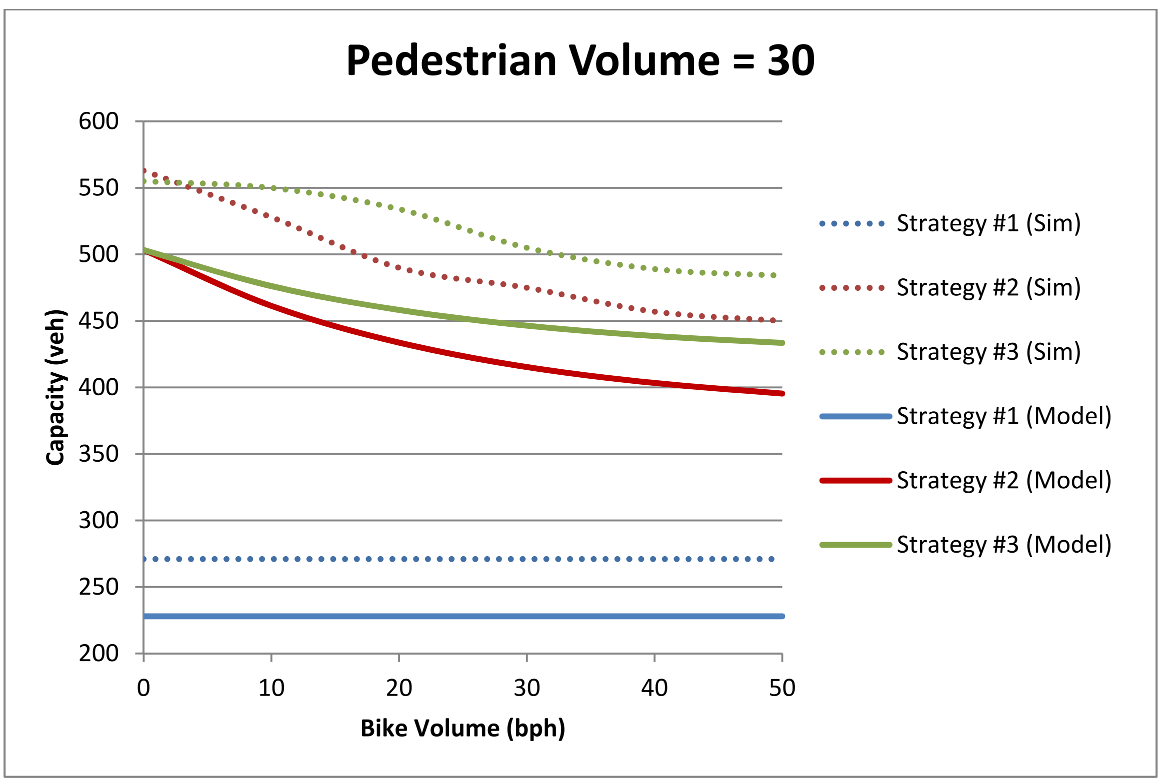
50	72.12	50.34	45.33	50	64.91294118	51.50518759	45.62227419
Pedestrian Volume =	20			Pedestrian Volume =	20		
Bicycle Volume	Strategy #1	Strategy #2	Strategy #3	Bicycle Volume	Strategy #1	Strategy #2	Strategy #3
0	72.12	40.46	40.89	0	64.91294118	42.3069429	42.3069429
10	72.12	45.01	43.82	10	64.91294118	46.17119366	44.66168622
20	72.12	46.9	44.26	20	64.91294118	48.71866476	46.21402869
30	72.12	48.54	46.21	30	64.91294118	50.39806122	47.23739592
40	72.12	49.99	46.75	40	64.91294118	51.50518759	47.91204118
50	72.12	50.4	48.14	50	64.91294118	52.23505028	48.35679474
Pedestrian Volume =	30			Pedestrian Volume =	30		
Bicycle Volume	Strategy #1	Strategy #2	Strategy #3	Bicycle Volume	Strategy #1	Strategy #2	Strategy #3
0	72.12	45.75	45.46	0	64.91294118	46.17119366	46.17119366
10	72.12	47.26	46.99	10	64.91294118	48.71866476	47.72353613
20	72.12	47.99	47.15	20	64.91294118	50.39806122	48.74690336
30	72.12	49.94	47.31	30	64.91294118	51.50518759	49.42154861
40	72.12	51.31	47.84	40	64.91294118	52.23505028	49.86630218
50	72.12	51.49	49.59	50	64.91294118	52.71620542	50.1595018
Pedestrian Volume =	40			Pedestrian Volume =	40		
Bicycle Volume	Strategy #1	Strategy #2	Strategy #3	Bicycle Volume	Strategy #1	Strategy #2	Strategy #3
0	72.12	46.88	48.11	0	64.91294118	48.71866476	48.71866476
10	72.12	48.93	48.52	10	64.91294118	50.39806122	49.74203199
20	72.12	49.76	49.34	20	64.91294118	51.50518759	50.41667725
30	72.12	51.33	50.29	30	64.91294118	52.23505028	50.86143081
40	72.12	51.71	50.62	40	64.91294118	52.71620542	51.15463043
50	72.12	51.88	51.75	50	64.91294118	53.03340244	51.34791953
Pedestrian Volume =	50			Pedestrian Volume =	50		
Bicycle Volume	Strategy #1	Strategy #2	Strategy #3	Bicycle Volume	Strategy #1	Strategy #2	Strategy #3
0	72.12	49.51	49.87	0	64.91294118	50.39806122	50.39806122
10	72.12	49.65	50.1	10	64.91294118	51.50518759	51.07270647
20	72.12	49.89	50.57	20	64.91294118	52.23505028	51.51746004
30	72.12	51.06	50.83	30	64.91294118	52.71620542	51.81065966
40	72.12	51.68	50.98	40	64.91294118	53.03340244	52.00394876
50	72.12	52.44	51.56	50	64.91294118	53.2425116	52.13137279
Strategy #1 Simulation Seed =				#15026 - 15050			
Strategy #2 Simulation Seed =				#4501 - 5400			
Strategy #3 Simulation Seed =				#6301 - 7200			

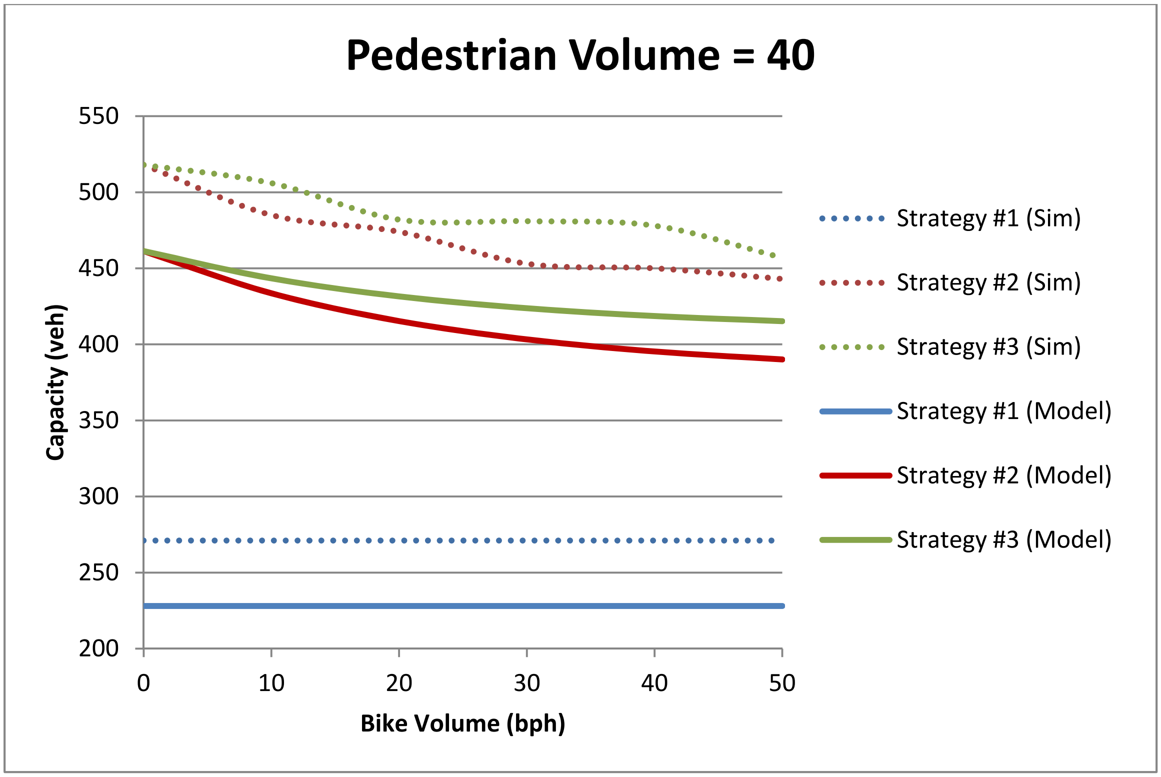
APPENDIX L: Lead-Lag Design Capacity and Delay Result Charts (W/O Clearance Time)

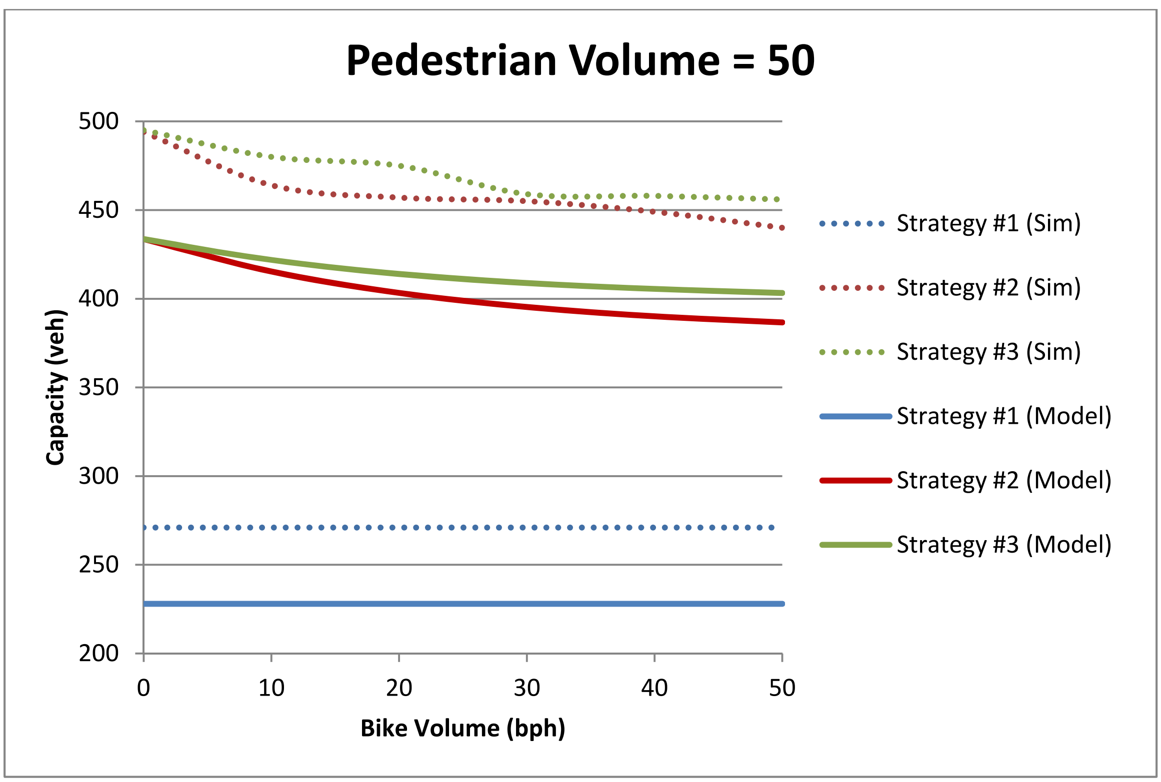




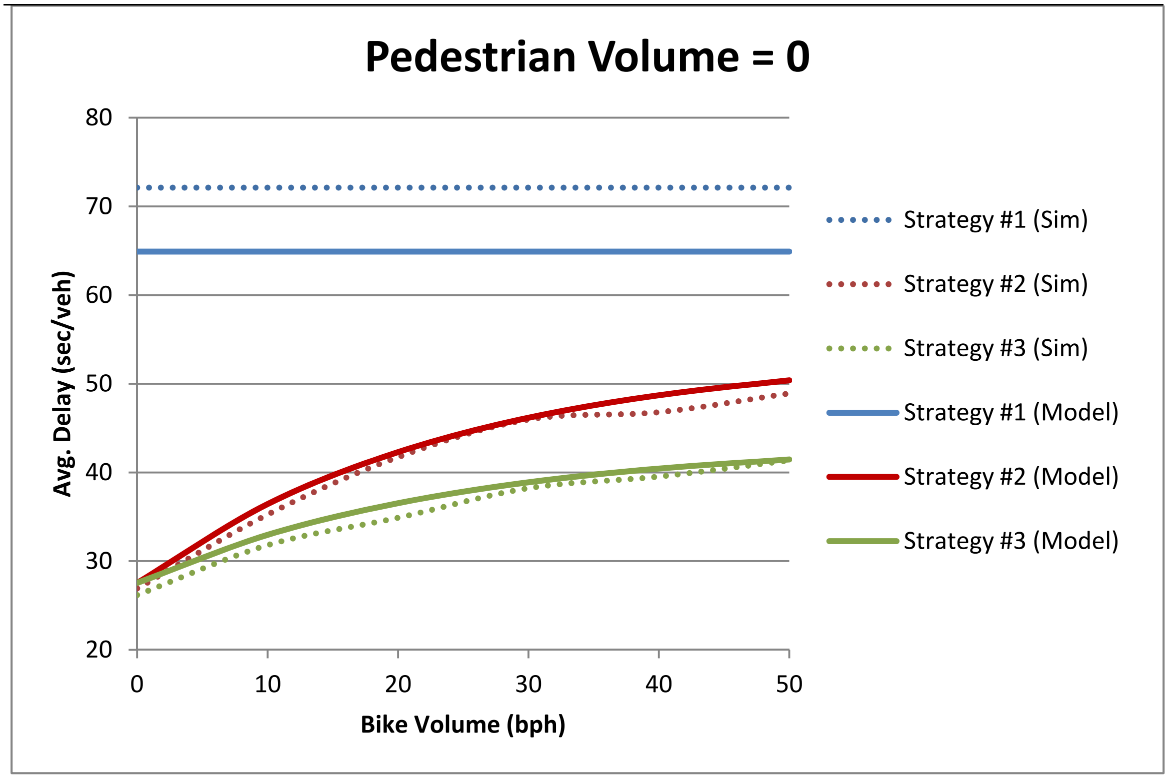

Pedestrian Volume = 20
650
600
550
500
450
400
350
300
250
200
Capacity (veh)
0
10
20
30
40
50
Bike Volume (bph)
Strategy #1 (Sim)
Strategy #2 (Sim)
Strategy #3 (Sim)
Strategy #1 (Model)
Strategy #2 (Model)
Strategy #3 (Model)

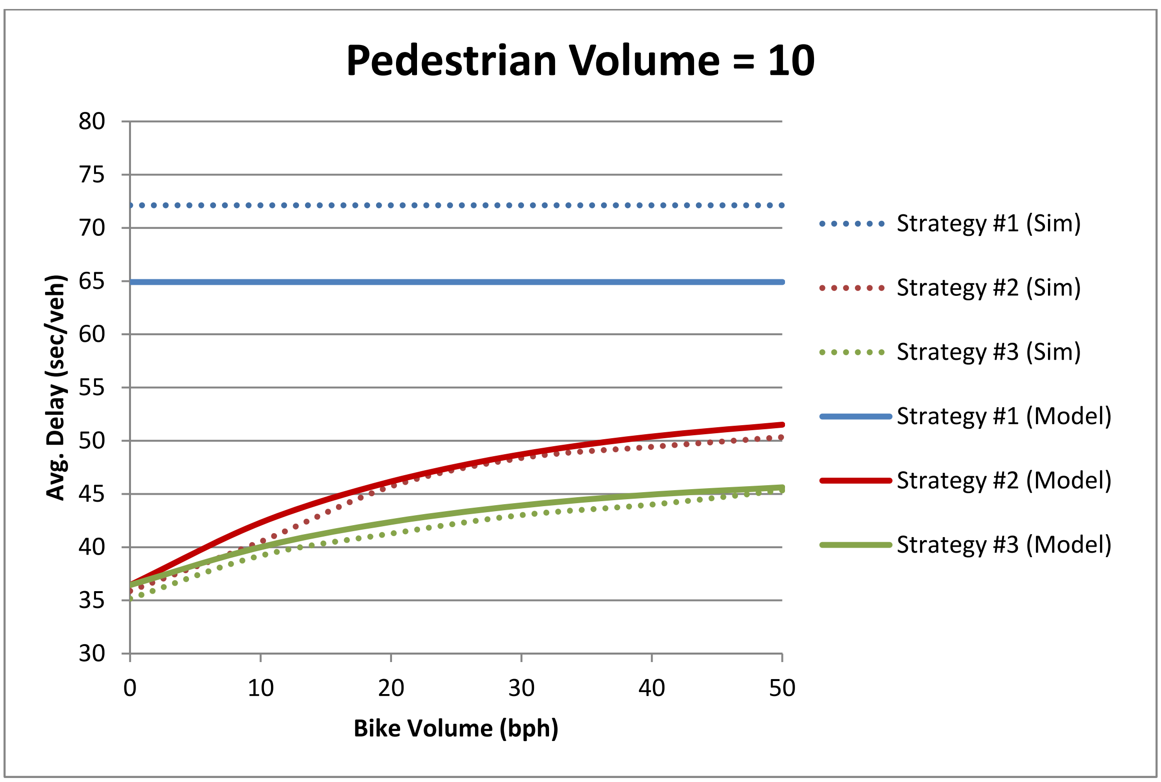

Pedestrian Volume = 30
600
550
500
450
400
350
300
250
200
Capacity (veh)
0
10
20
30
40
50
Bike Volume (bph)
Strategy #1 (Sim)
Strategy #2 (Sim)
Strategy #3 (Sim)
Strategy #1 (Model)
Strategy #2 (Model)
Strategy #3 (Model)

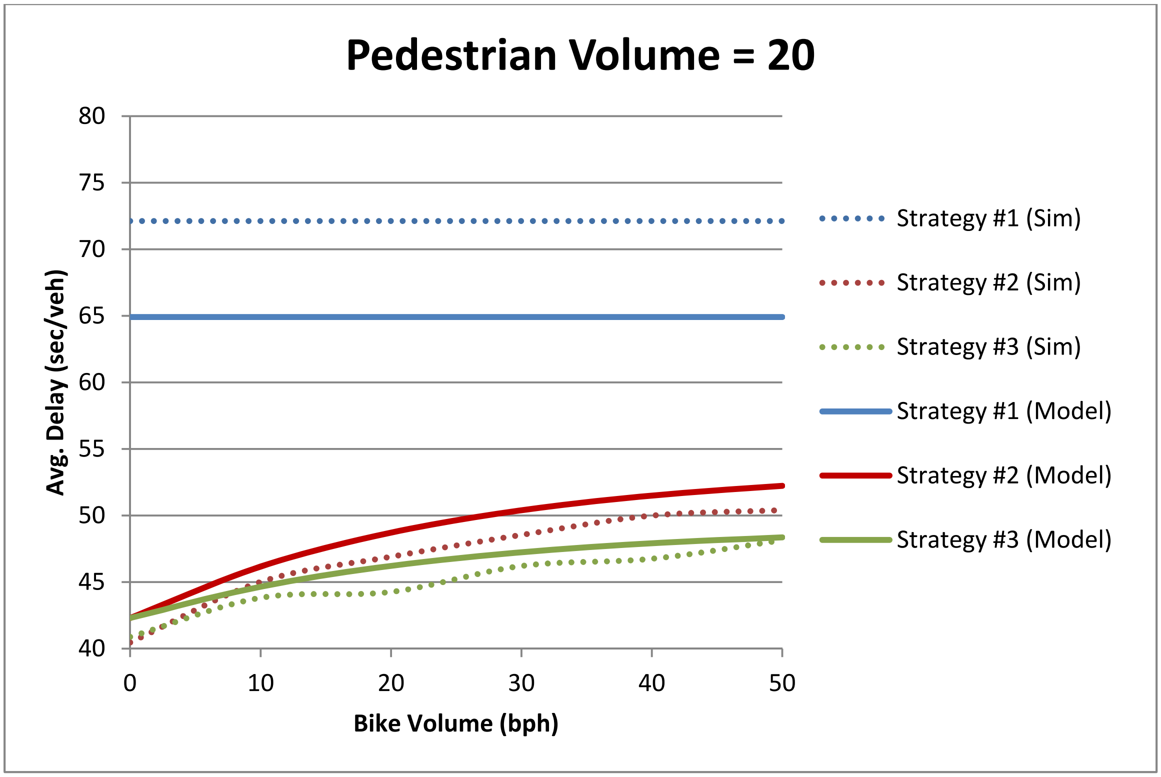

Pedestrian Volume = 40
Capacity (veh)
550
500
450
400
350
300
250
200
0
10
20
30
40
50
Bike Volume (bph)
Strategy #1 (Sim)
Strategy #2 (Sim)
Strategy #3 (Sim)
Strategy #1 (Model)
Strategy #2 (Model)
Strategy #3 (Model)


Pedestrian Volume = 50
Capacity (veh)
500
450
400
350
300
250
200
0
10
20
30
40
50
Bike Volume (bph)
Strategy #1 (Sim)
Strategy #2 (Sim)
Strategy #3 (Sim)
Strategy #1 (Model)
Strategy #2 (Model)
Strategy #3 (Model)

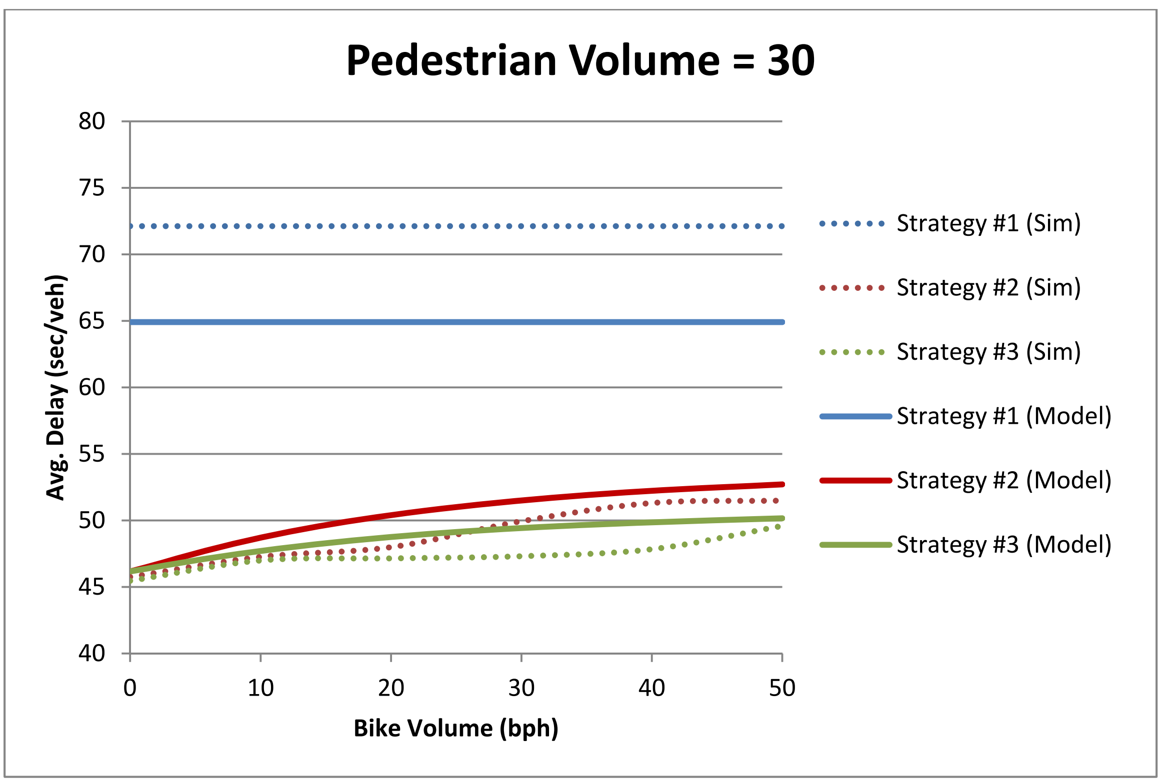
Delay Charts



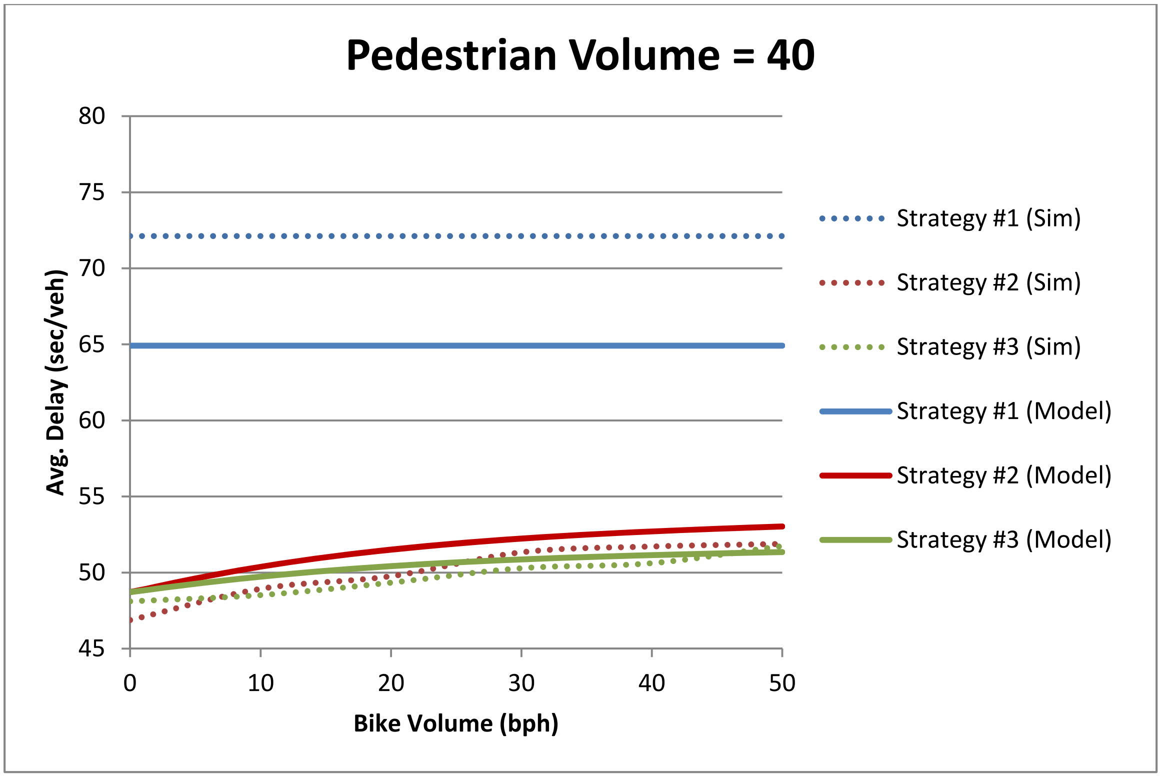




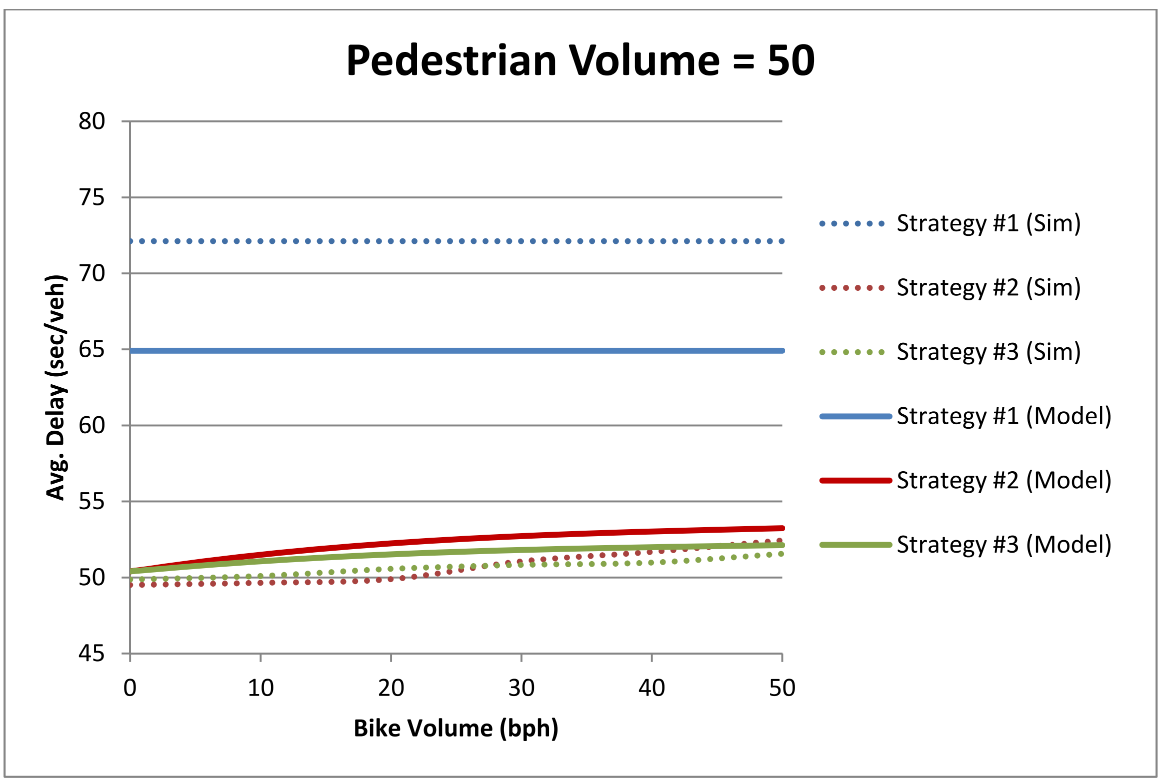
Pedestrian Volume = 20
Avg. Delay (sec/veh)
80
75
70
65
60
55
50
45
40
0
10
20
30
40
50
Bike Volume (bph)
Strategy #1 (Sim)
Strategy #2 (Sim)
Strategy #3 (Sim)
Strategy #1 (Model)
Strategy #2 (Model)
Strategy #3 (Model)



Pedestrian Volume = 30
Avg. Delay (sec/veh)
80
75
70
65
60
55
50
45
40
0
10
20
30
40
50
Bike Volume (bph)
Strategy #1 (Sim)
Strategy #2 (Sim)
Strategy #3 (Sim)
Strategy #1 (Model)
Strategy #2 (Model)
Strategy #3 (Model)



Pedestrian Volume = 40
Avg. Delay (sec/veh)
80
75
70
65
60
55
50
45
0
10
20
30
40
50
Bike Volume (bph)
Strategy #1 (Sim)
Strategy #2 (Sim)
Strategy #3 (Sim)
Strategy #1 (Model)
Strategy #2 (Model)
Strategy #3 (Model)



Pedestrian Volume = 50
Avg. Delay (sec/veh)
80
75
70
65
60
55
50
45
0
10
20
30
40
50
Bike Volume (bph)
Strategy #1 (Sim)
Strategy #2 (Sim)
Strategy #3 (Sim)
Strategy #1 (Model)
Strategy #2 (Model)
Strategy #3 (Model)

VITA

The author of this thesis, Mr. Andrew Jayankura, was born on August 3, 1988, in Castro Valley, California.

The author first attended Chabot Elementary School in Castro Valley, California from 1993 to 1996. The author, along with his family, then moved to Reno, Nevada, where, for the next 19 years, spent all his time attending school. He attended Sarah Winnemucca Elementary School, Billinghurst Middle School, and McQueen High School prior to attending the University of Nevada, Reno in 2006 where he pursued his Bachelors of Science in Civil Engineering and graduated in December 2010.

Mr. Jayankura then worked as a project coordinator at a local precast company from 2011 to 2013 before re-entering the University of Nevada, Reno in January 2014 and pursued for this Masters of Science in Civil Engineering, emphasizing in Traffic and Transportation Engineering.