Evaluating the Quality of Automatic Pedestrian Detection at Major Arterial Intersection

by

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Improvements in detection technology can provide full actuation for vehicles and pedestrians at a signalized intersection. The goal of this study was to assess the accuracy of an automatic camera detection system from GRIDSMART to detect pedestrians and make calls to the controller to provide pedestrian phases only when needed. Manual actuation has been proven ineffective due to individual behavior, so automatic detection is of interest as a solution in lower pedestrian areas to improve signal operations for all users. Video from the GRIDSMART system was analyzed to determine the accuracy of pedestrian detection. The detection system was not capable of accurately counting pedestrians due to vehicle interference and configuration issues. Pedestrian calls were made only for those who came to a stop in the detection zones. Weather and time of day also impacted accuracy with errors increasing during night and rainy conditions. The detection system averaged 2.4 calls/pedestrian which resulted in unnecessary pedestrian phases. A VISSIM model was created to determine the effects on vehicle delay from the current operations, and to determine the most appropriate pedestrian treatment for the subject intersection. Vehicle volumes on the critical approaches are significant enough that pedestrian green times do not extend the vehicle phases when no demand is present. The detection errors did not lead to statistically significant delay increases for vehicles or pedestrians, but there was no benefit identified. For this specific case, the intersection can be operated under pedestrian recall without increasing vehicle delay, even for low pedestrian volumes. For higher pedestrian volumes that can be expected in peak conditions, pedestrian recall would also be an appropriate signal operation. The detection software does not appear suited for controlling pedestrian crossings until improvements are made. Other intersections where pedestrian recall would increase vehicle delays may prove to be better candidates.

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1.0 Introduction

The treatment of pedestrians at signalized intersections requires balancing the safety of pedestrians with overall delay for both pedestrians and vehicles. Pedestrian recall provides a pedestrian phase with every vehicle phase. This can cause undesirable vehicle delay at intersections using actuated signals if the pedestrian phase extends the vehicle phase longer than necessary. Pedestrian pushbuttons are often used as an alternative so that there is only a call for the phase upon arrivals to the intersection (1). This improves vehicle delay and intersection capacity but can increase pedestrian delay and reduce safety (2). The best pedestrian treatment, or signal operation, depends on the intersection geometry and vehicle and pedestrian flows. There are conditions where either pedestrian recall or full actuation can be used, or where only one should be used (3).

The Manual on Uniform Traffic Control Devices (MUTCD) provides minimum "Walk" intervals based on pedestrian volumes (4). The "Flashing Don't Walk" (FDW) interval follows the Walk interval and is the determining factor for pedestrian phase times (5). This interval is determined by calculating the pedestrian clearance interval, or how much time is required to cross the width of the intersection using the required design speed for the crossing. The MUTCD recommends a minimum design speed of 3.5 ft/s, but lower speeds can be used in areas with predominately slower pedestrians, such as schools or nursing homes (4). This provides enough time for a pedestrian that begins crossing as the Walk interval ends to safely cross before an opposing vehicle phase is in conflict.

When a pedestrian clearance interval is greater than the accompanying minimum vehicle green, the pedestrian phase time becomes the minimum green time for the phase. When vehicle demand is not present, this will extend the phase longer than is required and increase delay to the other vehicles and pedestrians waiting to move through the intersection. Therefore, pedestrian recall is generally used only for the high-volume major street or in high pedestrian areas where crossings happen every cycle (1) and manual pushbuttons are used in low pedestrian areas. The issues with manual pushbuttons involve individual human behavior. Sulmicki (6) showed that 78% of study participants did not push the button and increased the number of crossings deemed risky. Pushbuttons also increase pedestrian delay (wait times) since a phase is not provided with every vehicle phase, which leads to lower pedestrian compliance and risky crossings (2,7,8). The study by Cesme et al. (3) of a coordinated network provides guidance for when to choose pedestrian recall or manual actuation, comparing the pedestrians per cycle to the ratio of pedestrian phase time to minimum vehicle green time. They found that there are low pedestrian volume scenarios where pedestrian recall is acceptable without reducing intersection capacity. Khoturi (9) found that pedestrian recall increased compliance and improved safety.

The emergence of automatic detection systems has expanded to include pedestrian actuations in addition to vehicles. Manual pushbuttons have proven to be ineffective (6), but there are still intersections where pedestrian recall is not desirable. New technology has been developed to use cameras to replace pushbuttons and make calls for pedestrians as they are detected arriving to the intersection. The cameras allow the entire signal operation to be fully automated and controlled by the detection system. Pedestrian detection is still improving, and this study provides an opportunity to assess the functionality and accuracy of one of the systems in the field.

1.1 Research Goal and Objectives

The Department of Mobility and Infrastructure for the City of Pittsburgh has a GRIDSMART detection system in place at the signalized intersection of Penn Avenue and 40th Street, two major arterial streets (10). There has been significant development in the area and the intersection sees heavy traffic volumes during peak periods. This study was designed to assess the operations of the advanced detection technology during the PM peak period and determine the effects on vehicles and pedestrians. The research objectives to satisfy this goal are:

- Collect vehicle and pedestrian data to determine the intersection peak hour and provide accurate counts for future use by DOMI
- Assess the accuracy of the advanced detection system to make pedestrian calls and accurately count pedestrians during peak hour operation
- Use VISSIM microsimulation software to build a model of the area network and assess the impact of automatic pedestrian actuations on signal operations in terms of vehicle and pedestrian delay
- Use VISSIM microsimulation software to assess vehicle and pedestrian delay under different control strategies and recommend the most appropriate treatment
- Provide recommendations to DOMI concerning the implementation of the GRIDSMART detection system in the City's traffic network

The intersection was studied during the PM peak period to assess the accuracy of the GRIDSMART cameras. Pedestrian data was collected manually by analyzing historical video downloaded from the GRIDSMART processor to validate the reports generated by the processor. The cameras can only place a call when pedestrians stop in the dedicated wait zone and can mistake vehicles or other objects for pedestrians, so analysis focused on false calls, multiple calls, and unnecessary pedestrian phases provided by detection that may increase vehicle delay.

A model of the area network was created using VISSIM to determine the impact of additional pedestrian phases provided by automatic detection that may not be needed. In addition, the model was tested under four control strategies, full actuation, pedestrian recall, minimum recall, and maximum recall, to determine the appropriate control strategy under low and high pedestrian volumes. The study was conducted during winter and pandemic conditions, so peak pedestrian activity was of interest to DOMI (i.e., peak summer activity). A recommendation for future signal operations was made based on the results of the manual and simulation analyses.

2.0 Technology and Literature Review

As ITS technology improves and planning focus shifts to multi-modal strategies, pedestrian treatments have become a priority for traffic signal operations. Automatic pedestrian detection is desirable because it can allow for actuated or adaptive signals to maximize their potential. Pedestrian safety is of increasing importance and finding an acceptable balance between vehicle and pedestrian delay to reduce risky or unsafe crossings is of interest.

2.1 Technology Review

2.1.1 GRIDMSART Detection Software

The automatic detection system in place is manufactured by GRIDSMART (parent company CUBIC). GRIDSMART advertises as “the world’s first single-camera solution for actuation, data collection, and situational awareness” and “delivers smart traffic management solutions to communities of all sizes so they can reduce urban congestion, maximize efficiency, and decrease environmental impact. Real-time performance data, including timestamped traffic volumes, turns, and average speeds, is collected and made available for analysis and better decision making.” (11,12). One camera can capture the entire intersection; however, two cameras are required by the manufacturer to enable pedestrian detection. The hardware operates using the GRIDSMART System Processor, a “suite of vision-tracking algorithms that build a three-dimensional model of approaching objects (11).” The processor is connected to the signal controller and can provide actuations and data collection from detection. GRIDSMART maintains it produces a comprehensive traffic management system for lower costs than their competitors.

2.1.1.1 SMARTMOUNT Bell Camera

The detection hardware is a bell-shaped, fish-eye camera that can do the work of four traditional cameras. According to GRIDSMART (12):

> "The SMARTMOUNT Bell Camera delivers the only field-tested, single-intersection sensor empowering tracking through the entire intersection, including the center where vehicles and vulnerable road users cross. The horizon-to-horizon approach offers highly accurate turn counts, unmatched situational awareness, views, and functionality from the center of the intersection, and unobstructed incident management views. The camera's virtual pan-tilt-zoom enables users to set up multiple views and adjust those anytime as needed without impacting performance. The aesthetically pleasing, environmentally conducive bell shape of the camera isn't just for looks. The iconic Bell Camera shape protects the lens by mitigating sun glare and adverse weather conditions while decreasing annual maintenance."

Installation is standardized and can be completed in less than 3 hours, saving time and money in the field. The cameras do not need to be focused or calibrated, and maintenance over the lifetime of the hardware is mainly keeping the lens clean. The mounting assembly has been tested in a wind tunnel with speeds greater than 150 mph. An image of the camera is in Figure 1 below (12).

Figure 1 SMARTMOUNT Bell Camera by GRIDSMART

2.1.1.2 GRIDSMART System Processor

The core of GRIDSMART detection is the GS2 system processor that runs the GRIDSMART Engine, vision-tracking algorithms based on real world testing that enable the detection features. According to GRIDSMART (11):

> "The Bell Camera is powered from a single-wire, Power over Ethernet (POE) connection by the GRIDSMART System Processor. GRIDSMART System, the intelligence of the GRIDSMART Solution, runs the GRIDSMART Engine, a suite of vision-tracking algorithms grown from a decade of real-world testing that builds a 3-dimensional model of cars, trucks, pedestrians, and other objects approaching the intersection. The object trajectories are tracked through user-defined zones at the intersection and follows them until vehicles exit, delivering unmatched accuracy."

The processor has an easy-to-read front panel that uses LEDs to display detection calls and current phase states. It can support two SMARTMOUNT Bell Cameras or four traditional cameras. The processor is NEMA TS2 certified and supports up to 24 optically isolated outputs and 64 programmable detectors. An image of the processor is shown in Figure 2 below (11).

Figure 2 GS2 System Processor by GRIDSMART

2.1.1.3 GRIDSMART Client App

GRIDSMART has developed a cloud-based client app that provides remote access to the cameras and various functional features. Data is uploaded to the GRIDSMART Cloud daily via a modem and can be accessed via the GRIDSMART App (13). According to GRIDSMART, "…the Client allows you to set up detection and counting zones, view intersections and highways, and even generate performance reports anytime, anywhere" (13). Data can also be collected directly from the processor using an external hard drive or USB drive, but cloud storage is unlimited. Video is not saved and can only be recorded directly from the processor. A view into the GRIDSMART App interface is in Figure 3 below (13).

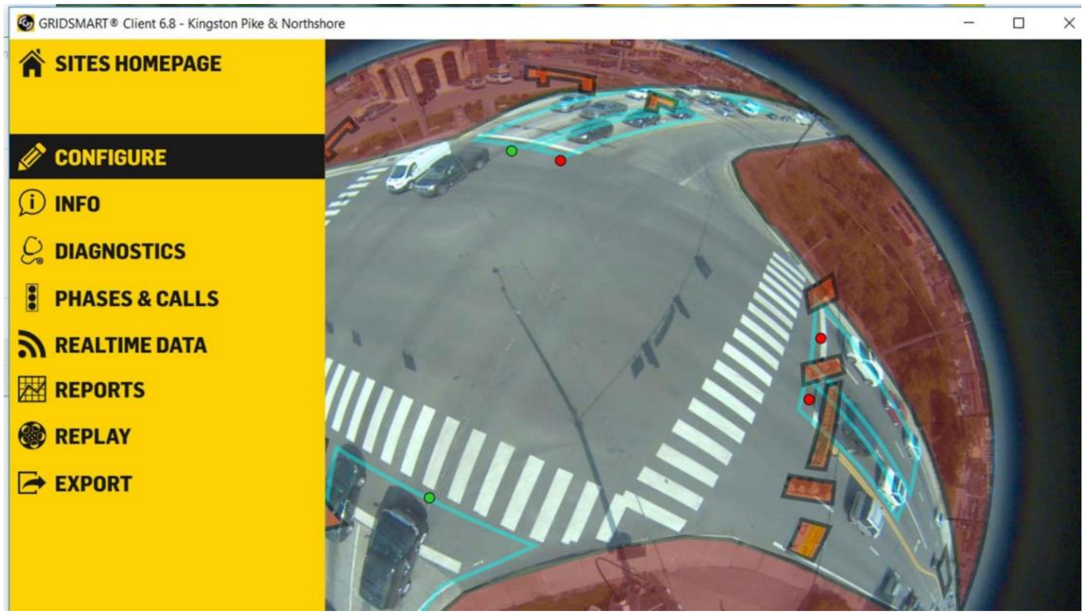


Figure 3 GRIDSMART Client API

The GRIDSMART App can be loaded onto unlimited computers and allows playback of saved video at variable speeds (-2x to 8x). During playback, a display that shows controller calls as they were made along with active phases as the cycles move forward is available. The functionality of the system can be improved by purchasing modular upgrades. According to GRIDSMART (13):

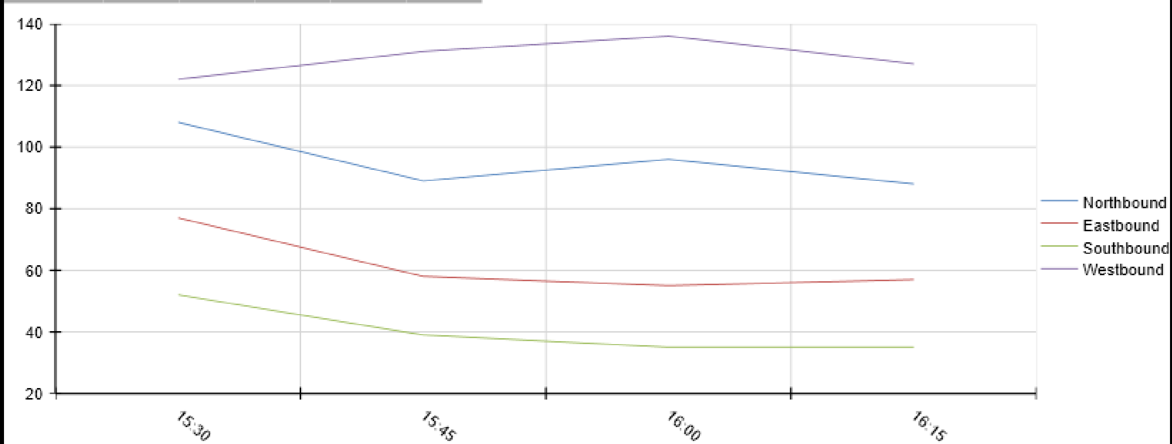
> "Modules are independently licensed software components that add flexibility, maximize value, and create simple solutions for diverse needs. Modules can be added at any time. All modules are perpetually licensed for your GRIDSMART intersection, regardless of future hardware and software updates."

There are two data modules that can be added, the Performance Module and the Performance Plus Module. The Performance Module "delivers an abundance of reports including counts, length-based classifications, turning movements, red and green occupancy, and cycle lengths. (13)" These reports can be generated over any selected time range for defined collection intervals of 5-, 15-, 30-, or 60-minutes. An example of a turning movement count report is shown in Figure 4 for the peak hour Thursday January 6, 2021, by 15-minute intervals.

GRIDSMART Turning Movement Counts

Intersection Penn Ave & 40th st
Date 1/6/2022

	Right	Through	Left	UTurn	Total
Northbound	30	172	179		381
Eastbound	21	217	8	1	247
Southbound	58	100	3		161
Westbound	209	278	29		516
Total	**318**	**767**	**219**	**1**	**1305**



	Northbound			Eastbound				Southbound			Westbound		
	R	T	L	R	T	L	U	R	T	L	R	T	L
15:30	7	48	53	7	68	2		19	31	2	50	65	7
15:45	5	35	49	3	53	1	1	19	20		54	68	9
16:00	7	54	35	9	45	1		9	25	1	58	72	6
16:15	11	35	42	2	51	4		11	24		47	73	7
Total	**30**	**172**	**179**	**21**	**217**	**8**	**1**	**58**	**100**	**3**	**209**	**278**	**29**

1 of 2

Figure 4 Turning Movement Count Report for Peak Hour 01/06/22

The Performance Plus Module adds Site and Zone email alerts to the full features of the Performance Module. Site Alerts include All System Events, Loss of Visibility, Cabinet Flash, and Volume Exceeded. Zone Alerts include Volume Exceeded and Zone Activated. This module also enables pedestrian detection for pedestrian phase extensions but does not provide counting or actuation (13). A March 2021 firmware update pedestrian actuation from pedestrian wait zones, as well as pedestrian counting to the Performance Module. This update established a requirement that two cameras be installed to allow these pedestrian features (14).

2.1.1.4 Florida DOT Ramp Metering Study

A Florida Department of Transportation study (15) tested multiple detection systems for use at a ramp metering location. They ultimately chose another product but highlighted some aspects of the GRIDSMART system. They noted that the system was easy to install and the setup is intuitive, but the technician had several technical problems setting it up. As stated in the product description, the cameras do not require calibration and work in any condition, but night conditions saw a 3% undercount of vehicles in the study period (15). Also, GRIDSMART was not able to produce vehicle occupancy, queue, or delay results that FDOT specifically requested. FDOT noted that it had the lowest total cost of ownership on the market and highlighted the benefits of free technical support, no recurring licensing fees, and new software is immediately available for download without charge (15).

2.1.2 GRIDSMART Configuration

Before the system can begin operating signal control and collecting data, the intersection or detection area must be programmed into a configuration file. The user defines vehicle zones (presence detectors), pedestrian wait zones (pedestrian ramp areas), pedestrian zones (crosswalks), and areas or objects to be ignored by the cameras. Vehicles and pedestrians are tracked throughout these zones to deliver counts. Vehicle zones and pedestrian wait zones are used to provide actuation for calls to the signal controller. Figure 5 below shows the user-defined zones at the subject intersection. Vehicle and pedestrian zones have no fill in the image. Purple-shaded polygons indicate areas outside of the relevant detection zones. Orange-shaded polygons cover permanent objects to be ignored by detection. These zones can be displayed with or without a fill or hidden according to the user's preferences.

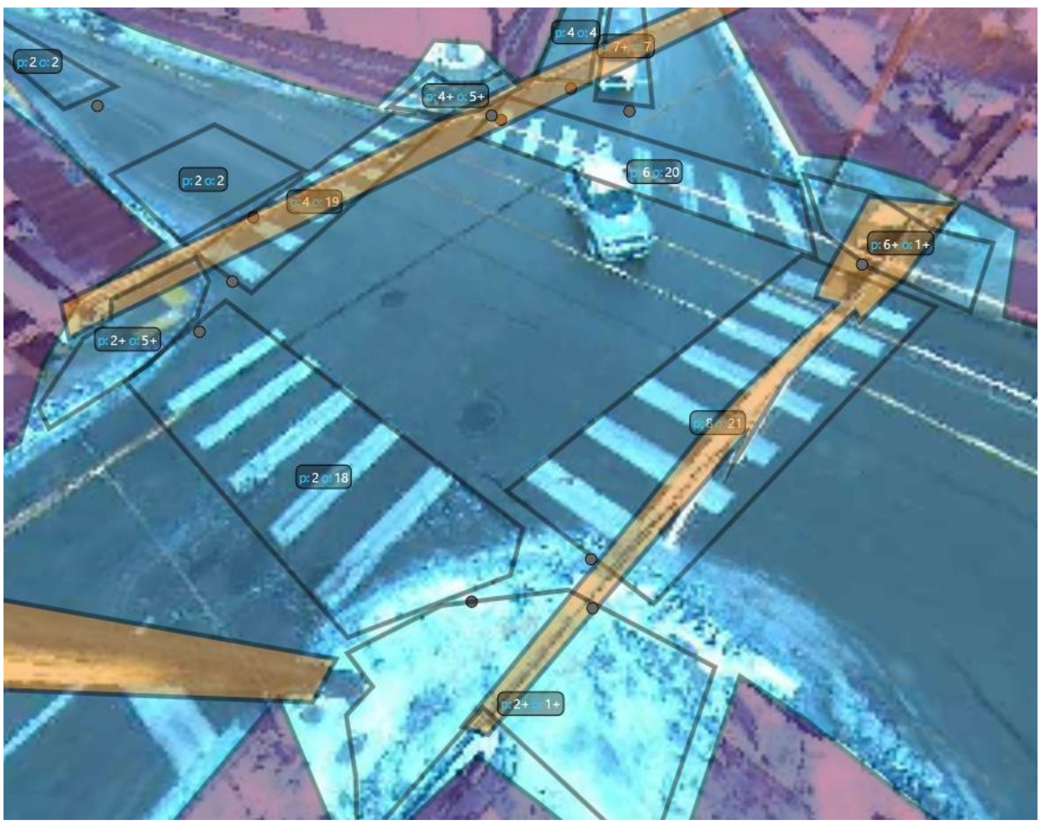


Figure 5 User-Defined Zones Viewed from GRIDSMART Client

The intersection for this research (Penn/40th) is shown in Figure 10 above. Two bell cameras are used, one located at the Southwest corner above the cabinet ("CABINET CORNER CAMERA" or "CABINET") and the other located at the Southeast corner ("SOUTHEAST CAMERA" or "SE"). In the GRIDSMART configuration, pedestrian wait zones were established covering the ADA ramp areas at each corner of the intersection and crosswalk zones were established for each crosswalk. The EB through movement corresponds to Phase 2 in the signal timing plan, so crosswalks are numbered counterclockwise from there.

The detection zones are used by both cameras but labeled individually for each camera. Figures 6 and 7 below show the orientation of the crosswalks and the label notation used for each camera. The phase and linked detector are the same for both (2 and 18, respectively).

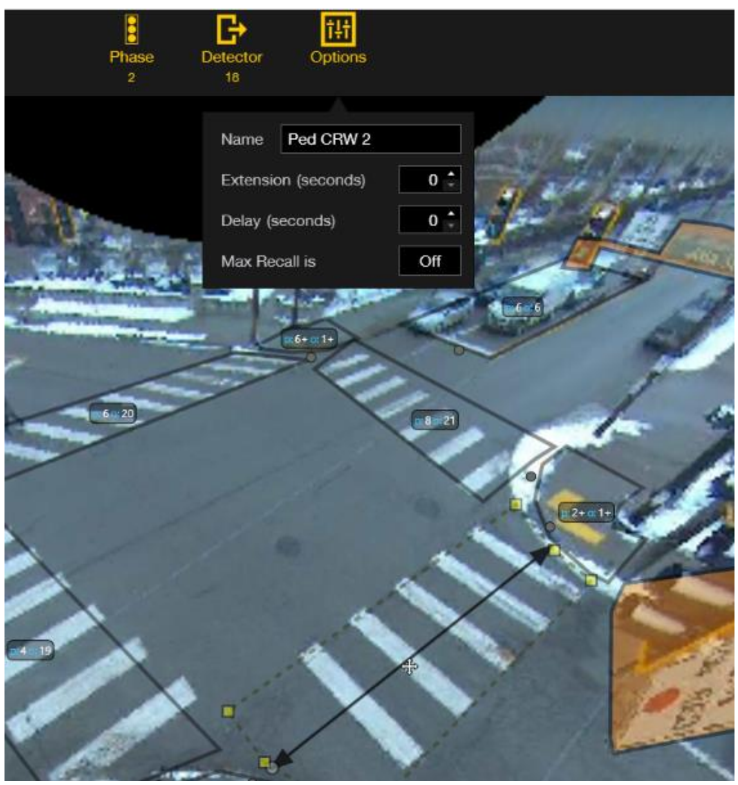


Figure 6 Cabinet Corner Camera Label of Crosswalk (Ped CRW 2)

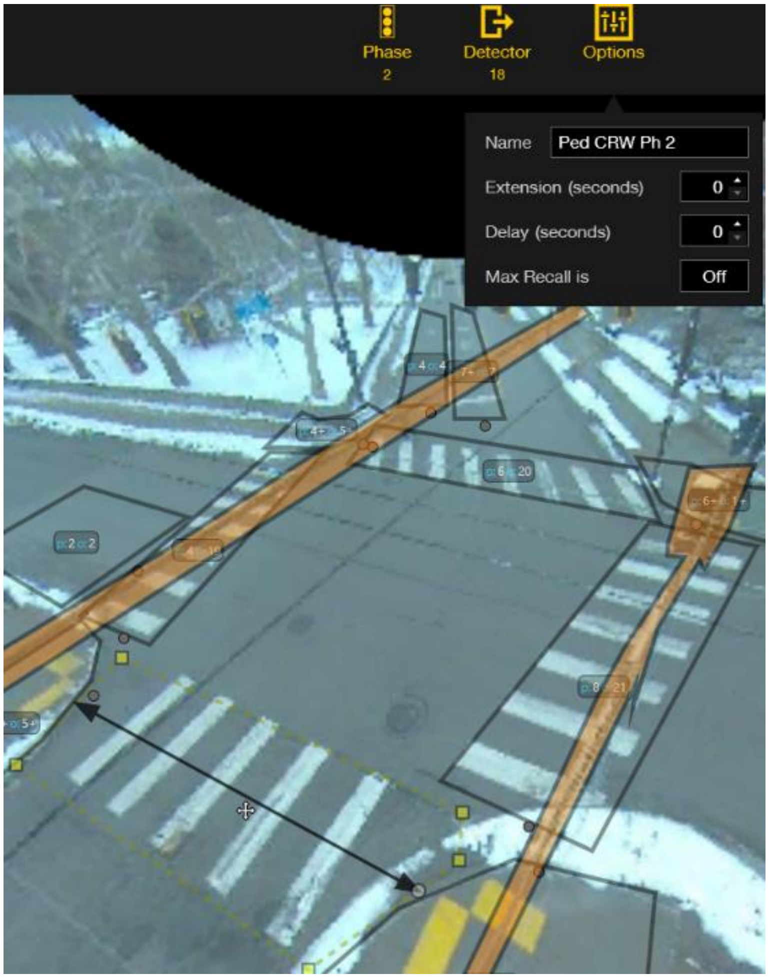


Figure 7 Southeast Camera Label of Same Crosswalk (Ped CRW Ph 2)

Figures 8 and 9 shows the labeling of the Southeast pedestrian waiting zone from each camera viewpoint. The cameras are linked to the same phases and output for pedestrian calls at each zone (2+ and 5+, respectively).

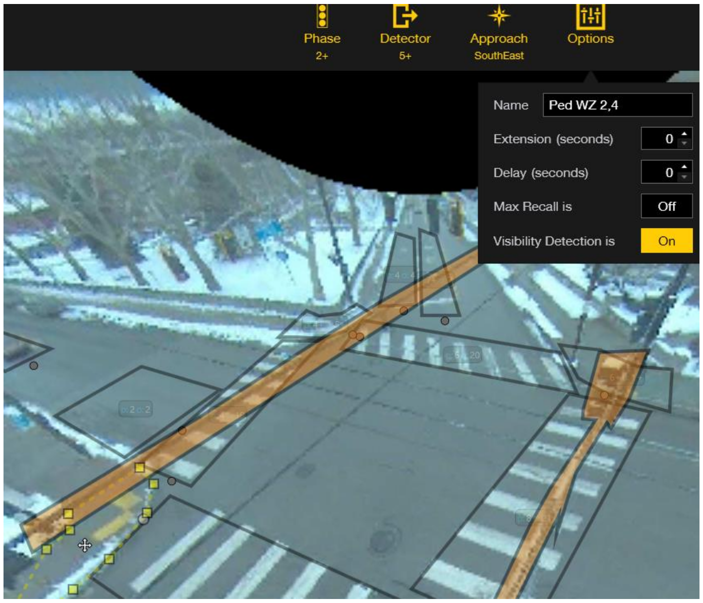


Figure 8 Southeast Camera Label of Southeast Pedestrian Waiting Zone (Ped WZ 2,4)

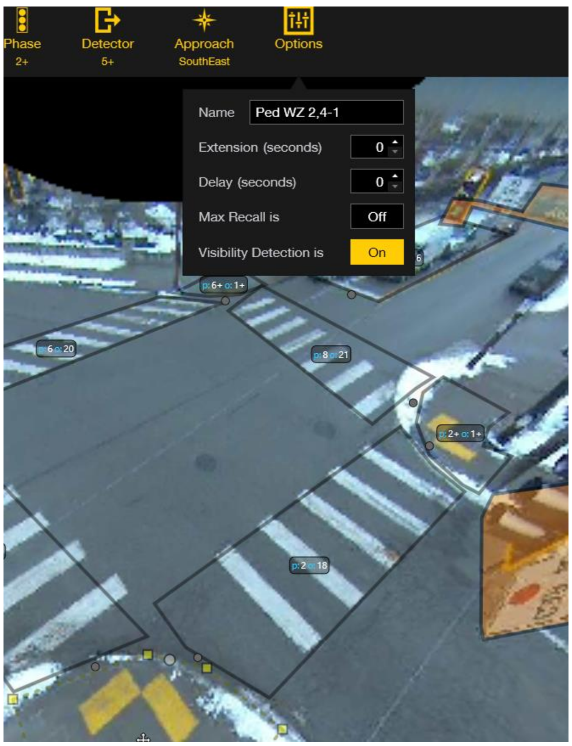


Figure 9 Cabinet Camera Label of Southeast Pedestrian Waiting Zone (Ped WZ 2,4-1)

2.1.2.1 Pedestrian Zone Configuration Issues

There is much confusion among the configuration labeling that GRIDSMART did not clarify. The first is with the directionality of the waiting zones. Figure 14 shows what is called the Southeast approach waiting zone, however it is located at the corner of the EB and NB vehicle approaches. In terms of intersection orientation, this corner is in the bottom-left, Southwest corner. Intuitively, this waiting zone would be called the “Southwest” (orientation) or “Northbound/Eastbound” (pedestrian movements departing).

There is also an error in approach assignment for the pedestrian waiting zone east of the Southeast zone. The SE camera follows the previous approach notation and uses “Southwest,” but the CABINET camera mislabels this approach as “Northwest”. The actual Northwest waiting zone from the CABINET camera viewpoint is assigned correctly, so there are two approaches with the same directional notation. This can be seen in Figures 10 and 11 below. It is unclear if these approach assignments affect data collection or signal operations.

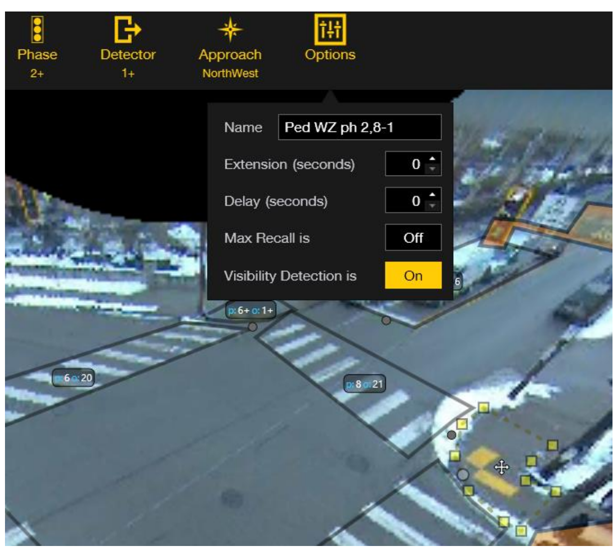


Figure 10 Cabinet Camera SE Wait Zone Approach Error

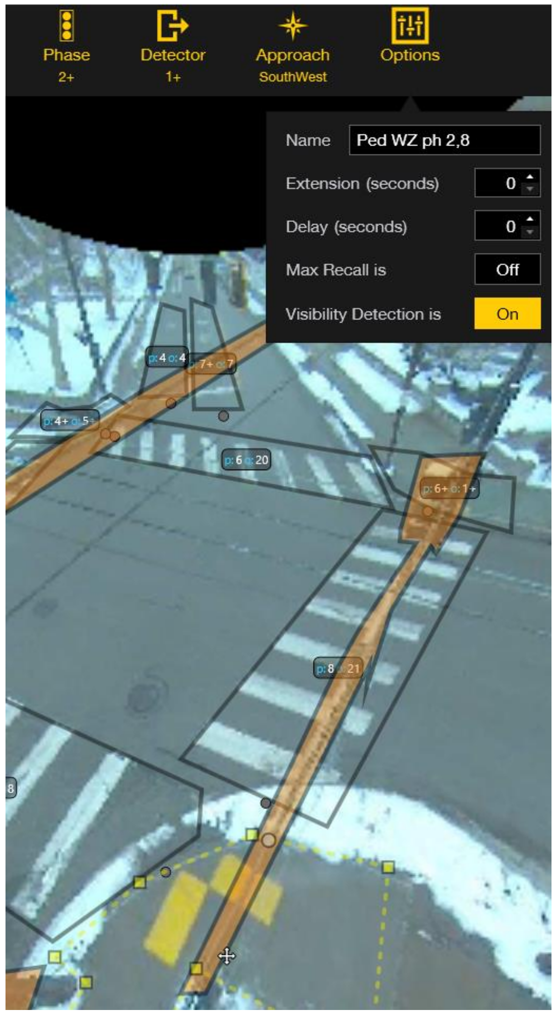


Figure 11 SE Camera SE Wait Zone Correct Approach

Table 1 summarizes the remaining waiting zone labels from the perspective of each camera. It becomes clear there is not a consistent labeling notation for the waiting zones. Three of the four approaches for the CABINET camera are consistent. Two of the four SE camera approaches are consistent. Two of the four approaches are consistent between cameras, with the CABINET camera adding “-1” to notation of the SE camera. The notation, “ph,” was previously used to differentiate the crosswalk notation for each camera (CRW2 = CABINET, CRWph2 = SE). It is unclear if these inconsistencies affect data collection or signal operation.

Table 1 Pedestrian Waiting Zone Notation

Waiting Zone Approach	Cabinet Camera Zone Notation	Southeast Camera Zone Notation
Southeast	Ped WZ 2,4-1	Ped WZ 2,4
Southwest	Ped WZ ph 2,8-1	Ped WZ ph 2,8
Northeast	Ped WZ 4,6-1	Ped WZ 4.6
Northwest	Ped WZ 6,8-1	Ped WZ ph 6,8

There is a separate issue with the base configuration file. Originally, a “40^{th}andPenn.ags” file (“*Config1*”) was provided by GRIDSMART for the subject intersection. An overview of the intersection is in Figure 12 below with the remaining waiting zones outputs in Table 2.

Figure 12 Original Configuration File of Subject Intersection with Southeast Waiting Zone Outputs

The crosswalks are shown with their protected phases following the counterclockwise notation from the EB through movement phase 2. The output number corresponds to the output from the waiting zone it is linked to. The output from the Southeast waiting zone can be seen in Figure 12. For example, the waiting zone can make calls for phases 2 and 4 to allow pedestrians to cross EB during phase 2 using CRW2 or to cross NB during phase 4 using CRW4. The output values link the detection zone to the crosswalk link by pedestrian phase (Ped Phase 13 for CRW2 and Ped Phase 14 for CRW4).

The issue arises when importing data from the external hard drive placed in the cabinet to record video footage for pedestrian analysis. There is a configuration file ("*Config2*") saved to the drive that is completely different from the one described above. An overview of the configuration is in Figure 13 below. The Southeast waiting zone seen in Figure 12 above is shown in Figure 14 using the *Config2* file, with the remaining waiting zone and crosswalk outputs in Table 4 below.

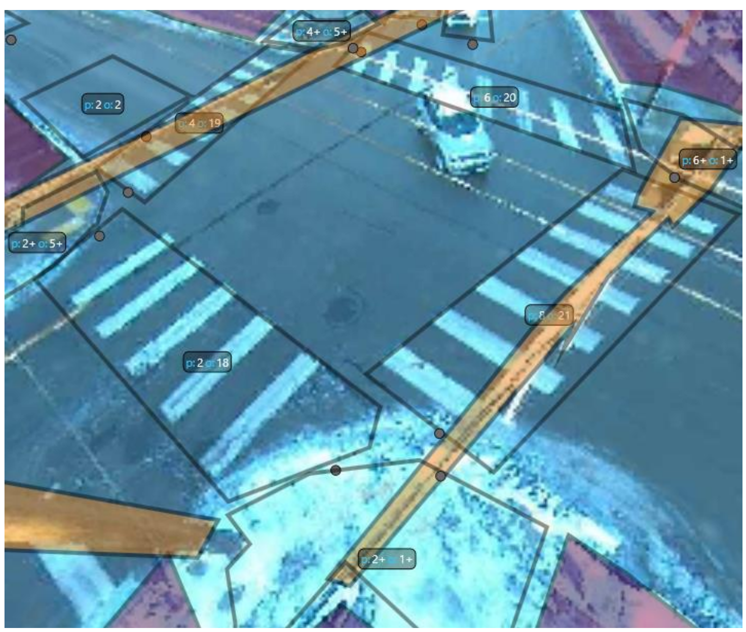


Figure 13 Configuration File Downloaded from Processor ("Config2")

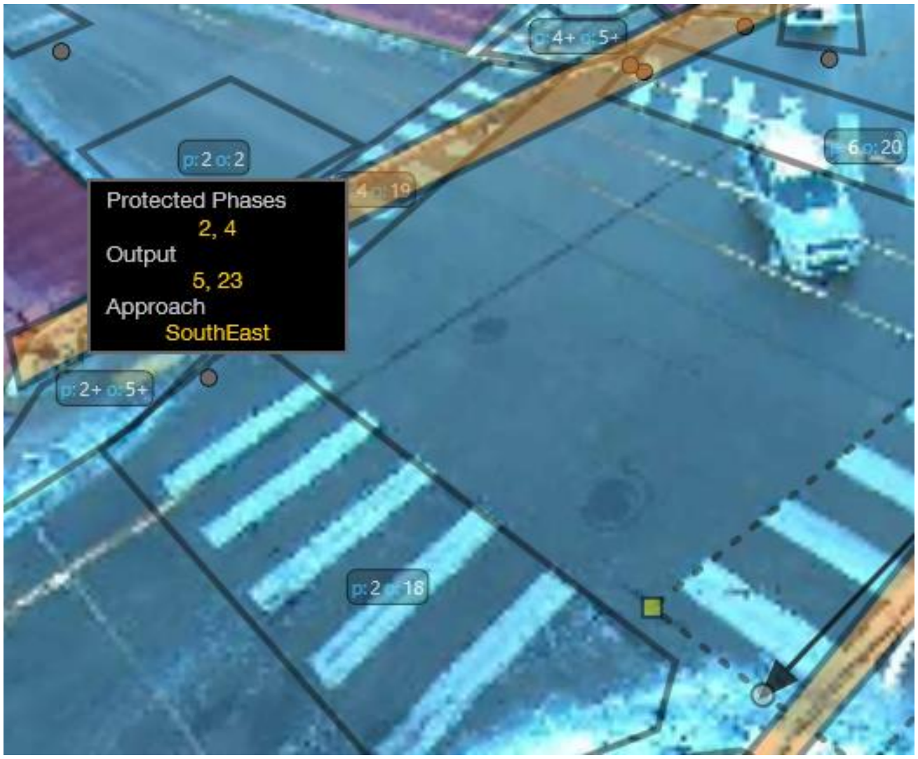


Figure 14 *Config2* with Southeast Waiting Zone Outputs

Immediately it is clear that the outputs from the waiting zones do not match the output values for the crosswalks. The inconsistencies become clearer in Table 2 which shows the phases and outputs for both configuration files. The protected phases of the waiting zones and crosswalks are correct, but the crosswalk outputs do not pair with any of their associated waiting zone outputs. The Southeast and Northeast waiting zones both share an output phase 5, while the Southwest and Northwest zones share output phase 1. The Northeast and Northwest zones share an output phase 24, while the Southeast and Southwest zones share an output phase 23.

Table 2 Phases and Outputs for GRIDSMART Configuration Files

	Configuration File Provided by GRIDSMART (Config1)							
	CRW2	**SE Zone**	**CRW4**	**NE Zone**	**CRW6**	**NW Zone**	**CRW8**	**SW Zone**
Protected Phases	2	2, 4	4	4, 6	6	6, 8	8	2, 8
Output	13	13, 14	14	14, 15	15	15, 16	16	13, 16
	Configuration File Downloaded from Processor (Config2)							
	CRW2	**SE Zone**	**CRW4**	**NE Zone**	**CRW6**	**NW Zone**	**CRW8**	**SW Zone**
Protected Phases	2	2, 4	4	4, 6	6	6, 8	8	2, 8
Output	18	5, 23	19	5, 24	20	1, 24	21	1, 23

The labeling of *Config1* follows logically. It is less clear why *Config2* is labeled the way it is. The shared waiting zone outputs makes sense, but the crosswalks do not share that output. A pedestrian using CRW2 requires an output (pedestrian call) on phase 23, but the output value of CRW2 is 18. The same is seen for CRW4 (5, 19), CRW6 (24, 20) and CRW8 (1, 21). It is unclear if these inconsistencies affect data collection or signal operations. These output phases are explored further as part of the manual counting analysis.

2.1.2.2 Vehicle Zone Configuration Issues

In terms of vehicle zones, the intersection configuration has the Southbound left turn vehicle zone (Phase 7) labeled incorrectly as a Northbound movement. This results in both minor street left turn movements labeled as Northbound and produces incorrect turning movement counts. The Northbound left turn movement (Phase 3) is significantly higher than the actual vehicle count since it includes the left turns from the higher volume Southbound left turn movement. Fortunately, GRIDSMART turning movement counts can be exported as .CSV files and then filtered by vehicle zone label. The specific zone "NB Leftturn Ph 7" can then be counted to provide the Southbound left turn count and subtracted from the total Northbound left turn movements to provide the actual Northbound left turn count for model approach volume inputs. Figure 15 below shows the incorrect vehicle zone label.

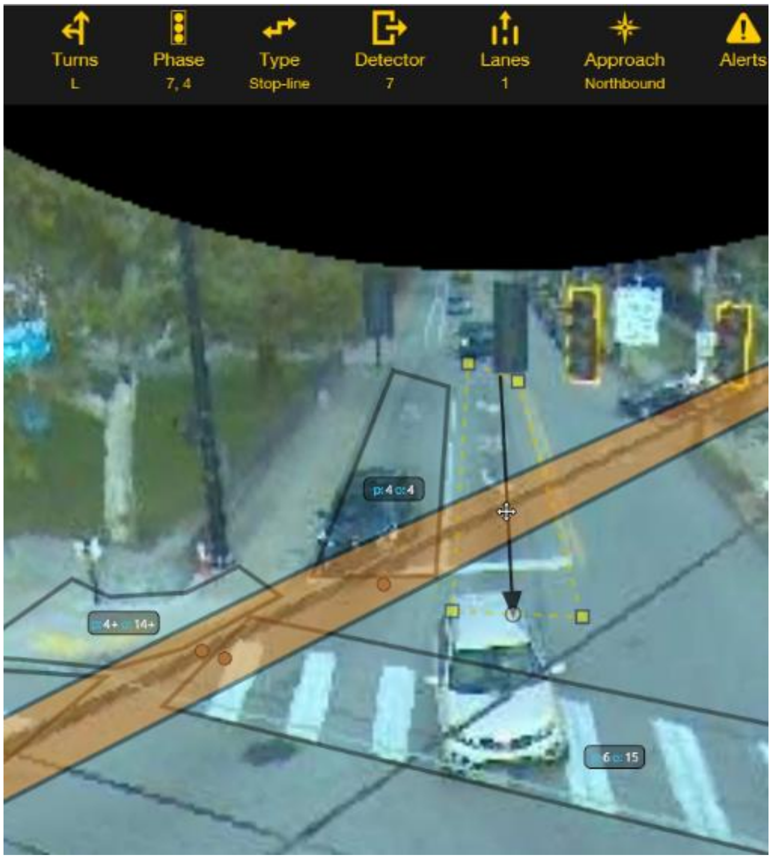
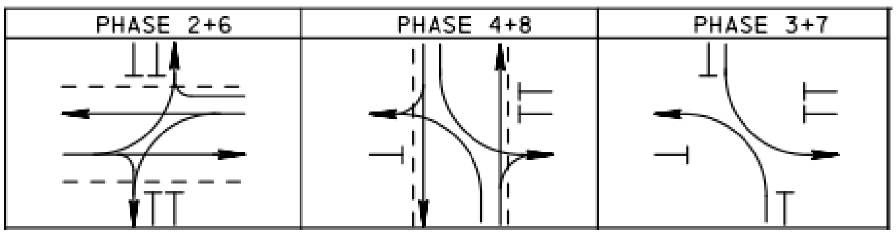


Figure 15 Incorrect Vehicle Zone Approach Label for SB Left Turn

2.1.3 MAXTIME Signal Controller

The signal controller in operation is a fully actuated ATC controller manufactured by Q-Free. It uses Intelight MAXTIME software (16). Figures 16 and 17 below show the phase sequence and signal timing plan for the intersection that is in operation weekdays after 14:00 when this research was conducted. The signal timing plan was taking from the MAXTIME database for the controller. Access to the MAXTIME database was provided by DOMI. Phases 2 and 6 correspond to the Penn Avenue major street movements, while Phases 4 and 8 correspond to the 40th Street minor street movements. Phases 3 and 7 have a permissive flashing yellow during the main phase. The SB left turn (Phase 7) has equal demand flow as the SB through and right lane group, so there is a lagging left turn phase for any vehicles that were not served by the main phase.



Source: DOMI

Figure 16 Phase Diagram at Penn/40th

Phase Plan 3 — Show All Phases — Show All Parameters

Phase	2	3	4	6	7	8
Description						
☑ Enabled	☑	☑	☑	☑	☑	☑
Walk	11	0	9	11	0	9
Ped Clear	18	0	14	18	0	14
Min Green	15	7	12	15	7	12
Passage	3.0	2.0	3.0	3.0	2.0	3.0
Max 1	32	7	26	32	7	26
Yellow Change	4.0	3.5	3.5	4.0	3.5	3.5
Red Clear	4.0	2.5	2.5	4.0	2.5	2.5
Red Revert	0.0	0.0	0.0	0.0	0.0	0.0
Advance Walk	3	0	3	3	0	3

Figure 17 PM Signal Timing Plan at Penn/40th

The MAXTIME suite provides real-time access to the controller operations. The status of the controller, current timing plan settings, and performance measures can be accessed. Figure 18 below shows the home screen of the program.

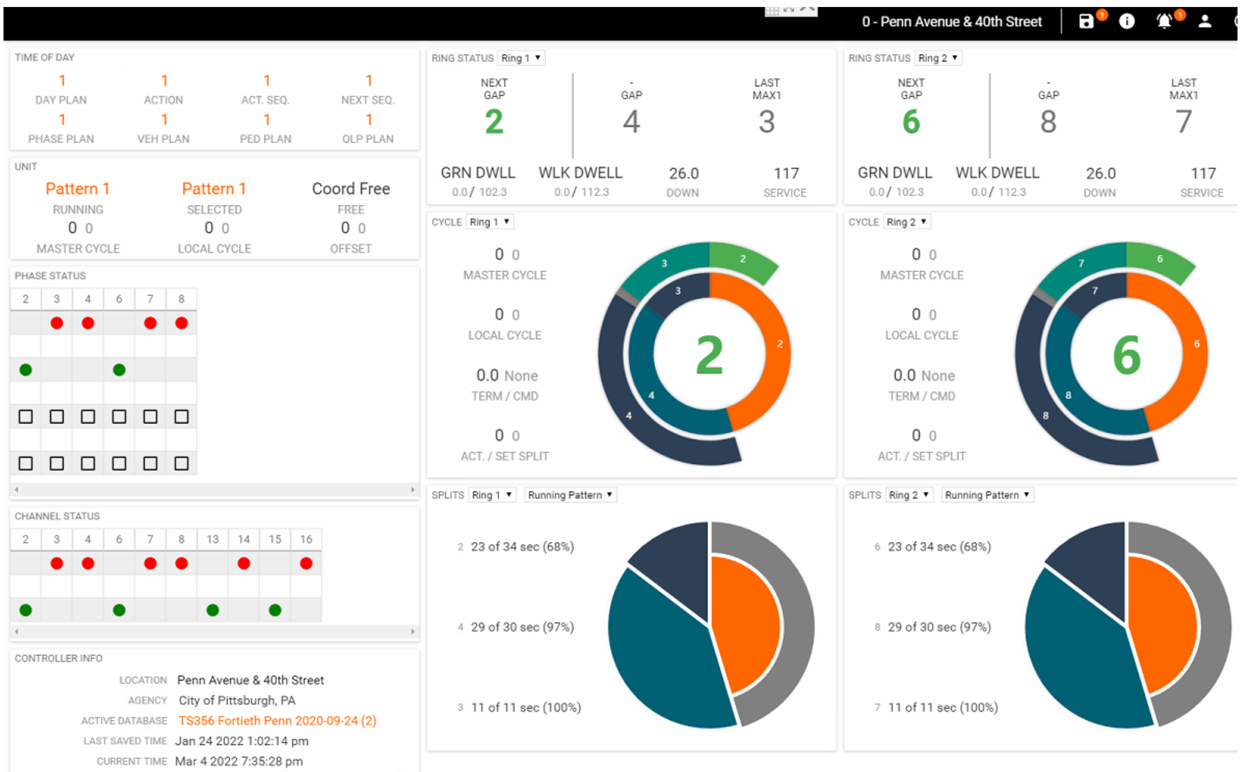


Figure 18 MAXTIME Suite Home Screen

2.2 Literature Review

2.2.1 Signal Timing

Uncoordinated intersections can be programmed to accommodate the specific conditions of an intersection by adjusting basic signal timing parameters or recall modes. The appropriate strategy depends on the vehicle and pedestrian demand volumes, as well as the level of actuation in place.

2.2.1.1 Actuated Signal Timing Parameters

The basic parameters of a signal timing plan are the green interval, yellow (permissive) interval, and red clearance interval required for each vehicle phase. This is based on the critical movement for each approach that makes up the intersection, or the highest volume demands entering the intersection that must be served. Green time must be provided to serve these volumes to prevent queues forming and increasing delay in the network. Actuated operations introduce additional parameters such as minimum green, maximum green, passage time, pedestrian intervals, and various recall settings that add complexity to the timing plan (5).

2.2.1.2 Yellow Interval

The yellow interval is determined by the approach speeds entering the intersection to provide sufficient time to clear the intersection before opposing vehicle phases begin. The Manual on Uniform Traffic Control Devices (MUTCD) recommends a minimum yellow interval of 3 seconds for any vehicle phase (4). *Traffic Engineering 5th Edition* (1) provides the equation shown below to calculate the yellow interval.

$$Y = t + [1.47v / 2(a + 32.2g)] \tag{2-1}$$

where,

Y = yellow interval (s)

t = perception reaction time (s)

v = approach speed (mph)

a = deceleration rate (ft/s/s)

g = approach grade

Perception reaction time (t) is generally assumed to be 1.0 second and deceleration rate (a) is assumed to be 10 ft/s/s. The grade is input as a decimal for this equation. The 85th percentile speed or the posted speed limit can be used for the approach speed (v) to determine this interval (5). Using the 85th percentile speed will provide a longer interval for safety precautions.

2.2.1.3 Red Clearance Interval

The red clearance interval provides an extra safety measure for vehicles or pedestrians that may still be in the intersection after the yellow interval. This provides additional time before the opposing vehicle phase enters the intersection, reducing potential conflicts. The interval is calculated as (1),

$$ar = (w + L) / 1.47v \tag{2-2}$$

where,

ar = red clearance interval or all-red interval (s)

w = width of street to be crossed, curb to curb (ft)

L = length of standard vehicle (ft)

v = approach speed (mph)

The clearance interval is normally calculated based on the 15th percentile speed, or the slowest moving vehicles that could be in conflict (1). The width of the intersection is the maximum distance needed to travel to exit the conflict area, and the length of a standard vehicle is generally 20 feet. The clearance interval reduces the available green time to serve vehicles, but it is an important precautionary measure.

2.2.1.4 Green Interval

The green interval is a function of critical vehicle volumes and is split between phases according to this demand. Subtracting the yellow and clearance intervals for all phase transitions (i.e., lost time) from the overall cycle time leaves the available, or effective, green time for a signal. Equation 2-3 below shows the calculation of effective green time for an individual phase (1).

$$G_i = (C - L) * (V_{ci}/V_c) \tag{2-3}$$

where,

G_i = effective green time (s)

C = cycle length (s)

L = total lost time per cycle (s)

V_{ci} = critical lane volume for Phase *i* (vph)

V_c = sum of critical lane volumes (vph)

For fully actuated signals, these green times can be considered the maximum green times for an individual phase, or the green time needed to serve the highest demand periods. The maximum green begins timing upon actuation of an opposing vehicle phase.

Minimum green times are the least amount of green provided to an individual phase every cycle. This can be determined based on the detection in place in order to clear stored vehicle queues at the beginning of a phase, the time needed for a pedestrian to safely cross, or for average driver expectations. Equations 2-4 and 2-5 show the calculations for minimum green according to the detection in place (1). Equation 2-4 is used when point detection is in place, while Equation 2-5 is used when presence detection is in place. Table 3 below shows minimum green times for driver expectations from the Traffic Signal Timing Manual (5).

$$G_{min} = \ell_1 + 2.0 * \mathit{Int}[d/25] \tag{2-4}$$

$$G_{min} = \ell_1 + 2.0n \tag{2-5}$$

where,

G_{min} = minimum green time (s)

ℓ_1 = start-up lost time (s)

d = distance between detector and STOP line (ft)

n = number of vehicles stored in the detection area (veh)

The value of 25 in equation 2-3 represents the assumed head-to-head spacing between vehicles in the queue and the integer function rounds d/25 to the next highest integer value (1). Rounding up allows for a vehicle partially over the detector to be served by the minimum green. The assumed headway between vehicles is represented by the value 2 in each equation.

Table 3 Minimum Green Time for Driver Expectation

Phase Type	Facility Type	Minimum Green (Seconds)
Through	Major Arterial (> 40 mph)	10 to 15
	Major Arterial (≤ 40 mph)	7 to 15
	Minor Arterial	4 to 10
	Collector, Local, or Driveway	2 to 10
Left Turn	Any	2 to 5

Source: Signal Timing Manual (2015)

The Passage Time serves multiple purposes for an actuated signal. It represents the maximum time between vehicle actuations before the phase will end after minimum green has been reached. It is also the amount of time added to the vehicle phase upon a vehicle actuation until the maximum green has been reached. Lastly, it must be long enough to allow a vehicle approaching at 15th percentile speed to travel from the detector to the STOP line (1). Equations 2-6 and 2-7 show passage time calculations for presence detection.

$$PT_{min} = d / 1.47S_{15} \qquad (2\text{-}6)$$

$$PT = MAH - [(L_v + L_d) / 1.47S_a] \qquad (2\text{-}7)$$

where,

PT_{min} = minimum allowable passage time (s)

d = distance between detector and STOP line (ft)

S_{15} = 15th percentile speed (mph)

PT = passage time (s)

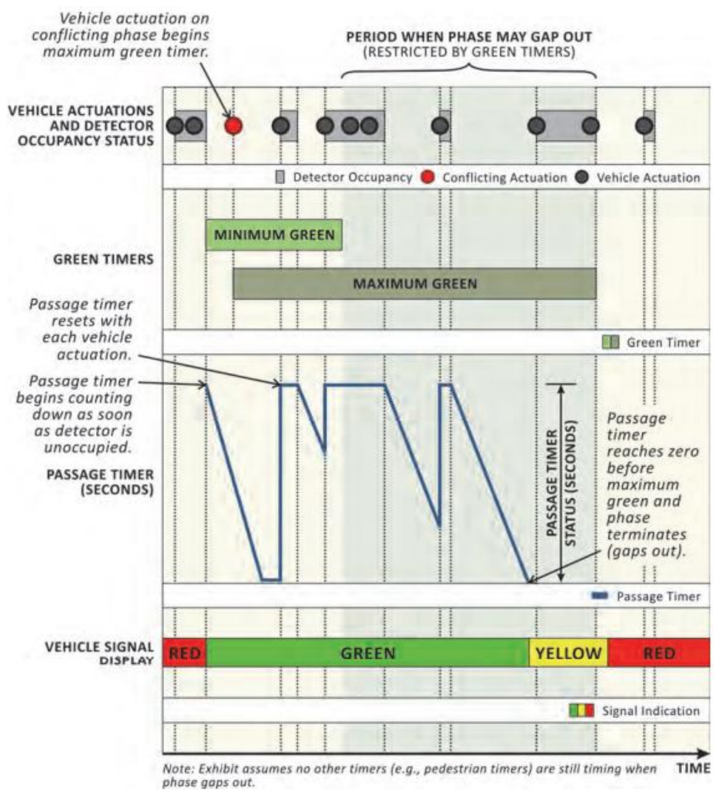
MAH = maximum allowable headway (s)

L_v = average length of vehicle (ft)

L_d = length of detection zone (ft)

S_a = average approach speed (mph)

The maximum allowable headway is the maximum gap between detections that will retain the green in a single lane (1). Generally, MAH is between 2 and 4 seconds, with larger values leading to higher delays (1). For point detection, the length of the vehicle is irrelevant, and the passage time is equal to the MAH (1). The passage time should not be long enough to extend the vehicle phase in light traffic conditions and reduce the effectiveness of actuated operations. The process of actuated operation is shown in Figure 19 below from the Signal Timing Manual (5).



Source: Signal Timing Manual (2015)

Figure 19 Actuated Signal Operations

2.2.1.5 Pedestrian Interval

Pedestrian intervals are a function of the walking speed of average pedestrians and the distance of the crossing. Equation 2-8 shows how the required minimum green time is calculated for each pedestrian phase. Table 4 shows the minimum walk intervals recommended by the Traffic Signal Timing Manual (5). The pedestrian clearance interval is calculated by dividing the length of the crosswalk by the design speed of pedestrians, generally assumed to be 3.5 ft/s. This is the minimum time that a pedestrian leaving the crosswalk after the Walk interval can safely cross before the phase ends. The walking speed can be lowered if the crossing is located in an area such as a school or healthcare facility, where slower pedestrians can be expected, and extra safety precautions are desired (MUTCD). In most cases, the yellow and red intervals are allowed to be used by pedestrians, decreasing the time that the pedestrian interval shares with the vehicle phase (5). In these cases, the FDW interval is the clearance interval minus the yellow and red intervals and indicates to pedestrians that the safe passage time is ending.

$$G_p = PW_{min} + PC \tag{2-8}$$

where,

G_p = minimum green time required for pedestrians (s)

PW_{min} = minimum pedestrian WALK interval (s)

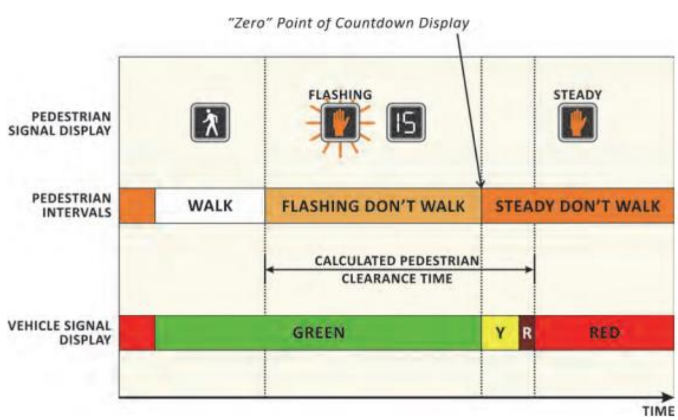
PC = pedestrian clearance interval (s)

Table 4 Minimum Pedestrian Walk Intervals

Conditions	Walk Interval (Seconds)
High-pedestrian-volume area (e.g., school, CBD, or sports and event venue)	10 to 15
Typical pedestrian volume and longer cycle length	7 to 10
Typical pedestrian volume and shorter cycle length	7
Negligible pedestrian volume and otherwise long cycle length	4

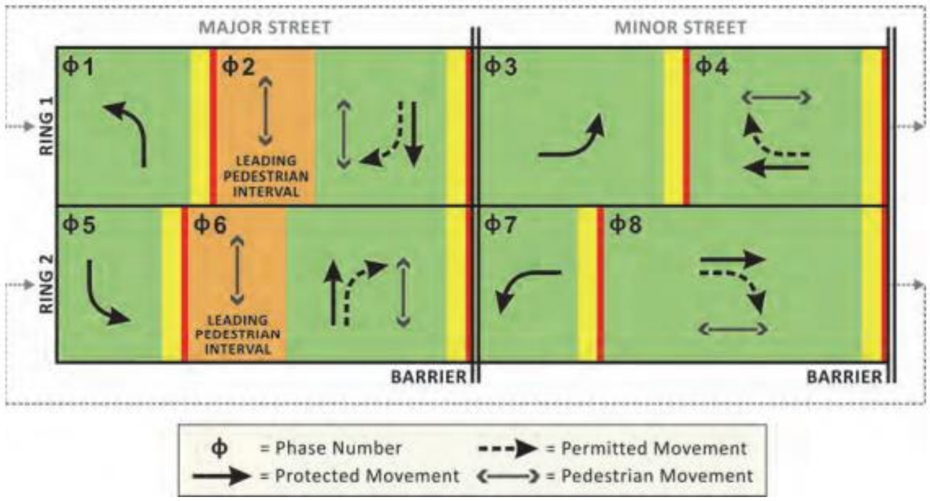
Source: Signal Timing Manual (2015)

In actuated operations, the minimum pedestrian time can be greater than the minimum green time. The pedestrian clearance interval, or FDW interval, is the limiting factor. Where this is the case, manual pushbuttons are provided to communicate to the controller that the minimum green time must at least serve the pedestrian interval during the accompanying vehicle phase. Pedestrians can be given a head-start before the vehicle phase begins to reduce the impact of extending minimum green times and provide additional safety. Figure 20 below shows a pedestrian interval in relation to the vehicle phase and Figure 21 shows a leading pedestrian interval from the Traffic Signal Timing Manual (5).



Source: Signal Timing Manual (2015)

Figure 20 Pedestrian Interval



Source: Signal Timing Manual (2015)

Figure 21 Leading Pedestrian Interval

2.2.1.6 Recall Settings

Recall modes can be set for individual phases in actuated signals to control signal operations in the absence of vehicle actuations. The appropriate mode depends on vehicle and pedestrian demand, and it can be changed throughout the day to accommodate common cyclical travel demands and time-of-day signal plans. According to *Traffic Engineering 5th Edition* (1):

- Minimum Recall places a call on the designated phase so that at least the minimum green time is provided during every cycle. This is commonly used for major street through movements.
- Maximum Recall places a continuous call on the designated phase that forces the phase to extend to its maximum green time regardless of demand. If applied to all phases, this allows for an actuated signal to temporarily operate as a fixed-time signal.

- Pedestrian Recall places a pedestrian call for every phase, forcing the vehicle phase to at least serve the minimum pedestrian green time. It is most common during high pedestrian demand periods and serves pedestrians as quickly as possible.
- Soft Recall places a call on the designated phase when there are no opposing calls. It is most common for major street through movements to ensure that the signal rests on the major street during light demand periods.

2.2.2 Pedestrian Delay

Pedestrian delay is a concern to transportation planners now that pedestrians are being given more equal attention as part of the traffic network. There is a limit to the amount of delay that pedestrians will tolerate, so they must be part of the signal operation decisions to increase safety and pedestrian level of service. van Houten et al. (2) have shown that pedestrian compliance at midblock crossings decreased significantly as cycle time increased. The cycle time for a midblock crossing is essentially the pedestrian wait time so as cycle time increases, pedestrian delay increases. For 30 and 60 second cycles, compliance was 98% and 85% respectively. For 120 second cycles, compliance dropped to 63.5%. This follows the research modeling pedestrian crossing behavior by Marisamynathan and Vedagiri where 65% of pedestrians did not comply where long red times existed for pedestrian signals (7). This study, as well as Cœugnet, et al., showed that time-pressure situations resulted in greater non-compliance (7,8). Cœugnet, et al. found that 65% of the risky crossings were a result of time-pressure via the surveys conducted after the study (8). Either a pedestrian reaches their internal limit of wait time, or they arrive under pressure and already feel like they can’t wait a certain amount of time, but both result in an increase in risky crossings. As shown in Khoturi (9), reducing pedestrian delay will have a positive effect on safety and avoid potential vehicle collisions.

2.2.3 Pedestrian Treatments

For fully actuated signals, the pedestrian interval significantly impacts the operation and overall efficiency of the signal. Using pedestrian recall to provide pedestrian phases for every vehicle phase, or even just on the major street phase, may result in wasted green time where pedestrian demand is low. Actuated pedestrian intervals attempt to reduce this effect, but pedestrian behavior impacts the effectiveness of these operations. Manual pushbuttons have proven to be ineffective (6) because every pedestrian will not push the button, whether they choose not to or because it is not easily accessible or visible. Further, assuming that pedestrians will wait for the called pedestrian phase is false for many reasons. Unless the push button always provides the pedestrian phase in the same cycle as the next possible parallel vehicle phase, pedestrian delay will occur, and compliance drops significantly. In the study by Sulmicki (6), 78% of the 2058 pedestrians surveyed did not push the button. In addition, 35% of pedestrians arrived just before or during the parallel vehicle green phase, which then requires a full cycle of delay because the actuation did not occur in time. Unless the actuation functions like a vehicle actuation and shortens the current phase to get to the pedestrian phase quicker, pedestrian service cannot be improved.

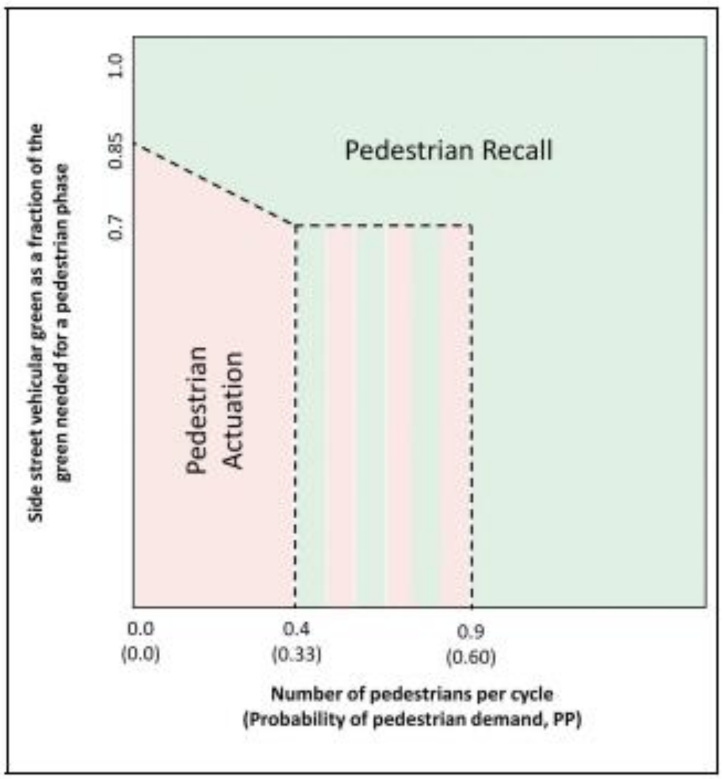
Automatic detection is seen as a solution to this problem by removing the push button entirely and always providing an appropriate call for pedestrians. Pre-arrival detection of pedestrians can provide even more time for the call to be served (6) without incurring a full cycle of delay for late detection. The benefits of automatic pedestrian detection are generally felt in low pedestrian areas, but it depends on the accuracy of detection. Weather and night conditions can inhibit visibility for cameras and result in missed calls or false calls. The same can occur if vehicles are identified as pedestrians through some system error and a call is made. Pre-arrival detections is an ideal feature, but it is very difficult to identify who is planning on crossing and who is simply passing by in urban areas, regardless of pedestrian activity.

2.2.3.1 Pedestrian Recall vs. Actuated Pedestrian Phases

Under fully actuated conditions it may not be desirable to provide a pedestrian phase every time if it will result in wasted green time where vehicle demand is not present. Pushbutton actuation for pedestrians is used in these cases to provide pedestrian phases only when needed, and automatic detection seeks to replace them. The drawbacks to push buttons have already been discussed, so exploring delays under these two control strategies is important.

Cesme et al. (3) studied the effects of pedestrian recall vs actuation along a coordinated network. Again, if pedestrian phases are provided when no demand is present, the signal is not operating at peak efficiency and capacity is reduced. Pedestrian recall is often placed only on the major street since the vehicle demand is generally high enough that the pedestrian phase will end before vehicle demand stops or the maximum green for that phase is reached. Pedestrian recall is usually avoided on minor streets because it will cause delays if demand is not sufficient (1). The study focused on this trade-off. By relating the share of pedestrians per cycle to the proportion of minor street green time to minimum pedestrian green time, a guideline was developed for when pedestrian recall should be implemented (3). The guideline developed from this study is shown in Figure 22 below. There is a defined area where manual pedestrian actuation is best for low pedestrian activity and pedestrian recall is best for high pedestrian activity. Khoturi (9) found that fully actuated operation reduces pedestrian delay for low pedestrian volumes and pedestrian recall lowers vehicle delays for high pedestrian volumes. There is a grey area between 0.4 and 0.9

pedestrians/cycle where either option can be used without significant vehicle delay. It should be noted that even for low pedestrian activity, there are situations where the minor street green time is long enough that pedestrian recall can be used without adding to vehicle delays. This study was conducted on a coordinated network where minor streets are usually low volume and therefore have shorter green times. For intersections like the subject intersection of this thesis, the minor street has vehicle volumes comparable to the major street and a lagging left turn phase, so the minor street green time is longer and can accommodate pedestrian green times.



Source: Cesme et al. (3)

Figure 22 Ped Recall vs. Actuation

Studies have also found that although pedestrian recall may result in added vehicle delay, it moderately reduced pedestrian delay and improved compliance compared to actuation (3,9). Under pedestrian recall, pedestrians will not face the situation of waiting a full cycle to cross due to a late call, as the next possible phase will always give a pedestrian phase. Khoturi (9) defines a "late call" as an actuation made in the yellow or all-red vehicle phase. As long as the vehicle phase green is longer than the minimum pedestrian interval, no added delays will incur. Safety can also be improved with a leading walk interval that starts the pedestrian phase early and reduces the share of pedestrian green time in the actuated vehicle phase. This will increase vehicle delays, however (9).

3.0 Methodology

This research study required data collection, both manually and from automatic collection sources, data analysis, a calibrated simulation model of the intersection network, and simulation under multiple pedestrian volume and control scenarios to assess vehicle and pedestrian delay. The methodology was as follows:

- Collect data from processor (vehicle/ped counts plus video)
- Determine peak period for vehicles and pedestrians
- Manually count traffic at upstream intersections during peak hour
- Manually count pedestrians via video footage
- Validate GRIDSMART counts
- Identify missed calls/false calls/unused phases
- Build simulation model of network with inputs from data collection
- Run simulation under 3 pedestrian volumes and 4 signal operations
- Identify impact of GRIDSMRT errors and identify the best operating conditions in terms of pedestrian and vehicle delay

3.1 GRIDSMART Data Collection

GRIDSMART detection provides reports with turning movement and pedestrian counts for the intersection sorted by time interval (5-, 15-, 30-, 60-min) over a specified time range. The pedestrian reports provide counts for three exit points at 8 individual outputs. The outputs are

CRW2, CRWph2, CRW4, CRWph4, CRW6, CRWph6, CRW8, CRWph8 and represent the crosswalk zones. The outputs with "-ph" in their notation correspond to the Southeast camera crosswalk notation, while the others correspond to the Corner Cabinet camera.

Before analysis could begin, data needed to be collected from the signal controller and GRIDSMART processor at 40th Street and Penn Avenue. DOMI provided a hard drive with vehicle and pedestrian data from August-November 2021. Additional counting data and the video footage used for this research were collected using a separate drive starting in December. The first attempt resulted in a corrupted drive that did not collect any data. It was replaced with another drive that worked properly and collected vehicle data and video footage for the first week of January (1/3-1/8). It was after collecting this data that the GRIDSMART Cloud became available, and vehicle count data from August to January could be downloaded remotely.

To find meaningful results from the model, it was determined that the available vehicle and pedestrian data from August or September would be more valuable than December. The weather reduces pedestrian activity and data was collected around the holidays.

3.1.1 Peak Hour Conditions

Using GRIDSMART vehicle counts, the peak hour for all available weekdays in August and September was analyzed to determine a representative peak hour to use. In accordance with regular practices and DOMI recommendations, the analysis focused on weekdays Tuesday-Thursday. The data for the first three weeks of January was added to verify assumptions. The full data can be found in Appendix B. The ADT for January was lower as expected, about 2000 veh/day, however the peak hour and peak 15-minute volumes were not significantly less. The peak hour volume day from the available data was 08/03/21 at 1426 veh/h from 16:45-17:45. The peak hour volume on Thursday, 01/06/22 was 1305 veh/h. Video footage was collected for 01/06/22, so this day became the focus of research. Pedestrian volumes were 50-200% greater during the summer, so these values were planned to be used for modeling inputs to better represent peak intersection conditions. For all days analyzed, the peak hour was in the late afternoon/early evening and the vast majority were between 15:30 and 17:30. The peak hour for 01/06/22 was 15:30-16:30.

The turning movement counts for 08/03/21 and 01/06/22 were compared to determine vehicle inputs for the model. The volumes in the EB/WB direction were nearly identical. There was an increase in vehicle volumes in the NB/SB direction, mainly for the left turn movements. Left turn movements have a significant impact on traffic signal operations, especially for the subject intersection, so the model inputs were updated using the 08/03/21 data. The TMC diagrams can be seen in Figures 23 and 24 below with each movement turning ratio calculated as well.

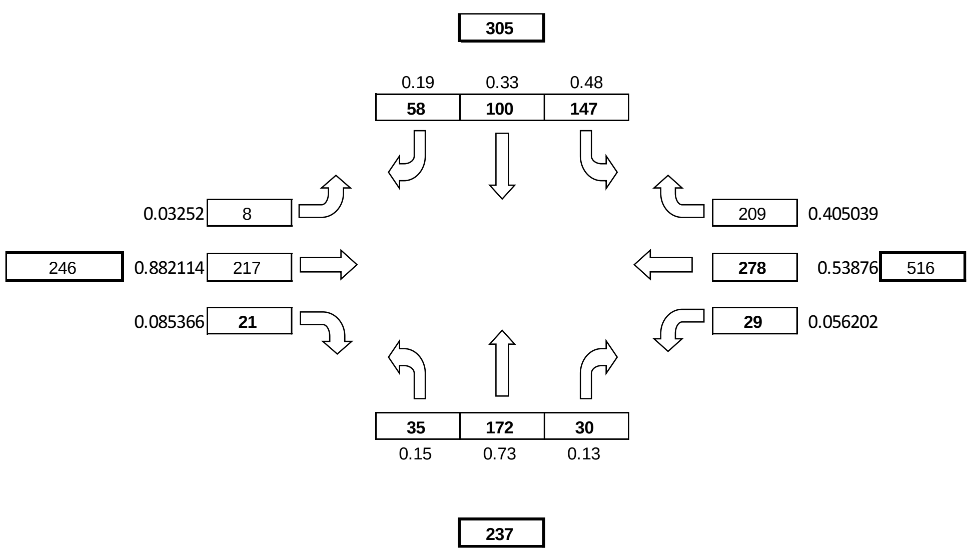


Figure 23 TMC Including Turn Ratios 01/06/22

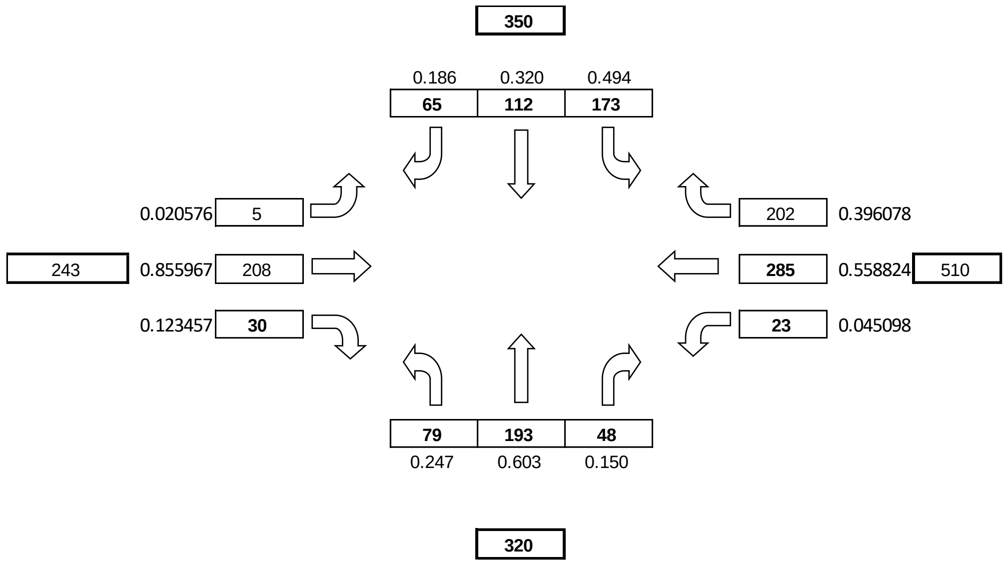


Figure 24 TMC Including Turn Ratios 08/03/21

3.2 Field Data Collection

3.2.1 Manual Traffic Counts

Vehicle counts from DOMI or other partner organizations did not exist for the area, and therefore manual counting of the relevant upstream intersections was required to determine vehicle inputs and turning ratios in the VISSIM model. Streetlight data was not used due to the variability in accuracy.

The relevant intersections included in the VISSIM model include the south intersection at Liberty Avenue and 40th Street, and the three coordinated intersections east on Penn Avenue at Main Street, 44th Street, and 45th Street. The closest intersections to the west and north were considered far enough way that the approach vehicles can be considered as random arrivals. The GRIDSMART vehicle counts were used for these approaches.

Manual counting was conducted twice to verify accuracy for the upstream intersection input volumes. The first count was conducted before the peak hour analysis on 1/19/22 between 16:53 and 18:18, assuming the peak hour would occur in the middle of the PM rush hour period. After the peak hour analysis and noting the peak hour of 1/6/22, a second count was conducted on 1/27/22 during 15:30 and 16:51PM. The manual 15-minute TMC diagrams are in Appendix C.

Manual counts and turning ratios were very similar with slight volume increases for the EB/WB movements on Penn Avenue. The upstream intersections were input with the field data and turning ratios from 1/27/22 with one exception. The NB approach volumes to the subject intersection from GRIDSMART were significantly higher than the manual counting of vehicles at the upstream intersection 40th/Liberty. The majority of vehicles move EB/WB on Liberty Avenue and do not interact with the subject intersection. The input volumes at this intersection were increased to provide appropriate approach volumes at the subject intersection based on the turning ratios from manual counting.

3.2.2 Manual Pedestrian Counting

Pedestrian counts from GRIDSMART needed to be validated to provide accurate pedestrian inputs before running simulations. Using available video footage from 01/06/22, manual pedestrian counts were conducted from 15:00-18:00 from the view of the CABINET camera. The time of crossing, number of pedestrians, crosswalk used, and direction of crossing were recorded for each pedestrian. Also, it was noted if a manual call was made, whether the waiting zone was triggered in GRIDSMART (automatic call), and what pedestrian phase was used by each pedestrian. An example of the process is shown in Figures 25-29 below during the time interval 15:05-15:10.

Figure 25 Pedestrian Arriving at NE Waiting Zone – Manual and Automatic Actuation (*Config2*)

Two more pedestrians crossed during this interval, but they did not stop. No actuations occurred. Figures 26-29 show their arrivals and the lack of pedestrian phase without actuation. This occurred frequently during the analysis period, with many pedestrians arriving on Walk or crossing without complying with the pedestrian signal.

Figure 26 Pedestrian Arrival at NW Waiting Zone – No Actuation

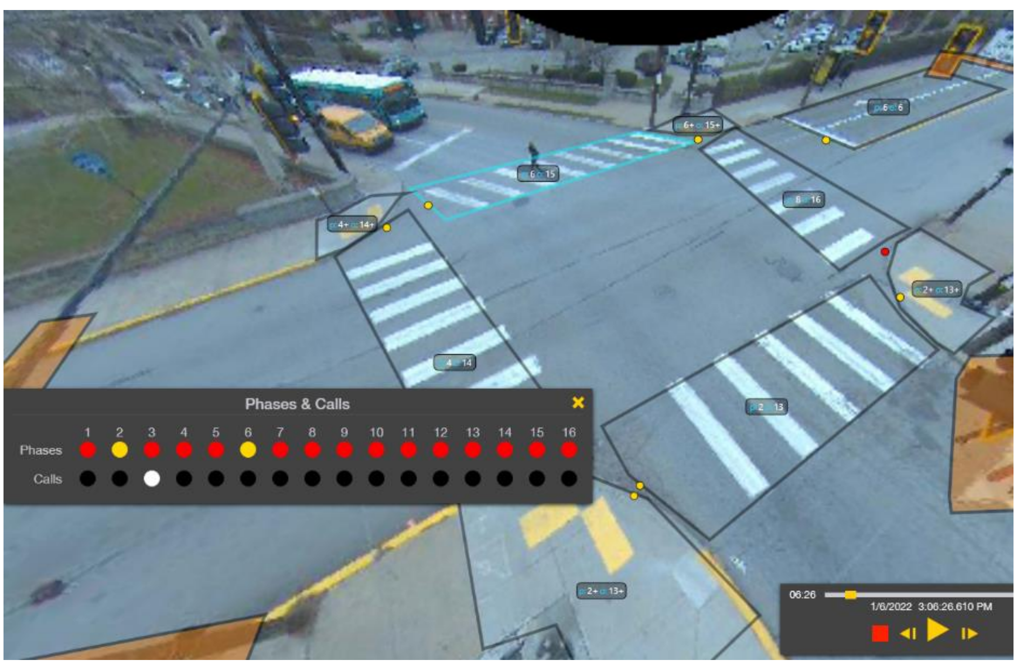


Figure 27 Pedestrian Mid-Crossing of CRW6 – No Pedestrian Phase

Figure 28 Pedestrian Arrival at NE Waiting Zone – No Actuation

Figure 29 Pedestrian Mid-Crossing of CRW6 – No Pedestrian Phase

The pedestrians arrive on Phase 2 green and continue through the intersection. The second pedestrian crosses through the “Flashing Don’t Walk” phase from the first pedestrian in Figure 25. The third pedestrian arrives on green but does not have a pedestrian phase and crosses on “Don’t Walk”. The times were recorded for the last two pedestrians when they were in the middle of the waiting zone since they did not come to a stop. The crosswalk zones detect the pedestrians appropriately. The manual recording for these pedestrians is shown in Table 5 below.

Table 5 Manual Pedestrian Data Collection

Date	Time Entering Waiting Zone	Ped Count	Crosswalk Used	Waiting Zone Triggered?	Manual Call?	Ped Phase Used (W/FDW/W)	Direction Traveled
1/6/2022	15:05:21	1	CRW6	YES	YES	W	W-E
1/6/2022	15:06:22	1	CRW6	NO	NO	FDW	E-W
1/6/2022	15:07:36	1	CRW6	NO	NO	DW	W-E

There is a wrongly placed pedestrian call during this interval as well. A bus moves through the intersection from 40th NB. This causes an incorrect call at the NW waiting zone that can be seen in Figure 30 below, with the call placed for Phase 1. This call corresponds to the output for CRW 8 in *Config2*. Figure 31 shows the pedestrian phase given for this actuation with green for phase 15. This corresponds to the output of CRW 6 in *Config1*. This call/phase behavior follows the first pedestrian behavior.

Figure 30 Incorrect Pedestrian Call from Automatic Detection of Passing Bus

Figure 31 Pedestrian Phase Given from Incorrect Automatic Detection of Passing Bus

3.3 GRIDSMART Data Validation

There is another issue with the GRIDSMART configuration files. In Figure 32, the pedestrian arrives to the waiting zone where GRIDSMART detects the pedestrian and makes an automatic call. A call is displayed for the output Phase 5 in the “Phases and Calls” box in the image. Figure 32 has the configuration *Config1* loaded, which needs to be imported into the client in order to access data reports in cloud storage, such as vehicle and pedestrian counts for validation, with the output related to *Config 2*. There is no output for a phase greater than 16, so it is unclear if a call is being made for Phase 24 as well according to the configurations in Table 2.

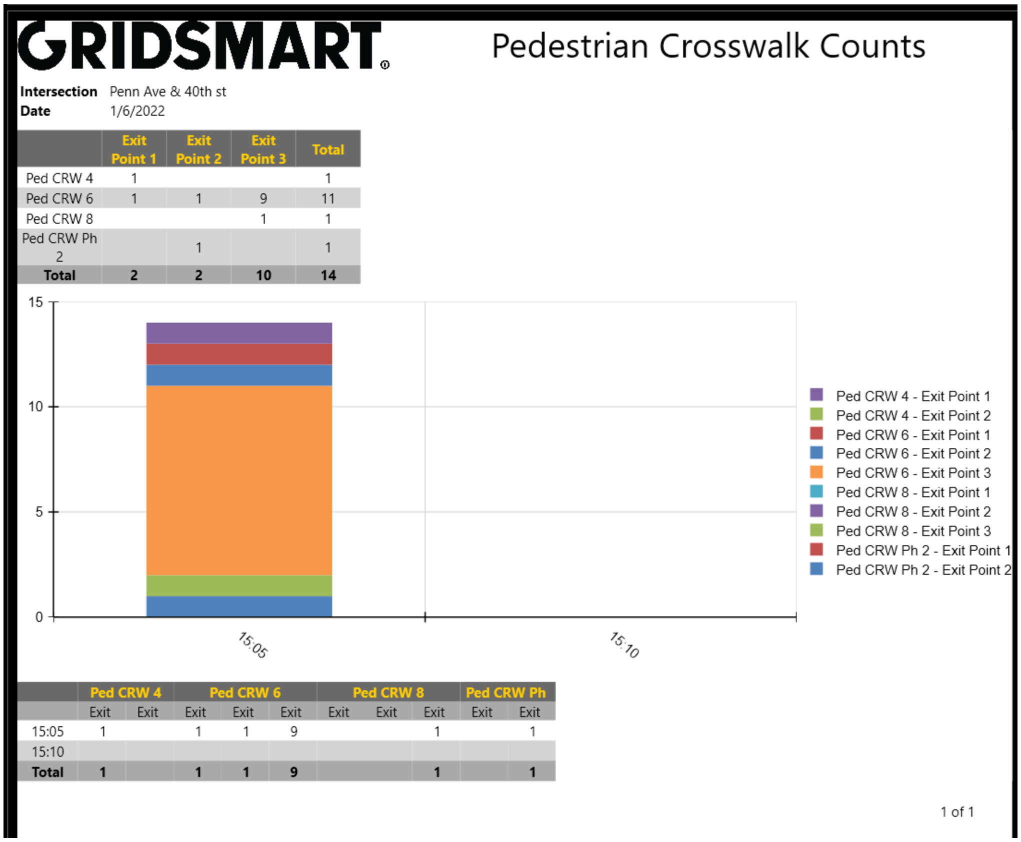
Video playback can occur over either configuration file, but *Config2* is automatically loaded when video is imported into the app. Figure 33 below shows the same pedestrian with *Config2* loaded crossing on the active pedestrian phase 15. After waiting correctly for the pedestrian phase, the pedestrian crosses CRW6 and continues.

Figure 32 Pedestrian Arrival at NE Waiting Zone (*Config1*)

Figure 33 Pedestrian Mid-Crossing of CRW 6

Phase 15 matches the output of *Config1* for CRW6. Actuation occurred, a call was placed, and next cycle the pedestrian phase was provided. However, actuation occurred with a call on phase 5 which corresponds to *Config2* for movements between NE and SE, i.e., CRW 4. It is unclear why this occurs, but the pedestrian crossed appropriately and safely.

Each pedestrian was counted regardless of GRIDSMART detection. After analyzing the video footage and manually counting pedestrians in 5-minute intervals, GRIDSMART reports were generated for each hour in 5-minute intervals. The counts for each of these outputs and exit points was recorded for each 5-minute interval and can be seen in Appendix D. The manual counting results immediately showed errors from the GRIDSMART detection software. The automatic detection resulted in what appears to be significant over-counting of pedestrians. It provided pedestrian counts with outputs at crosswalks unused by pedestrians and missed counts where pedestrians clearly crossed. The results for the time interval 15:05-15:10 used in the manual counting example above can be seen in Figure 34 below.



GRIDSMART

Pedestrian Crosswalk Counts

Intersection Penn Ave & 40th st
Date 1/6/2022

	Exit Point 1	Exit Point 2	Exit Point 3	Total
Ped CRW 4	1			1
Ped CRW 6	1	1	9	11
Ped CRW 8			1	1
Ped CRW Ph 2		1		1
Total	**2**	**2**	**10**	**14**

	Ped CRW 4		Ped CRW 6			Ped CRW 8			Ped CRW Ph	
	Exit	Exit	Exit	Exit	Exit	Exit	Exit	Exit	Exit	Exit
15:05	1		1	1	9			1		1
15:10										
Total	**1**		**1**	**1**	**9**			**1**		**1**

1 of 1

Figure 34 GRIDSMART Report for Time Interval 15:05-15:10

The report produces a pedestrian count of 14 compared to the manual count of 3 shown in Table 6. Each of the pedestrians used CRW6, however the report has output data for CRW4, CRW6, CRW8, and CRWph2. The SE camera records for CRWph2, while the CABINET camera records for the other three. This occurs throughout the analysis and the results are summarized in Table 6 below with the GRIDSMART report for each hour in Appendix D.

Table 6 Manual Pedestrian Counting vs. GRIDSMART Data Collection

Interval	15:00-16:00	16:00-17:00	17:00-18:00
Manual Counts	36	44	41
GRIDSMART	129	117	117

According to GRIDSMART, the cameras record when pedestrians cross the end of a crosswalk or leave at some point in the crosswalk. The third exit point represents pedestrians leaving the crosswalk midway. This is compromised by vehicles moving over the crosswalk. Removing the data for Exit 3 still results in inflated pedestrian numbers, so it is assumed that vehicles interfere with the other exit points as well. This would most likely happen with vehicles slowly turning right from Penn WB or 40th SB due to the location of both cameras on the south side of the intersection and the resulting depth issues that the cameras cannot properly solve. GRIDSMART support indicated that they are continually working on improving pedestrian detection and that the issue for the subject intersection could be due to the nature of the intersection or the configuration of the detection hardware, neither of which could be changed during this study.

As a result, it became clear that the pedestrian data from GRIDSMART is not reliable. The differences in peak summer data versus current winter data could not be quantified, as there is no available video from that time to allow manual counting. It is very likely still greater but there is no way to determine by how much, even with the available manual pedestrian counts from 01/06/22. This is not ideal; however, it does not affect signal timing since pedestrian calls are made from the wait zone areas which are separate from crosswalk zones.

3.4 Pedestrian Call Analysis

The focus of this study shifted to determining how many actual pedestrian calls are being made by GRIDSMART, how accurate are the calls, and how are the calls affecting signal operations. The actual pedestrian counts from manual counting will be compared to the GRIDSMART calls via simulation to determine delay impacts to vehicles. The signal operations at the subject intersection are for a fully actuated signal. If a pedestrian phase is provided, the vehicle phase is essentially forced to max out and this can result in wasted green time and vehicle delay if there is no pedestrian using the pedestrian phase.

3.4.1 Analysis of Pedestrian Actuations

The video for each of the three hours was analyzed again to record every pedestrian call made, either manual or via automatic detection. Each wait zone detection is an individual pedestrian call. If a pedestrian does not stop in the wait zone for a "long second" (12), no automatic call is made. The video was also analyzed to determine how many unused pedestrian phases occurred that may have impacted vehicle delay. An example of the wait zone actuation recording is shown in Table 7 below. Further notation provides context for the pedestrian behavior and phase sequence which leads to the determination of whether a pedestrian phase was appropriately used or unnecessary. Table 8 provides a summary of the total calls made by pedestrians, noting the number of false calls made, and comparing these to the actual pedestrians that used the intersection. Table 9 shows the manual pedestrian counts previously determined with the number of manual pushbutton calls. In this period, 74.4% of pedestrians did not use the push-button. This validates the behavior seen in the study by Sulmicki (6), where 78% of pedestrians did not use the push-button.

Table 7 Example of Pedestrian Wait Zone Detections

	Camera	Time	Waiting Zone Actuations				Manual Call?	Ped Phase Given?	Ped Phase	Crosswalk
			NW	NE	SW	SE				
	CC	15:04:40		1			NO	YES	15	CRW6
SAME PED	CC	15:04:42	1				NO	YES	15	CRW6
	CC	15:04:46	1							
SAME PED	CC	15:05:21		1			YES	YES	15	CRW6
	CC	15:05:27		1						
	CC	15:05:51		1						
	CC	15:05:55		1						
FALSE CALL	CC	15:08:00	1				NO	YES	15	
FALSE CALL	SE	15:14:11	1				NO	YES	15	
	CC	15:21:29		1			YES	YES	14/15	CRW4
	SE	15:21:29			1		NO	YES	13	CRW8
	SE	15:23:53		1			YES	YES	14/15	CRW4/CRW2

Table 8 Summary of Pedestrian Call Analysis

	Total Automatic Calls Made										
Interval	**NW**	**NE**	**SW**	**SE**	**Total**	**False Calls**	**% False Calls**	**Peds Detected in Wait Zone**	**Peds Not Detected**	**% Detected**	**Calls Made per Ped Detected**
1500-1600	18	12	14	6	50	3	6.0%	21	15	58.3%	2.24
1600-1700	22	11	15	5	53	3	5.7%	29	15	65.9%	1.72
1700-1800	34	26	15	14	89	16	18.0%	30	11	73.2%	2.43
				Overall	**192**	**22**	**11.5%**	**80**	**41**	**66.1%**	**2.40**

Table 9 Pedestrian Pushbutton Analysis

Interval	Manual Count	Manual Pushbutton Calls	% Using Manual Call
1500-1600	36	11	30.6%
1600-1700	44	11	25.0%
1700-1800	41	9	22.0%
Overall	**121**	**31**	**25.6%**

The actual pedestrian count is consistent throughout the peak period. The lowest detection of pedestrians occurred during 15:00-16:00 at 58% and was the result of many pedestrians arriving on a pedestrian phase or vehicle phase and continuing through without stopping. The highest detection occurred during 17:00-18:00 at 73% while also recording the highest false calls at 18% of total wait zone actuations. It should be noted that visibility declined significantly during this interval due to sunset, as well as heavy rain starting at 17:30. GRIDSMART cameras are supposed to be able to handle nighttime and poor weather conditions (12), but this was not the case during this time. Figure 35 below shows the camera unable to detect a pedestrian due to darkness and Figure 36 shows a false call from a permanent object that was marked to be ignored by GRIDSMART. All but one of the false calls occurred either at the NW or SW pedestrian wait zones. The NW false calls were a result of pedestrians accessing stairs to the nursing home located at the intersection or from the permanent object error. The SW false calls were for unknown reasons as they were all in the 17:00-18:00 interval but occurred before and after the rain began with no visible object to detect. One false call occurred in the NE wait zone after a pedestrian exited the crosswalk appropriately and continued on without stopping but was detected anyway.

Figure 35 GRIDSMART Unable to Detect Pedestrians at Night

Figure 36 False Call from Permanent Object

The number of automatic calls made by GRIDSMART due to movement within the zone was important for determining potential delays. Removing false calls, the calls made per pedestrian detected was calculate and the average for the analysis period was 2.4 calls/pedestrian detected. Multiple calls do not always present a problem, however if they are made during successive vehicle phases this can result in unnecessary pedestrian phases after the initial phase needed is provided.

The figures below show this issue. Figure 37 shows a detected pedestrian waiting to use Phase 16 who had placed a manual call during Phase 4. Phase 13 was provided and went unused. The pedestrian moved within the wait zone during this Phase 2 and was detected by GRIDSMART again, placing another call. Figure 38 shows the pedestrian crossing during the desired Phase 16. Figure 39 below shows pedestrian phases provided during the next vehicle phase after the pedestrian properly crossed. Automatic calls were placed during Phase 4 and the following Phase 2. Pedestrian Phases were provided during the next Phase 2, the subsequent Phase 4, and then the next cycle Phase 2.

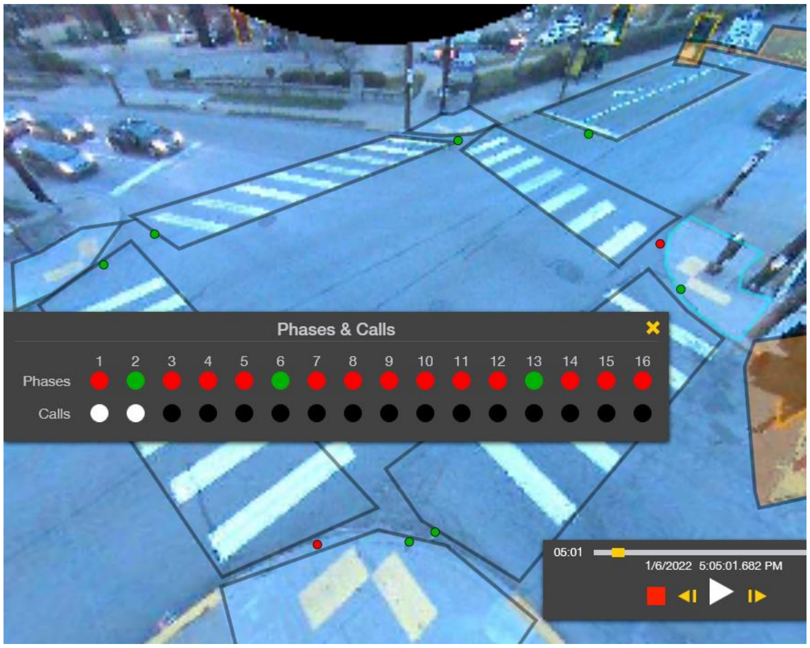


Figure 37 Pedestrian Correctly Detected Waiting to Cross NB

Figure 38 Pedestrain Correctly Using Provided Pedestrian Phase

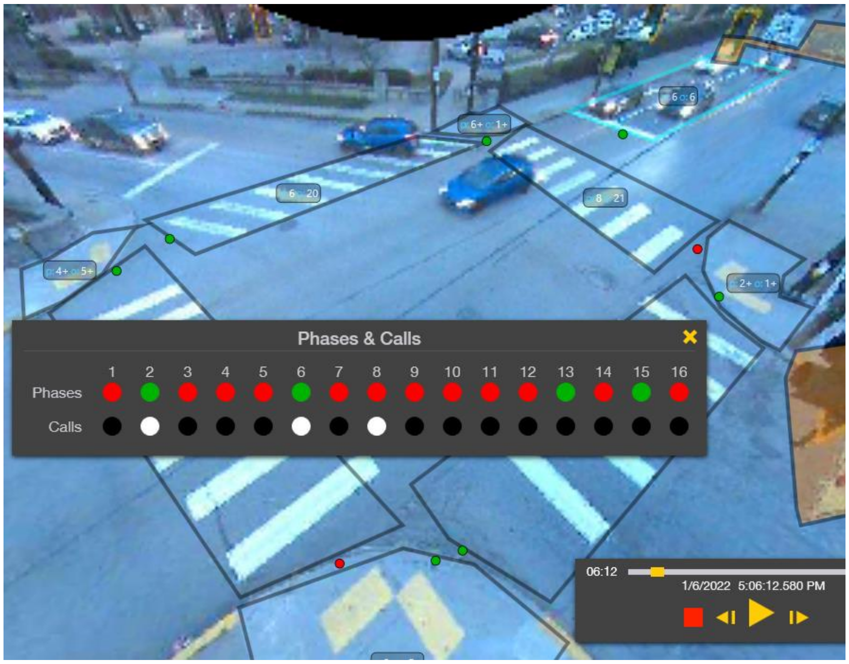


Figure 39 Unnecessary Pedestrian Phases from Multiple Automatic Actuations

This provides evidence that GRIDSMART is providing pedestrian phases for pedestrians that do not need them, resulting in potential vehicle delay. In addition, individual pedestrian behavior varies drastically based on many variables discussed previously. Time of day, weather, physical abilities, current vehicle traffic/gap acceptance, disregard for signals, etc. Sometimes GRIDSMART places a call and provides the phase correctly, however the pedestrian has already crossed for one of many reasons. Some pedestrians cross during the all-red before the pedestrian phase starts, while some cross during a gap in the opposite vehicle phase. This is not a case of incorrect operation, but it results in unnecessary pedestrian phases and vehicle delay.

3.4.2 Pedestrian Phase Analysis

The video recordings were analyzed once more to identify when a pedestrian phase is provided and unused. If a pedestrian arrived and used the unnecessary phase, it was not considered unused. If an unnecessary pedestrian phase was provided in parallel with its partner pedestrian phase that was used, it was not considered unused. These cases are still evidence of unnecessary pedestrian phases provided from detection; however, they do not increase vehicle delays. Table 10 provides an example of the analysis and Table 11 provides a summary of the unused pedestrian phases.

Table 10 Example Notation of Video Analysis for Unused Ped Phases

Time	Ped Phase	Reason
15:01:22	15	Manual Call - Ped crossed immediately during all-red
15:04:59	15	Auto Call - 2 Peds crossed during all-red
15:08:22	15	False Call - Large shuttle bus incorrectly detected
15:15:07	15	False Call - Ped accessing nursing home. Call made during Phase 2. Provided ped phase during next cycle Phase 2.
15:21:34	13/15	Auto Call - 2 peds waiting to cross using 14 and 16. Provided 13 and 15 in next phase.

Table 11 Summary of Unused Ped Phase Analysis

Total Unused Phases				
15:00-16:00	**16:00-17:00**	**17:00-18:00**	**Total**	**Hourly Average**
15	13	20	48	**16**
Cycle Length (s)	**Cycles per Hour**	**Phases per Cycle**	**Phases per Hour**	**% Unused Phases per Hour**
80	45	2	90	**17.8%**

The most unused pedestrian phases occurred during the 17:00-18:00 time interval and were most likely the result of the high number of false calls and automatic calls overall during that interval. An average of 16 pedestrian phases per hour went unused during the analysis period. Using the timing plan base cycle length of 80 seconds, the number of available phases for pedestrian phases is 90 phases per hour. This results in 17.8% of vehicle phases having an unused pedestrian phase potentially extending the vehicle phase longer than needed. Pedestrian activity is primarily along the major street with 71.6% of manually counted pedestrians traveling East or West. Unused pedestrian phases were also provided primarily along the major street with 89.6% of unused pedestrian phases for Phases 13 or 15. This indicates a preference for GRIDSMART to always call for these phases first and then provide Phases 14 or 16 only if a pedestrian presence is still detected after the end of vehicle Phase 2.

3.5 VISSIM Model

A model of the subject intersection and relevant upstream intersections was created using VISSIM to simulate different signal operations. The GRIDSMART detection system immediately showed operational errors, so the simulation allowed analysis of these detection errors on vehicle delay. Different control strategies were investigated to determine if fully actuated, automatic detection is even the best strategy for this intersection.

3.5.1 Model Network

The intersections were modeled using permit drawings provided by DOMI and Google Maps satellite images when needed. The network created for this analysis is show in Figure 40 below. The network is located in a dense urban environment and all speed limits are 25 mph. The three intersections to the east are coordinated, while the other two operate freely. Figure 41 shows a closer look at the subject intersection overlayed over a satellite map.

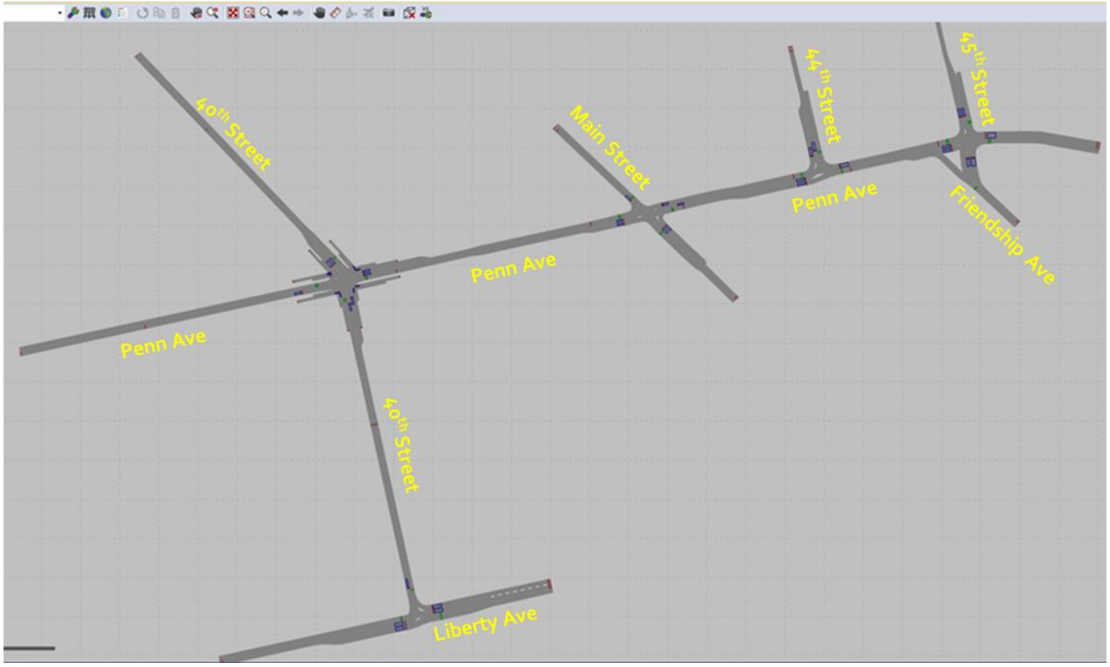


Figure 40 VISSIM Network

Figure 41 Model of Penn/40th Intersection

3.5.1.1 Vehicle Inputs

Vehicle inputs and turning ratios were collected from GRIDSMART for the subject intersection, and manual field counting for the upstream intersections. Heavy vehicles were 2% of the vehicle share and lane widths varied between 8 and 10 feet according to the DOMI permit drawings. The desired vehicle speed for all inputs was set at 50 km/h (31.06 mi/h). Figure 42 below shows the vehicle inputs used in the model in vehicles per hour.

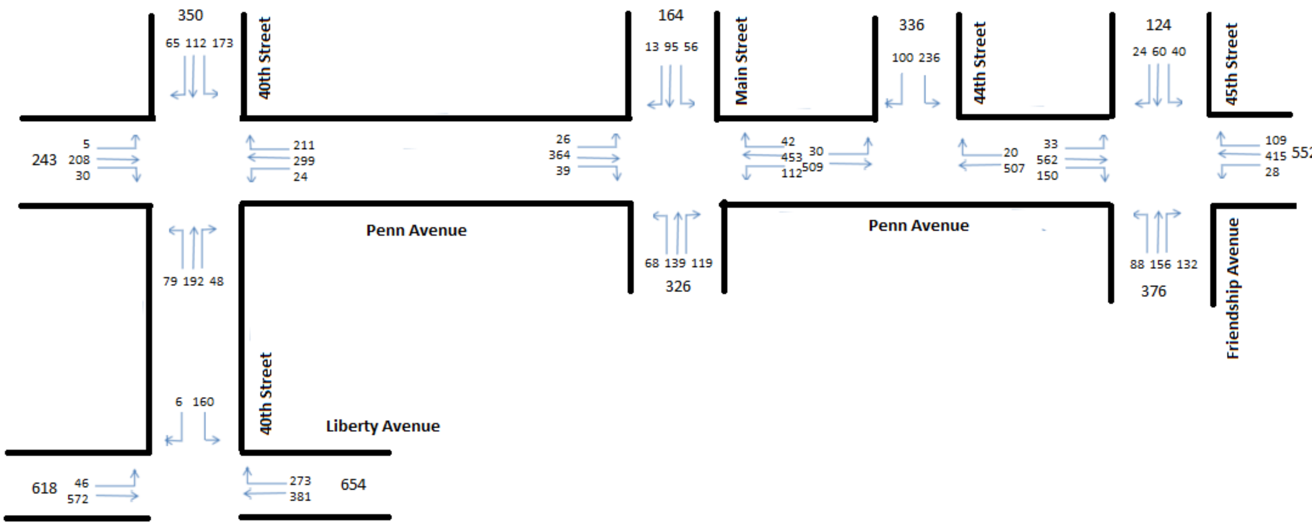


Figure 42 Model Vehicle Inputs

3.5.1.2 Pedestrian Inputs

Pedestrian crossings were modeled using two one-way vehicle links for each crosswalk with individual signal heads and detectors. Each crosswalk had a width of 5.5 feet. Pedestrian speeds were set at 5 km/h (3.1 mi/h). Pedestrian volumes were determined from the manually collected pedestrian data as a base value. Table 12 below shows the manual counts for each interval according to direction of crossing with an average hourly volume for each directional crossing to be used for the model inputs. In total there were 121 pedestrians over three hours, or 40.3

pedestrians per hour. One exception was made with regards to the E-W crossing inputs where CRW2 was reduced to 6.33 peds/hr and CRW6 was increased to 10 peds/hr.

Table 12 Pedestrian Volume Inputs from Manual Counting

Interval	1500-1600		1600-1700		1700-1800		Total		Hourly Average Volume for Inputs	
Direction	**WB**	**EB**	**WB**	**EB**	**WB**	**EB**	**WB**	**EB**	**WB**	**EB**
CRW2	9	3	9	7	1	9	20	19	6.3	6.3
CRW6	7	7	13	3	10	8	29	18	10.0	6.0
Direction	**SB**	**NB**	**SB**	**NB**	**SB**	**NB**	**SB**	**NB**	**SB**	**NB**
CRW4	2	2	3	1	5	3	10	6	3.3	2.0
CRW8	1	5	4	4	3	2	8	11	2.7	3.7

The effect of pedestrian phases provided by automatic detection that went unused is captured in the “ManualPlus” scenario. An average of 16 pedestrian phases per hour went unused which were then split according to directional distribution and added to the “Manual” volumes. In terms of directional distribution, 43 of the 48 unused phases (89.6%) occurred in the E-W direction. Splitting the 16 unused phases results in 14.33 E-W and 1.67 N-S. For simplicity, these numbers were rounded to 14 E-W and 2 N-S and then split according to crosswalk distribution. CRW6 added 10 “pedestrians”, CRW2 added 4, and CRW4 and CRW8 added 1 each. These values were then split between directional inputs for each crosswalk. Considering the low pedestrian volumes, CRW4 and CRW6 inputs were split evenly with 0.5 “pedestrians” added to each input. CRW2 has equal distribution so 2 “pedestrians” were added to each input. CRW6 has roughly a 60/40 directional distribution, so 6 “pedestrians” were added to the WB input and 4 were added to the EB input.

For the “Peak” pedestrian volume, the manual count was increased by 400% for each input to provide a reasonable scenario. There was no historical data available for pedestrian volumes. Although the GRIDSMART data is unreliable, the peak hour pedestrian count (excluding “Exit 3”) from 08/03/21 is 447% greater than the peak hour of analysis on 01/06/22. This data can be found in Appendix B. It is not that high for all days where data was available, so it was considered to be a representative extreme peak of pedestrian activity. At higher pedestrian volumes, the impact of unused phases is diminished since it is very likely that another pedestrian will arrive and use the phase. Therefore, the unused phases from automatic detection errors were not included in this peak volume. Table 13 below shows the pedestrian inputs for each of the pedestrian volume scenarios.

Table 13 Pedestrian Volume Inputs for Simulation Scenarios

	Manual Avg Hourly Volume		ManualPlus Avg Hourly Volume		Peak Avg Hourly Volume	
Direction	**WB**	**EB**	**WB**	**EB**	**WB**	**EB**
CRW2	6.3	6.3	8.3	8.3	25.3	25.3
CRW6	10.0	6.0	16.0	10.0	40.0	24.0
	SB	**NB**	**SB**	**NB**	**SB**	**NB**
CRW4	3.3	2.0	3.8	2.5	13.3	8.0
CRW8	2.7	3.7	3.2	4.2	10.8	14.8

3.5.2 Ring Barrier Controllers

Signal timing plans for the intersections were provided by DOMI and all controllers were input as Ring Barrier Controllers (RBC). The upstream intersections on Penn Avenue are coordinated, while the subject intersection and the Liberty/40th intersection are free. The base cycle lengths for all signals are 80 seconds and the signal timing plans can be seen in Appendix A.

Figures 43-47 show the ring barrier controllers created in VISSIM. The RBC for Penn/40th is shown for fully actuated operation but was modified to simulate other signal operations. The coordinated intersections upstream on Penn Avenue operate with Start-up Green and Minimum Recall on Phases 2 and 6. Liberty and 40th operates as a fixed time signal.

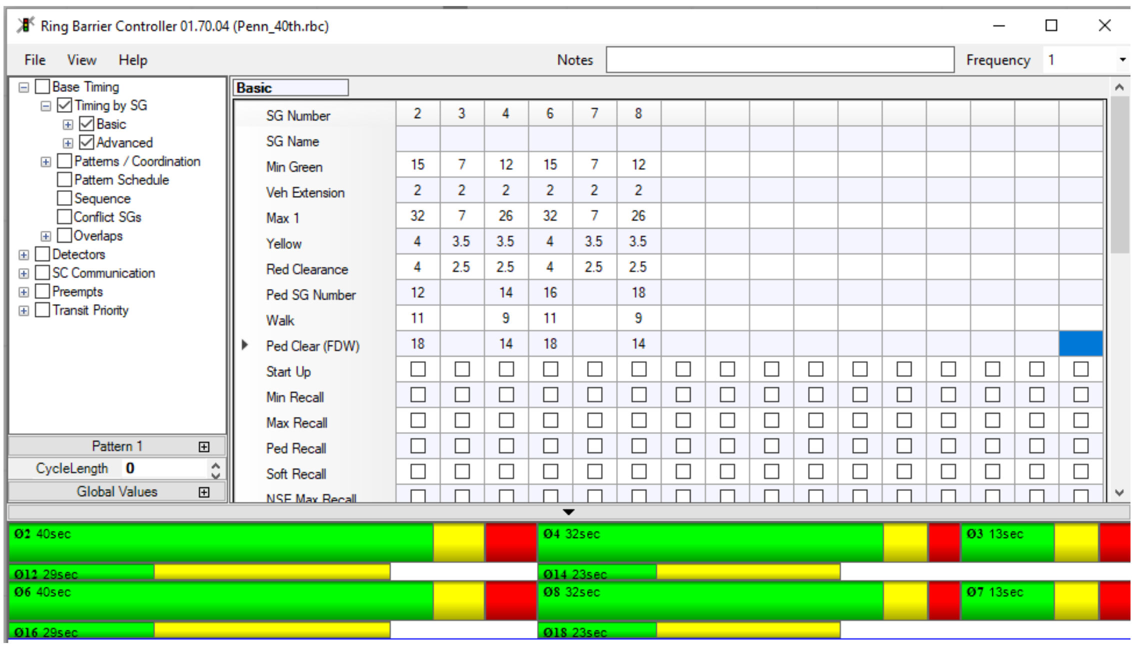


Figure 43 RBC for Penn Ave/40th St

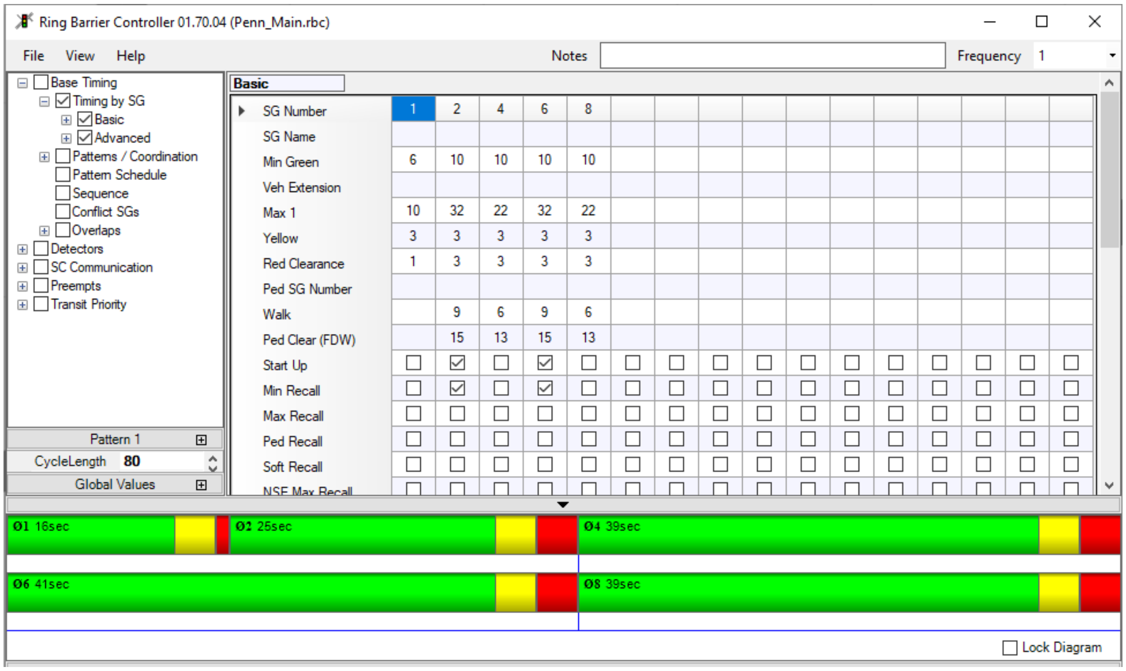


Figure 44 RBC for Penn Ave/Main St

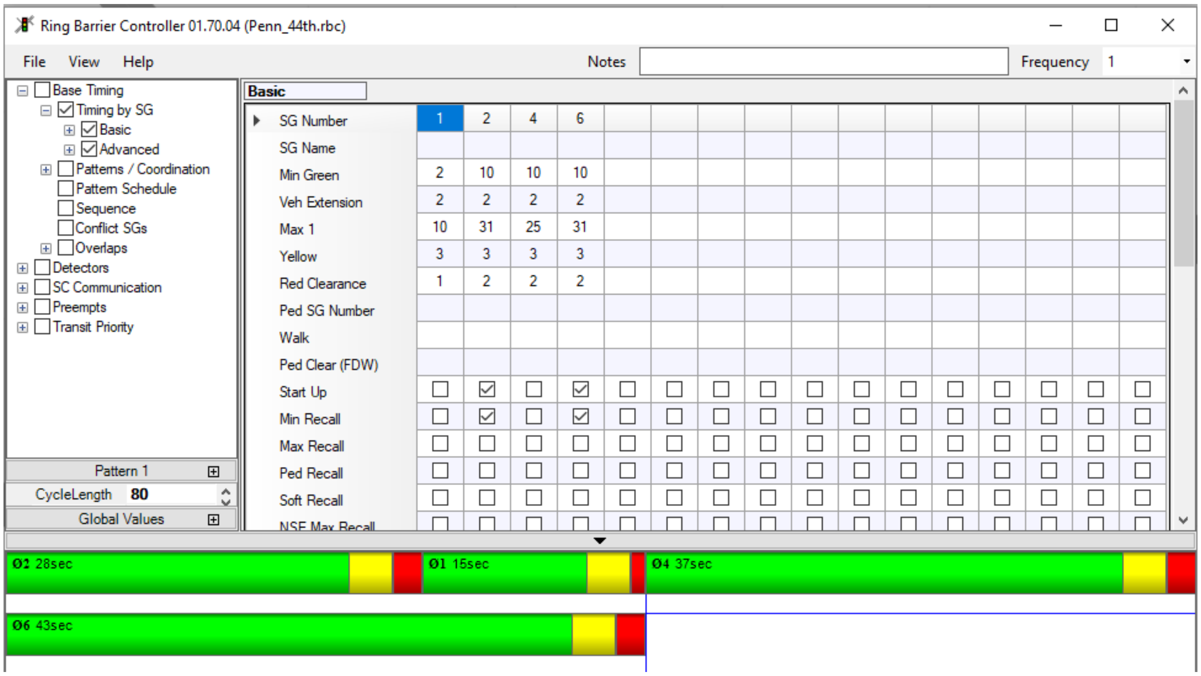


Figure 45 RBC for Penn Ave/44th St

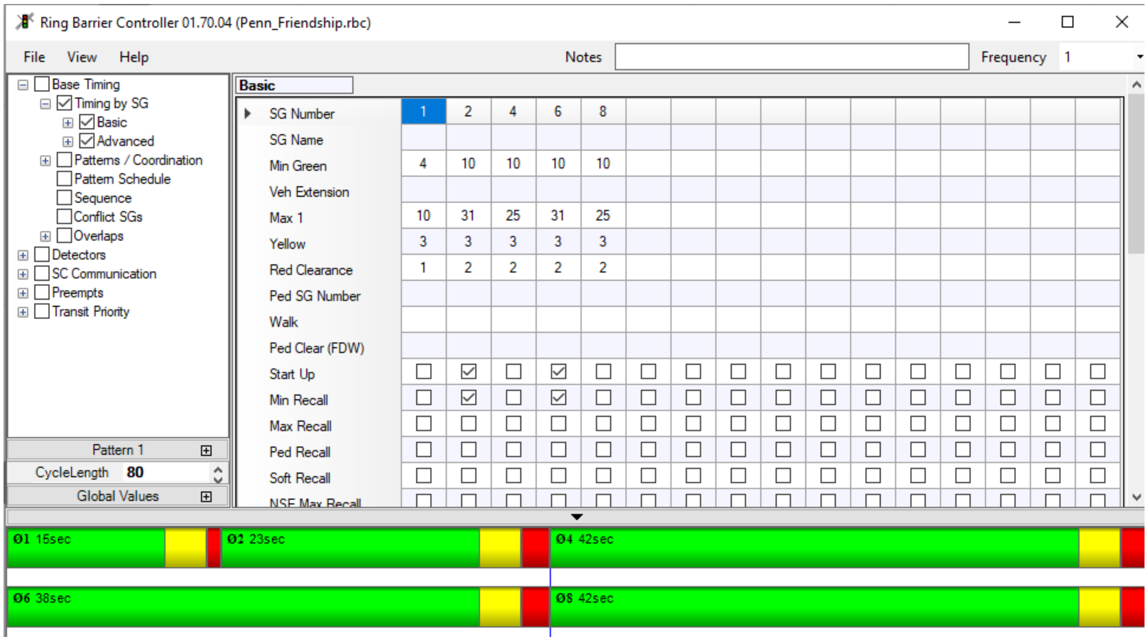


Figure 46 RBC for Penn Ave/45th St/Friendship Ave

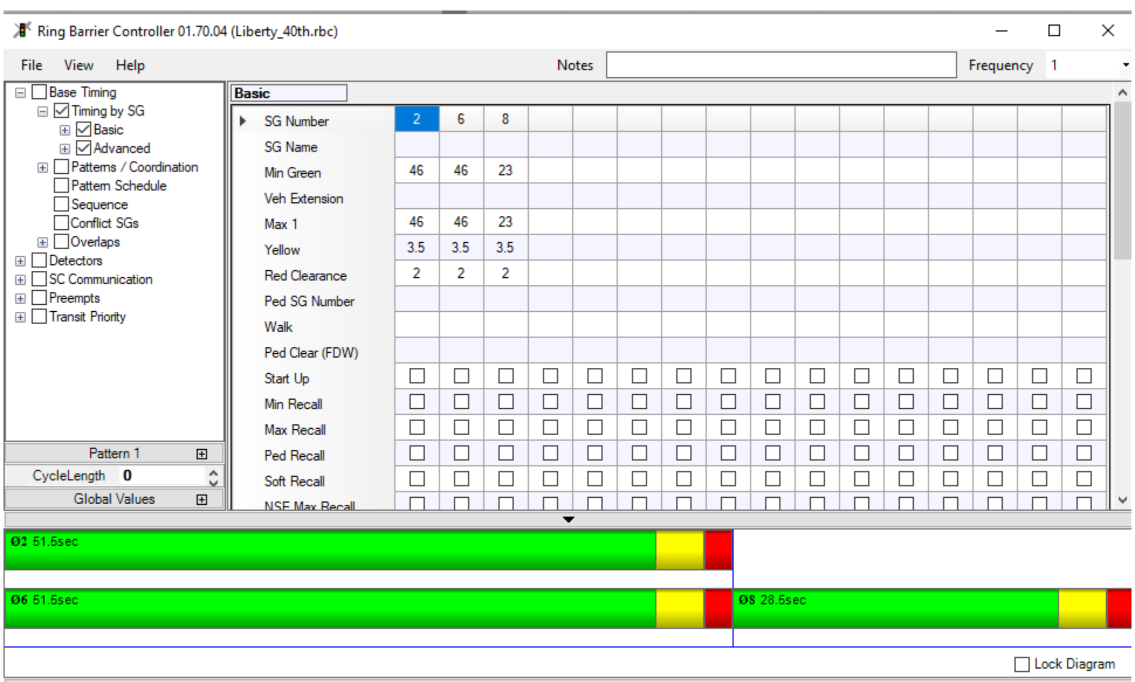


Figure 47 RBC Liberty Ave/40th St

3.5.3 Simulation Parameters

The simulation was run for three pedestrian volumes under four control strategies for a total of 12 operational scenarios. The three pedestrian volumes used for simulations are "Manual," "ManualPlus," and "Peak", and are referred to this way hereafter. "Manual" refers to the pedestrian count from manual data collection. "ManualPlus" refers to the manual count with the unused pedestrian phases from GRIDSMART calls treated as additional pedestrians. "Peak" refers to a reasonable, expected pedestrian volume during peak conditions. The peak data could not be verified with GRIDSMART data, so the manual count was increased by 400% to provide a representative case. Vehicle volumes remained the same for all scenarios.

The four control strategies used were full actuation, pedestrian recall on all phases, minimum recall on the major street thru phases, and maximum recall on all phases. Due to the nature of the network layout, pedestrian and vehicle delays were recorded using two separate nodes which required separate simulation runs for pedestrians and vehicles.

The simulation was run 10 times for each of the 12 conditions, 5 for pedestrians and 5 for vehicles. The simulation interval was for 4500 seconds with the first 900 seconds used to populate the network and left out of analysis, leaving an analysis period of one hour from 900-4500. The time step/simulation second resolution was set at 10 steps/simulation second to provide smooth VISSIM operations and better results (17). A random seed of 38 was used initially and increased by one for each of the 5 simulation runs.

3.5.4 Model Validation Using GEH Statistic

The model was validated using the GEH statistic comparing input volumes to the model from the field to output volumes from running the simulation. The statistic is calculated for each of the vehicle movements and pedestrian crossings by using Equation 3-1 below. The results for the subject intersection movements are shown in Table 14 below for the fully actuated, manual count scenario with the results for all intersection movements in Appendix F. A result less than 5.0 indicates an acceptable fit for the model, while a result greater than 10.0 is unacceptable. Results in between indicate there may be errors in the model or bad input data. All values were less than 5.0 indicating an acceptable model for this analysis. Figure 48 below represents the field data inputs and simulation outputs for all movements within the network graphically. The linear trendline with an R^2 value of 0.9913 validate the simulation model fit.

$$GEH = \sqrt{\frac{2(m-c)^2}{m+c}} \tag{3-1}$$

where,

m = output volumes from simulation (vph)

c = input volumes to simulation (vph)

Table 14 GEH Statistic Calculation for Penn/40th

Movement	SIM	FIELD	GEH
NB LEFT	83	79	0.444
NB RIGHT	32	48	2.530
NB THRU	221	192	2.018
WB THRU	295	299	0.232
WB LEFT	16	24	1.789
WB RIGHT	190	211	1.483
EB THRU	191	208	1.204
EB RIGHT	31	30	0.181
EB LEFT	5	5	0.000
SB RIGHT	52	65	1.700
SB LEFT	178	173	0.377
SB THRU	95	112	1.671
14NB	0	2	2.000
12EB	5	6.3	0.547
18NB	3	3.7	0.382
14SB	5	3.3	0.834
16WB	9	10	0.324
18SB	1	2.7	1.250
16EB	7	6	0.392
12WB	7	6.3	0.271

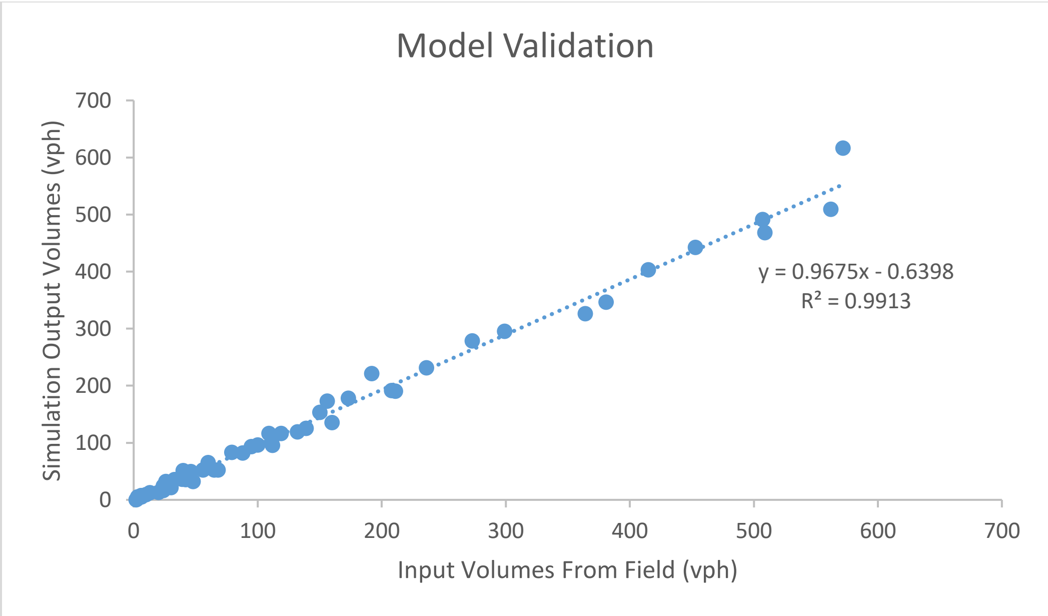


Figure 48 Model Input Volumes vs Simulation Output Volumes

4.0 Results

The simulation results were analyzed to determine the effect of GRIDSMART automatic detection on vehicle and pedestrian delay. Automatic detection provides pedestrian phases that go unused and may add to delays instead of reducing them. The pedestrian input volumes were increased to a peak volume to assess the best operational strategy for the subject intersection.

4.1 Vehicle Delay

Vehicle delay was calculated for each of the scenarios by movement, approach, and intersection. Following the Highway Capacity Manual, aggregate delay was calculated using a weighted average based on vehicle flows (18). Movement delays were determined first to find the average delays from the 5 simulation runs, followed by approach delay and then overall intersection delay. Level of service was determined according to the HCM criteria shown in Table 15 below (18).

Table 15 HCM LOS Criteria

LOS	Delay (s/veh)
A	≤ 10
B	10 < 20
C	20 < 35
D	35 < 55
E	55 < 80
F	> 80

Under fully actuated operation, intersection vehicle delay increases marginally from 19.84 seconds to 20.65 seconds per vehicle as a result of the unused pedestrian phases called for by GRIDSMART detection. Increasing pedestrian volumes by 400% results in delay of 21.87 seconds per vehicle, or a 10.2% increase in delay. These delay results are consistent with fully actuated operations and LOS drops from B to C. Figure 49 below shows vehicle delay results for each pedestrian volume scenario under full actuation.

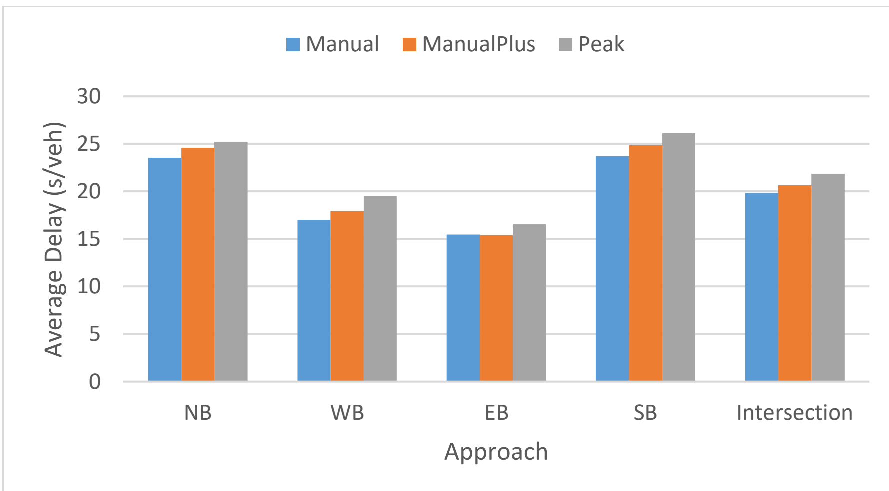


Figure 49 Vehicle Delay for Full Actuation

Figures 50-52 show the vehicle delay results for each pedestrian volume scenario under four different signal operations: fully actuated, pedestrian recall (all phases), minimum recall (phases 2 and 6), and maximum recall (all phases). Min recall and max recall increase delay compared to full actuation for all pedestrian volumes with max recall the worst operational strategy as expected. Pedestrian recall resulted in the lowest vehicle delay for all pedestrian volumes, with peak pedestrian volume decreasing significantly more. It was determined that min recall and max recall should not be considered for signal operations, and the remaining analysis focused on the results for full actuation and pedestrian recall.

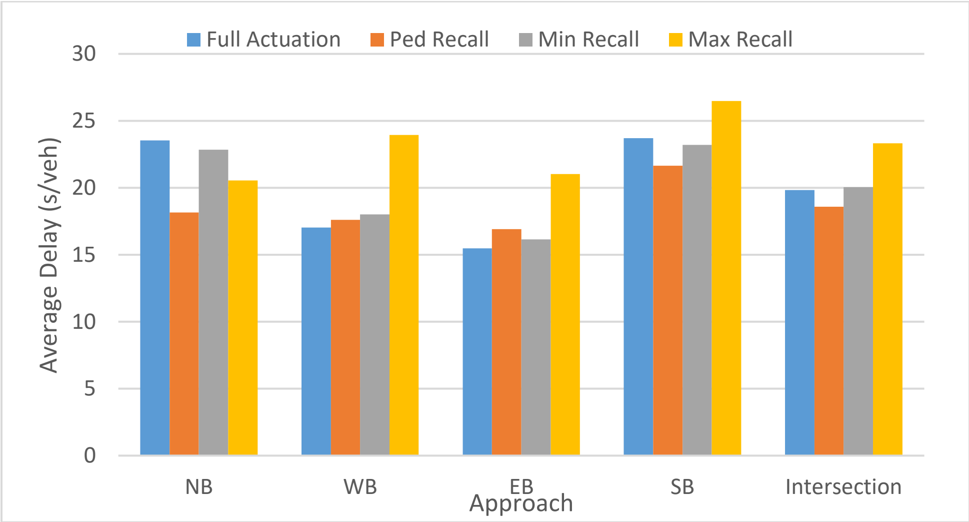


Figure 50 Vehicle Delay Results for Manual Pedestrian Volume

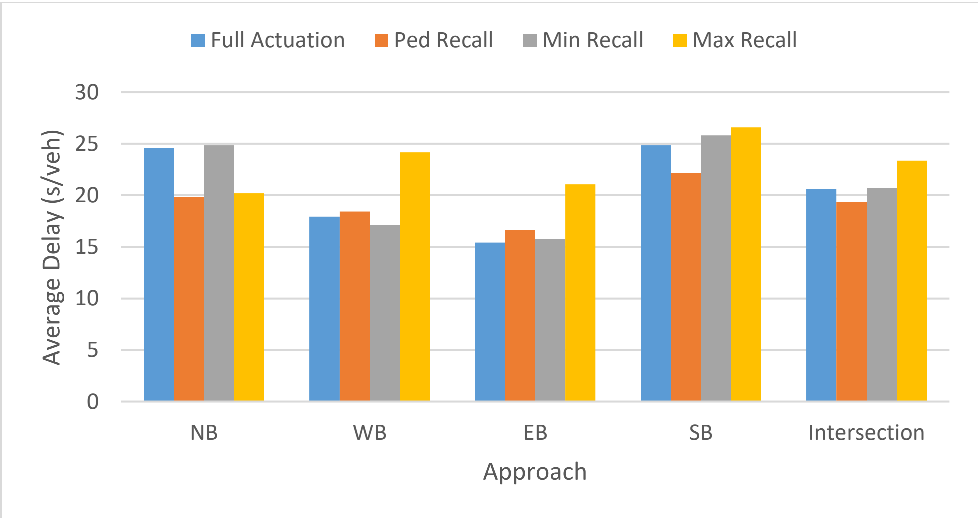


Figure 51 Vehicle Delay Results for ManualPlus Pedestrian Volume

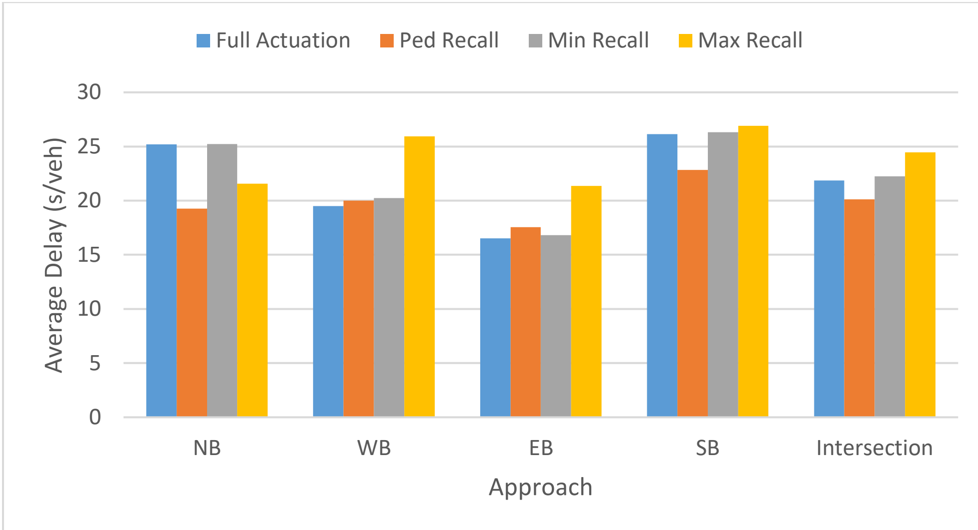


Figure 52 Vehicle Delay Results for Peak Pedestrian Volume

Pedestrian recall is best used when pedestrian volumes are high (4,8,11). Simulation results validate this with vehicle delay decreasing more under pedestrian recall compared to full actuation as pedestrian volume increases. Table 16 shows the delay change between control operations for each pedestrian volume.

Table 16 Change in Intersection Delay Under Ped Recall

Ped Volume	Full Actuation Delay (s/veh)	Ped Recall Delay (s/veh)	Percent Change
Manual	19.841	18.593	-6.29%
ManualPlus	20.650	19.364	-6.23%
Peak	21.868	20.122	-7.98%

Compared to full actuation, pedestrian recall lowers vehicle delay for all pedestrian volume scenarios, so if pedestrian volumes are not very large, there is still a positive impact to vehicles. However, if pedestrian volumes sharply increase, vehicle delay will be reduced more, and the intersection will operate more efficiently. Level of service remains the same for the Manual volume (LOS B) and Peak volume (LOS C) and improves for the ManualPlus volume (LOS C to LOS B). The Peak result for pedestrian recall falls just outside the limit for LOS B. Full results for vehicle delays are in Appendix F.

4.1.1 Vehicle Delay T-Test

The intersection delay results for full actuation and pedestrian recall were compared using the Independent Sample T-Test to determine if there is any statistical significance to the results. The overall intersection delay for each of the five simulation runs and the standard deviation were calculated for each signal control scenario. The t-value compares the difference between groups and is then used to estimate the p-value for the data to determine if the results happened by random chance. Due to the small sample size of this study, the t-table is used to find the p-value. For this study, where the degrees of freedom are 4 and the confidence interval is 95% ($\alpha = 0.05$), the p-value is 2.132. The results for vehicle delay are in Table 17 below. For the Manual and Peak pedestrian volumes, the t-value is greater than the p-value indicating statistically significant results between signal control operations. There is no statistical significance to the ManualPlus vehicle delay results. The t-value for Peak is the greatest and indicates a stronger difference between the groups, or largest reduction in vehicle delay from implementing pedestrian recall.

Table 17 T-Test for Vehicle Delay

	Sim Run	Vehicle Delay Full Actuation	Vehicle Delay Ped Recall	T-Value
Manual Ped Volume	1	18.922	17.200	**2.520**
	2	19.362	18.244	
	3	20.102	18.583	
	4	20.812	18.929	
	5	19.956	19.954	
	Avg	19.841	18.593	
	StdDev	0.648	0.898	
ManualPlus Ped Volume	1	19.969	18.661	**1.898**
	2	21.071	18.389	
	3	18.708	19.817	
	4	22.812	20.084	
	5	20.665	19.830	
	Avg	20.650	19.364	
	StdDev	1.348	0.691	
Peak Ped Volume	1	21.276	19.851	**3.725**
	2	22.922	21.176	
	3	21.134	19.035	
	4	22.692	20.442	
	5	21.283	20.112	
	Avg	21.868	20.122	
	StdDev	0.777	0.703	

The current operations under full actuation were also compared for the Manual and ManualPlus volume scenarios. The impact of GRIDSMART operations is reflected in the ManualPlus pedestrian volume, so it is of interest to see if the increase in vehicle delay is statistically significant. Delay results for these scenarios are in Table 17 above, and the calculated t-value was -1.272. This value is not statistically significant for the sample size and 95% confidence interval. The negative impact of the detection errors cannot be confidently concluded, but there is no positive benefit from its implementation.

4.2 Pedestrian Delay

Pedestrian delay is difficult to measure due to the wide-ranging pedestrian behaviors, in addition to detection. As previously discussed, GRIDSMART is incapable of accurately counting pedestrians, but the video footage allows for some manual calculations. Previous research by Khoturi (9) has taken advantage of existing TSP infrastructure to measure pedestrian delay by marking timestamps when a pedestrian actuated a push-button and when the pedestrian phase was provided.

4.2.1 Manual Pedestrian Delay Results

For this case, pedestrians that were detected and false calls that were treated as random arrivals were analyzed. Pedestrians undetected were excluded from analysis. In total, there were 73 detections used in the analysis period. The time was recorded when a manual actuation was made or GRIDSMART detected them. The next time recorded was when the appropriate pedestrian phase was provided. Table 18 below shows an example of the manual pedestrian delay results with the full results in Appendix G.

Table 18 Pedestrian Delay from Automatic Detections

Detection Time	Time Ped Phase	Delay	Detection Time	Time Ped Phase	Delay	Detection Time	Time Ped Phase	Delay
15:04:40	15:04:53	00:13	15:21:29	15:21:34	00:05	15:38:53	15:39:22	00:29
15:05:21	15:05:52	00:31	15:23:53	15:24:54	01:01	15:41:43	15:42:02	00:19
15:08:00	15:08:22	00:22	15:24:34	15:25:40	01:06	15:44:59	15:45:07	00:08
15:14:11	15:15:07	00:56	15:26:31	15:26:38	00:07	15:45:15	15:45:50	00:35
15:21:29	15:22:14	00:45	15:29:08	15:29:09	00:01	15:46:21	15:46:38	00:17

Pedestrian delay was determined to be an average of 34 seconds for the data collected. The actual number will likely be lower after accounting for the pedestrians that experienced no delay. This value was compared to the simulation results for the fully actuated, Manual pedestrian volume model scenario. Overall pedestrian delay, or wait time, was 29.13 seconds for the simulation. The simulation model uses vehicle links and does not fully model pedestrians; however, it does not allow pedestrians to cross any time since they function as vehicles waiting at a signal head. Therefore, this provides a good model for "appropriate" pedestrian behavior and resulting delays.

4.2.2 Simulation Pedestrian Delay Results

The delay values for each crosswalk link were aggregated using a weighted average to find the overall pedestrian delay (18). Table 19 below shows results for pedestrian delay under each control operation for the Manual (low ped volume) and Peak (high ped volume) conditions.

Table 19 Pedestrian Delay Results

	Full Actuation		Ped Recall		Min Recall		Max Recall	
CRW	**Manual**	**Peak**	**Manual**	**Peak**	**Manual**	**Peak**	**Manual**	**Peak**
12	28.229	29.204	21.287	26.925	26.634	28.962	41.750	31.640
14	25.932	34.659	29.398	31.539	28.283	35.698	39.519	33.191
16	30.083	29.285	27.847	28.851	27.836	28.889	36.734	30.570
18	30.958	33.081	23.460	31.700	32.434	31.806	40.041	35.335
Overall	29.130	30.577	25.624	29.055	28.465	30.270	39.053	32.068

Pedestrian delay decreases under pedestrian recall for both low and high pedestrian volumes. This may be due to efficiency achieved serving pedestrians at the same time or serving more pedestrians under favorable conditions, such as arriving on the Walk interval. In terms of control strategies, max recall had the highest delay just as was the case with vehicle delay, and the analysis focused on full actuation vs. pedestrian recall. Compared to full actuation, delay decreases under pedestrian recall by 13.6% for the Manual volume and 5.2% for the Peak volume. The Peak volume under pedestrian recall results in the same delay as the low volume under full actuation. Full results for pedestrian delay are in Appendix G.

4.2.3 Pedestrian Delay T-Test

The overall pedestrian delay results for full actuation and pedestrian recall were compared using the Independent Sample T-Test to determine if there is any statistical significance to the results. The overall pedestrian delay for each of the five simulation runs and the standard deviation were calculated for each scenario. The t-value compares the difference between groups and is then used to estimate the p-value for the data to determine if the results happened by chance. Due to the small sample size of this study, the t-table is used to find the p-value. For this study, where the degrees of freedom are 4 and the confidence interval is 95% ($\alpha = 0.05$), the p-value is 2.132. In terms of pedestrian delay, the results are not statistically significant for the signal control operations. The results are summarized in Table 20 below.

The current operations under full actuation were also compared for the Manual and ManualPlus volume scenarios. The impact of GRIDSMART operations is reflected in the ManualPlus pedestrian volume, so it is of interest to see if the increase in pedestrian delay is statistically significant. Delay results for these scenarios are in Table 20, and the calculated t-value was -0.618. This value is not statistically significant for the sample size and 95% confidence interval. The negative impact of the detection errors cannot be confidently concluded, but there is no positive benefit to pedestrians from its implementation.

Table 20 T-Test for Pedestrian Delay

	Sim Run	Ped Delay Full Actuation	Ped Delay Ped Recall	T-Value
Manual Ped Volume	1	31.415	30.186	**1.225**
	2	24.011	23.643	
	3	33.578	18.230	
	4	22.666	27.054	
	5	34.107	28.002	
	Avg	29.130	25.624	
	StdDev	4.853	4.174	
ManualPlus Ped Volume	1	31.316	31.316	**1.373**
	2	35.093	35.093	
	3	29.067	29.067	
	4	30.836	30.836	
	5	25.781	25.781	
	Avg	30.715	28.241	
	StdDev	3.053	2.631	
Peak Ped Volume	1	28.593	31.288	**1.246**
	2	28.764	28.585	
	3	31.732	27.409	
	4	34.192	31.097	
	5	29.935	27.275	
	Avg	30.577	29.055	
	StdDev	2.099	1.747	

4.3 Ped Recall vs. Actuation

Simulation results indicate that operating under pedestrian recall will decrease vehicle delay for low pedestrian volumes as well as for high volumes. The manual counting data for pedestrians and the signal timing plan was used to validate these results according to the guidelines provided by Cesme et al. (3). Manual counting produced 121 pedestrians over the three-hour analysis period for 40.33 peds/hr. Assuming a maximum cycle time of 80 seconds, there are 45 cycles per hour which results in 0.896 peds/cycle. The maximum minor street green time is 26 seconds, and the pedestrian phase is 23 seconds for a green time ratio of 1.13. According to Figure 5 (3), these values confirm that pedestrian recall is the best operational strategy. The minor street is not a typical minor street in that it has comparable vehicle volumes to the major street and a 45% share of effective green time. The major street does not have a substantial crossing distance either, so a pedestrian phase can easily be incorporated into the vehicle phase without increasing delay. The 3-second advanced walk setting in use always incurs some vehicle delay, but it creates a 6-second window between the pedestrian phase and maximum vehicle phase where actuated operation provides flexibility. Pedestrian recall will not force the vehicle phase to max out, so any delay effects are minimized.

5.0 Conclusions

Automatic pedestrian detection can be useful to improve multi-modal service at an intersection, eliminating the need for ineffective pushbuttons and allowing actuated signals to operate at greater capacity. However, the benefits depend on the accuracy of the detection system and the specific conditions of the intersection. In this case, the intersection consists of two major arterials and fluctuating pedestrian activity due to its location in the Northeast.

Looking at the available data from GRIDSMART, there is an obvious decline in pedestrian activity from the August data to the January analysis period data, with vehicle volumes remaining similar. However, after analyzing video from the GRIDSMART detection system, it was clear that the detection software is incapable of providing accurate pedestrian counts with the SMARTCOUNT bell cameras. In terms of automatic actuation, the detection system worked well placing calls for waiting zone detections, but often resulted in a full cycle of pedestrian delay which encouraged risky crossings. Many pedestrians did not stop to allow detection which diminishes the returns from using automatic detection. Detection suffered in the night and rainy conditions, resulting in false calls that provided unnecessary pedestrian phases. These unnecessary phases and unused phases by non-compliant pedestrians reduce the benefits of automatic detection and slightly increased vehicle and pedestrian delays, although the results were not statistically significant. The detection system is not improving delay under current operations.

The simulation model validated that the intersection could operate under pedestrian recall without incurring vehicle delay at low pedestrian volumes. Pedestrian and vehicle delay decreased under pedestrian recall for both low and high pedestrian volumes. The minor street vehicle demand is sufficient to accommodate the pedestrian phase within its green time. This will allow consistent operations without pushbuttons that removes decision-making by the pedestrian or an expensive detection system that can be prone to errors. Pedestrian recall has also been shown to increase pedestrian safety by providing pedestrian phases in every phase and eliminating any full cycle delay times that increase risky crossing.

GRIDSMART is continuously working to improve its products and the pedestrian detection features are a recent addition to the suite of offerings. The inability to accurately count pedestrians is a significant drawback to the product. There were many other errors and technical issues throughout the system that question the ease of use that is advertised. Future use of GRIDSMART products may be warranted at better-suited intersections or after improvements to the software are made, but it does not appear to provide any benefits to this specific intersection.

Further studies are recommended to analyze GRIDSMART or similar detection products in more depth. The small scope of this study limited analysis of pedestrian activity to three hours in sub-optimal, winter conditions. A longer study during higher pedestrian activity periods would provide a better understanding of the accuracy of detection and effects to signal operation. Taking this research further, open-source detection algorithms could be used to validate the pedestrian and vehicle counts from the available video.

Studying pedestrian detection at multiple locations and camera positions would provide insight into how to best implement advanced detection. Developments in detection algorithms based on walking behavior have been made which may allow for improvements in GRIDSMART detection, or as part of separate product development. The sooner a pedestrian is identified as needing to cross, the more effective the detection system can be in terms of signal control. Also, weight or vibration sensors could be studied in use at the wait zones for pedestrians. This could provide more accurate counting but also identify the number of pedestrians, as well as identify if actuations are coming from the same pedestrian shifting in the wait zone. This could limit the extra phases provided from multiple actuations or from non-compliant pedestrians that have left the wait zone and will not be using the called for pedestrian phase.

Pedestrian compliance was very poor during the analysis period, so a study focusing on pedestrian behavior under different signal control strategies should be considered to validate the assertion that pedestrian recall increases compliance and safety without intolerable delay effects. Also, a study to validate the vehicle counts at the subject intersection should be considered to calibrate the VISSIM model and determine if there is a more optimal cycle length.

Appendix A Signal Timing Plans

Table 21 LibertyAve /40th Street Timing Plan

Cycle	Signal Length	Offset 1	Offset 2	Offset 3	Offset 4
A	60	59	0	0	0
B	80	46	0	0	0
C	80	41	48	0	0
D	0	0	0	0	0

Step	Time	Signal Days	Function
1	06:00 - 10:00	Mon - Sat	B - OFF 1 (PG1 PL4)
2	10:00 - 14:30	Mon - Sat	C - OFF 1 (PG2 PL7)
3	14:30 - 21:00	Mon - Sat	C - OFF 1 (PG2 PL7)
4	21:00 - 00:00	Sun - Sat	A - OFF 1 (PG1 PL1)
5	00:00 - 06:00	Sun - Sat	A - OFF 1 FLASH
6	06:00	Sun	A - OFF (PG1 PL1)
7	Kentron	Kentron	Kentron 170E

Cycle Int	A	B	C	D
1	30	40	46	0
2	3.5	3.5	3.5	0
3	2	2	2	0
4	19	29	23	0
5	3.5	3.5	3.5	0
6	2	2	2	0

*Cycle C (80s) is under operation during the PM peak period relevant to analysis

Table 22 Penn Ave/Main Street Timing Plan

D + C + 0 + Key			D + C + Phase + Key					Phase				
FUNCTION	KEY	12345678	FUNCTION	KEY	Ph 1	Ph 2	Ph 3	Ph 4	Ph 5	Ph 6	Ph 7	Ph 8
Vehicle Recall	0	1	Max I	0	10	32	0	22	0	32	0	22
Ped Recall	1	2 4 6 8	Max II/HFDW	1	0	0	0	0	0	0	0	0
Red Lock	2		Walk	2	0	17	0	6	0	17	0	6
Yellow Lock	3	2 4 6 8	Flashing DW	3	0	15	0	13	0	15	0	13
Permits	4	12 4 6 8	Max Initial	4	0	0	0	0	0	0	0	0
Ped Phases	5	2 4 6 8	Min Green	5	6	10	0	10	0	10	0	10
Lead Phases	6	1 3 5 7	TBR	6	0	0	0	0	0	0	0	0
Double Entry	7	4 8	TTR	7	0	0	0	0	0	0	0	0
Sequential Timing	8		Observe Gap	8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Startup Green	9	2 6	Passage	9	0.0	3.0	0.0	3.0	0.0	3.0	0.0	3.0
Overlap A	A		Min Gap	A	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Overlap B	B		Added Actuation	B	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Overlap C	C		Yellow	C	3.0	3.0	0.0	3.0	0.0	3.0	0.0	3.0
Overlap D	D		Red Clear	D	1.0	3.0	0.0	3.0	0.0	3.0	0.0	3.0
Exclusive	E		Red Revert	E	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Simultaneous Gap	F		Walk II	F	0	0	0	3	0	0	0	3

Table 23 Penn Ave/44th Street Timing Plan

D + C + 0 + Key			D + C + Phase + Key					Phase				
FUNCTION	KEY	12345678	FUNCTION	KEY	Ph 1	Ph 2	Ph 3	Ph 4	Ph 5	Ph 6	Ph 7	Ph 8
Vehicle Recall	0	23 6	Max I	0	10	31	0	25	0	31	0	0
Ped Recall	1	2	Max II/HFDW	1	0	0	0	0	0	0	0	0
Red Lock	2		Walk	2	0	16	0	7	0	0	0	0
Yellow Lock	3		Flashing DW	3	0	15	0	15	0	0	0	0
Permits	4	12 4 6	Max Initial	4	0	0	0	0	0	0	0	0
Ped Phases	5	2 4	Min Green	5	2	10	0	10	0	10	0	0
Lead Phases	6	1 3 5 7	TBR	6	0	0	0	10	0	0	0	0
Double Entry	7		TTR	7	0	0	0	10	0	0	0	0
Sequential Timing	8		Observe Gap	8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Startup Green	9	2 6	Passage	9	2.0	2.0	0.0	2.0	0.0	2.0	0.0	0.0
Overlap A	A		Min Gap	A	1.0	1.0	0.0	2.0	0.0	1.0	0.0	0.0
Overlap B	B		Added Actuation	B	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Overlap C	C		Yellow	C	3.0	3.0	0.0	3.0	0.0	3.0	0.0	0.0
Overlap D	D		Red Clear	D	1.0	2.0	0.0	2.0	0.0	2.0	0.0	0.0
Exclusive	E		Red Revert	E	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Simultaneous Gap	F		Walk II	F	0	0	0	3	0	0	0	0

Table 24 Penn Ave/45th Street/Friendship Ave Timing Plan

D + C + 0 + Key			D + C + Phase + Key					Phase				
FUNCTION	KEY	12345678	FUNCTION	KEY	Ph 1	Ph 2	Ph 3	Ph 4	Ph 5	Ph 6	Ph 7	Ph 8
Vehicle Recall	0	2 4 6 8	Max I	0	10	31	0	25	0	31	0	25
Ped Recall	1	2 4 6 8	Max II/HFDW	1	0	0	0	0	0	0	0	0
Red Lock	2		Walk	2	0	16	0	7	0	16	0	7
Yellow Lock	3		Flashing DW	3	0	15	0	15	0	15	0	15
Permits	4	12 4 6 8	Max Initial	4	0	0	0	0	0	0	0	0
Ped Phases	5	2 4 6 8	Min Green	5	4	10	0	10	0	10	0	10
Lead Phases	6	1 3 5 7	TBR	6	0	0	0	0	0	0	0	0
Double Entry	7	4 8	TTR	7	0	0	0	0	0	0	0	0
Sequential Timing	8		Observe Gap	8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Startup Green	9	2 6	Passage	9	2.0	3.0	0.0	3.0	0.0	3.0	0.0	3.0
Overlap A	A		Min Gap	A	2.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Overlap B	B		Added Actuation	B	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Overlap C	C		Yellow	C	3.0	3.0	0.0	3.0	0.0	3.0	0.0	3.0
Overlap D	D		Red Clear	D	1.0	2.0	0.0	2.0	0.0	2.0	0.0	2.0
Exclusive	E		Red Revert	E	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Simultaneous Gap	F		Walk II	F	0	0	0	3	0	0	0	3

Appendix B GRIDSMART Vehicle and Pedestrian Peak Hour Data

Table 25 Peak Hour Analysis from GRIDSMART Data

Date	Peak Hour	Peak Hour Volume	Peak 15 Minute Volume	PHF	Ped Volume (Peak Hour)	Date	Peak Hour	Peak Hour Volume	Peak 15 Minute Volume	PHF	Ped Volume (Peak Hour)
8/2/2021	1630-1730	1315	352	0.934	294	9/8/2021	1630-1730	1271	353	0.900	370
8/3/2021	**1645-1745**	**1426**	**369**	**0.966**	**546**	9/9/2021	1500-1600	1250	333	0.938	324
8/4/2021	1630-1730	1432	382	0.937	399	9/10/2021	1515-1615	1287	330	0.975	450
8/5/2021	1630-1730	1372	355	0.966	348	9/13/2021	1545-1645	1263	343	0.921	562
8/6/2021	1600-1700	1361	365	0.932	277	9/14/2021	1630-1730	1261	356	0.886	388
8/9/2021	1630-1730	1290	333	0.968	250	9/15/2021	1645-1745	1347	373	0.903	370
8/10/2021	1545-1645	1369	348	0.983	244	9/16/2021	1600-1700	1395	362	0.963	458
8/11/2021	1630-1730	1327	347	0.956	256	9/17/2021	1500-1600	1294	331	0.977	350
8/12/2021	1645-1745	1348	343	0.983	282	9/20/2021	1630-1730	1217	308	0.988	345
8/13/2021	1800-1900	1343	361	0.930	308	9/21/2021	1630-1730	1386	354	0.979	463
8/16/2021	1630-1730	1286	343	0.937	233	9/22/2021	1530-1630	1292	337	0.958	502
8/17/2021	1615-1715	1350	358	0.943	376	9/23/2021	1630-1730	1434	367	0.977	377
8/18/2021	1645-1745	1210	322	0.939	360	9/24/2021	1500-1600	1292	337	0.958	371
8/19/2021	1730-1830	1389	355	0.978	383	9/27/2021	1630-1730	1285	339	0.948	240
8/20/2021	1545-1645	1258	352	0.893	303	9/28/2021	1630-1730	1277	328	0.973	366
8/23/2021	1630-1730	1193	321	0.929	247	9/29/2021	1545-1645	1203	311	0.967	451
8/24/2021	1630-1730	1204	310	0.971	259	9/30/2021	1630-1730	1354	356	0.951	416
8/25/2021	1630-1730	1324	355	0.932	359	1/4/2022	1415-1515	1199	322	0.931	90

Table 25 continued

Date	Peak Hour	Peak Hour Volume	Peak 15 Minute Volume	PHF	Ped Volume (Peak Hour)	Date	Peak Hour	Peak Hour Volume	Peak 15 Minute Volume	PHF	Ped Volume (Peak Hour)
8/26/2021	1630-1730	1344	368	0.913	296	1/5/2022	1630-1730	1201	310	0.969	122
8/27/2021	1545-1645	1237	321	0.963	300	**1/6/2022**	**1530-1630**	**1305**	**359**	**0.909**	**150**
8/30/2021	1615-1715	1266	334	0.948	354	1/11/2022	1630-1730	1187	309	0.960	93
8/31/2021	1645-1745	1384	368	0.940	416	1/12/2022	1530-1630	1284	354	0.907	197
9/1/2021	1615-1715	1281	325	0.985	285	1/13/2022	1615-1715	1255	320	0.980	168
9/2/2021	1645-1745	1203	348	0.864	379	1/18/2022	1645-1745	1037	276	0.939	84
9/3/2021	1430-1530	1397	384	0.910	255	1/19/2022	1600-1700	1215	313	0.970	79
9/6/2021	1415-1515	869	247	0.880	190	1/20/2022	1545-1645	1235	332	0.930	121
9/7/2021	1630-1730	1255	323	0.971	377						

Appendix C 15-Minute Turning Movement Counts

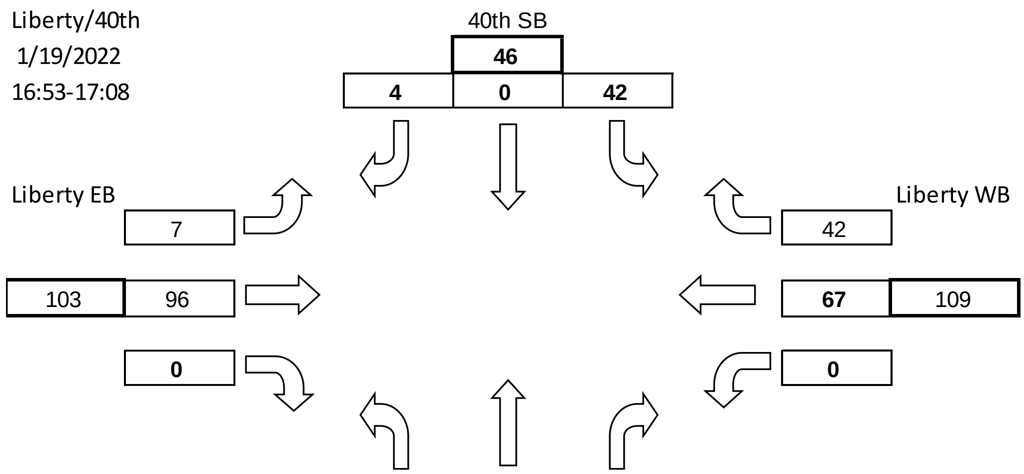


Figure 53 Liberty/40th Vehicle Counts 1/19/22

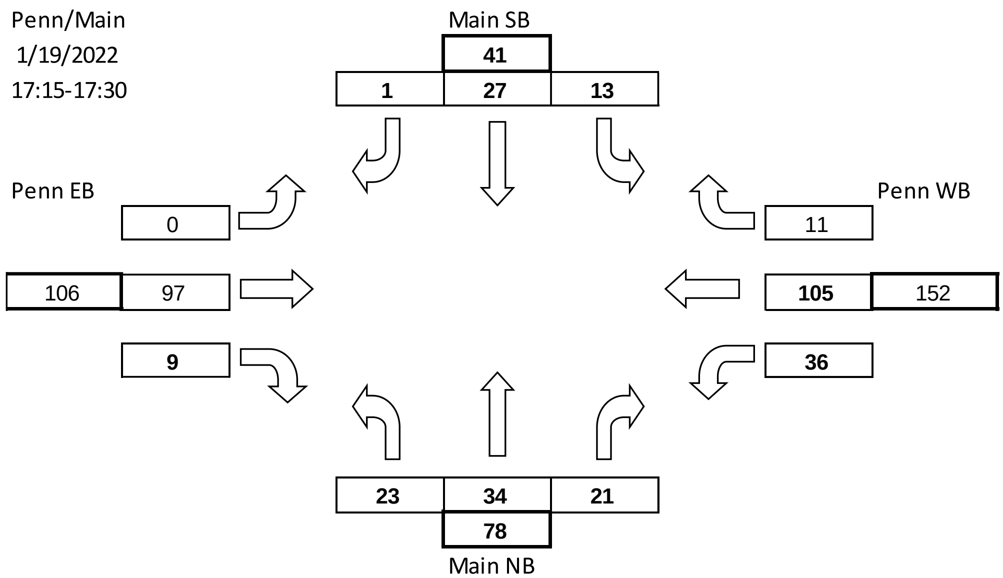


Figure 54 Penn/Main Vehicle Counts 1/19/22

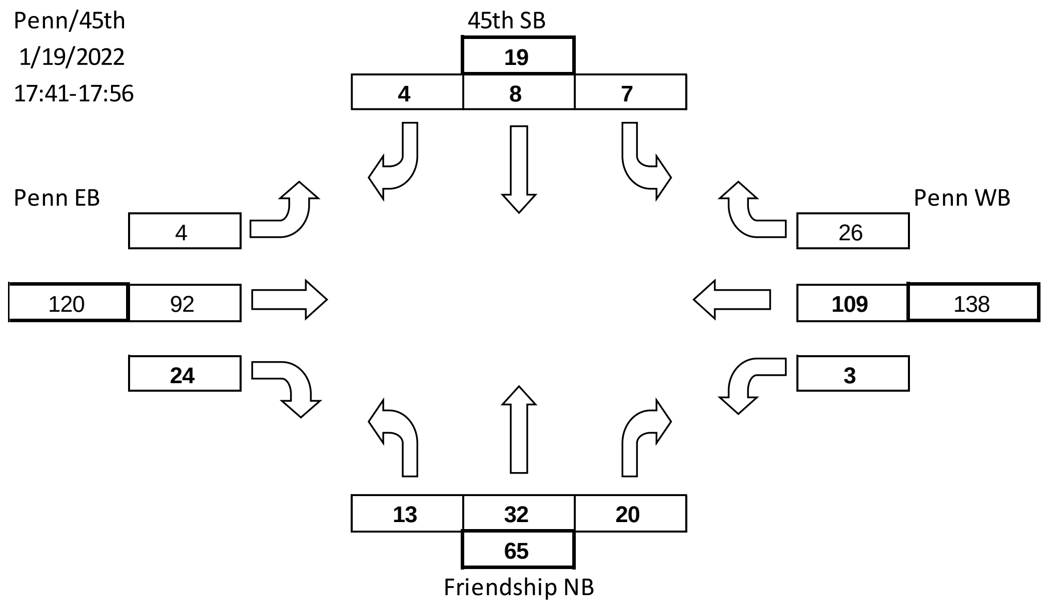


Figure 55 Penn/45th Vehicle Counts 1/19/22

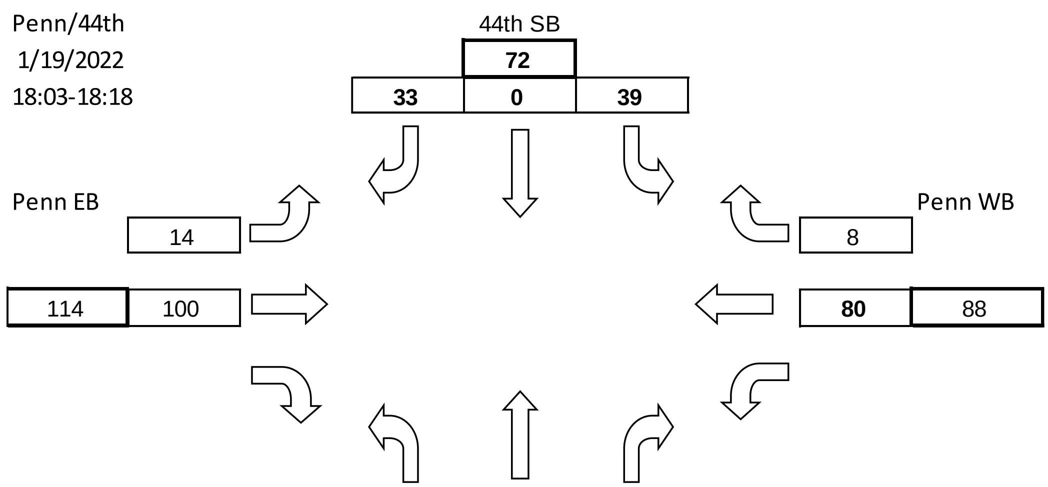


Figure 56 Penn/44th Vehicle Counts 1/19/22

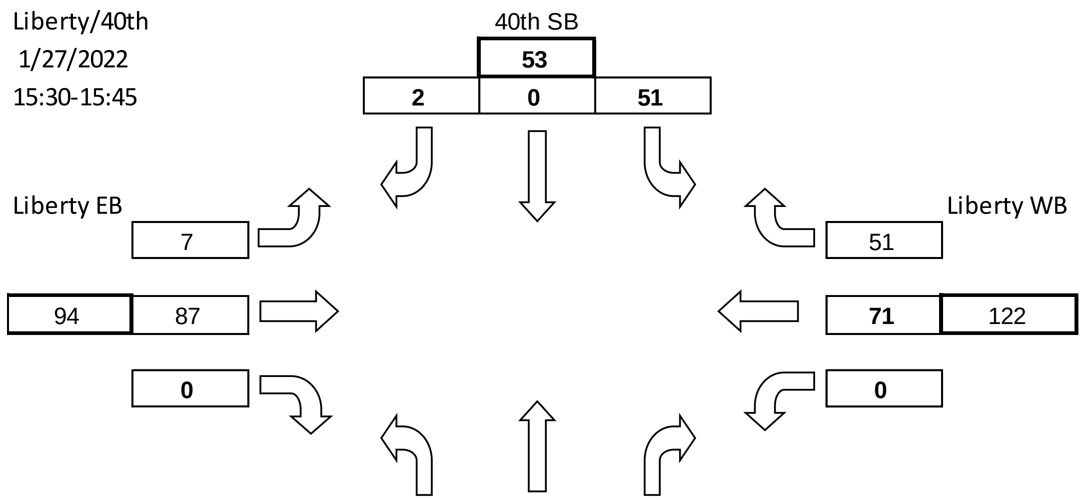


Figure 57 Liberty/40th Vehicle Counts 1/27/22

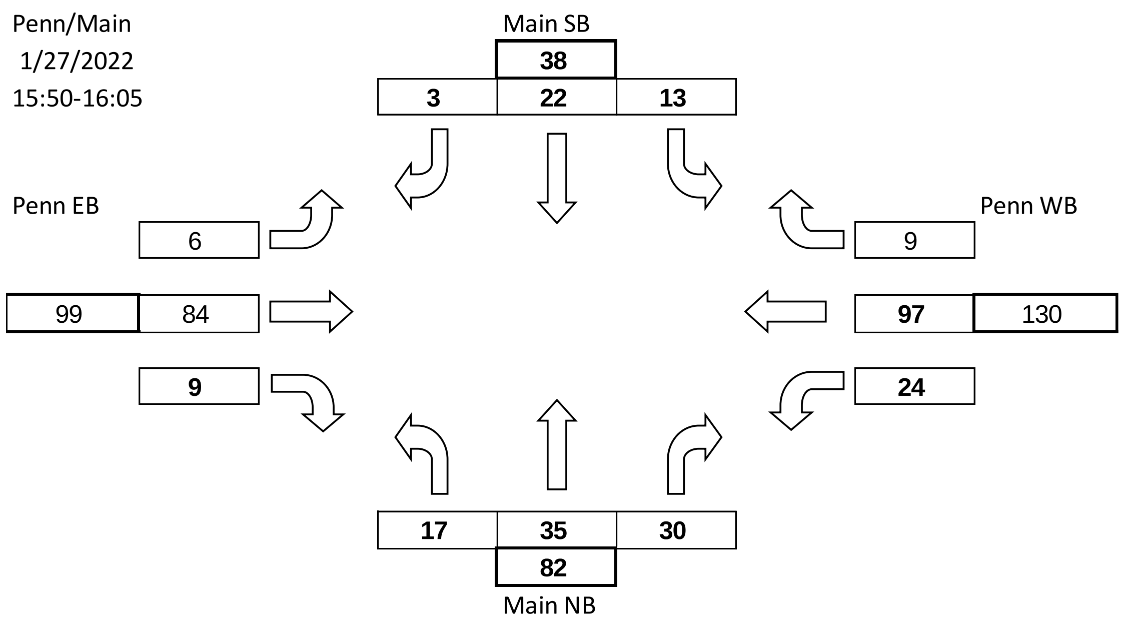


Figure 58 Penn/Main Vehicle Counts 1/27/22

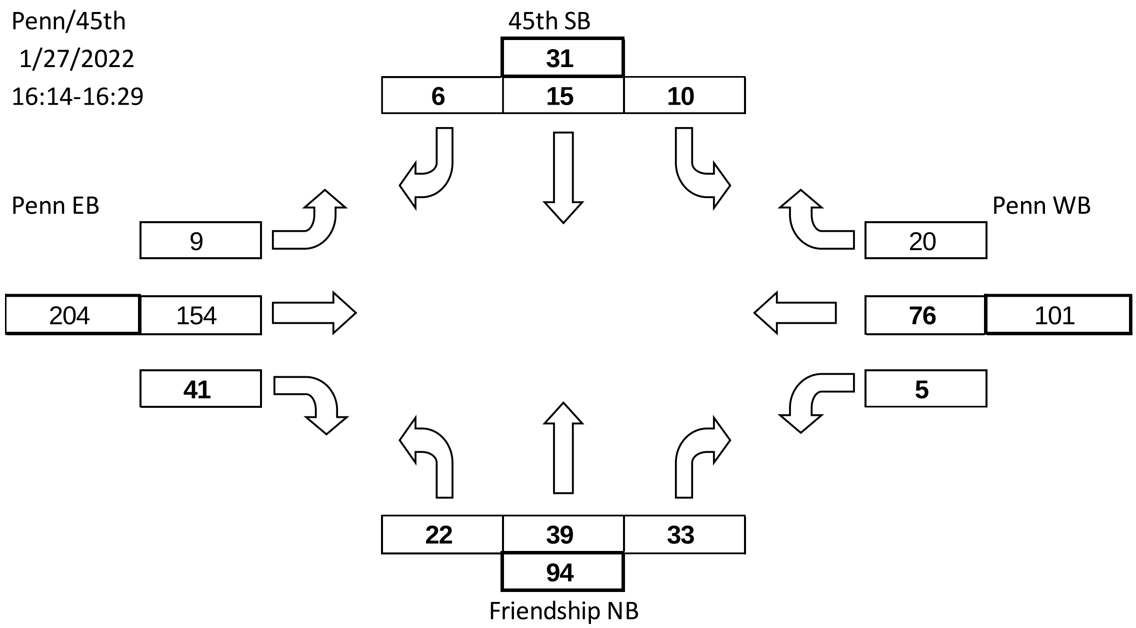


Figure 59 Penn/45th Vehicle Counts 1/27/22

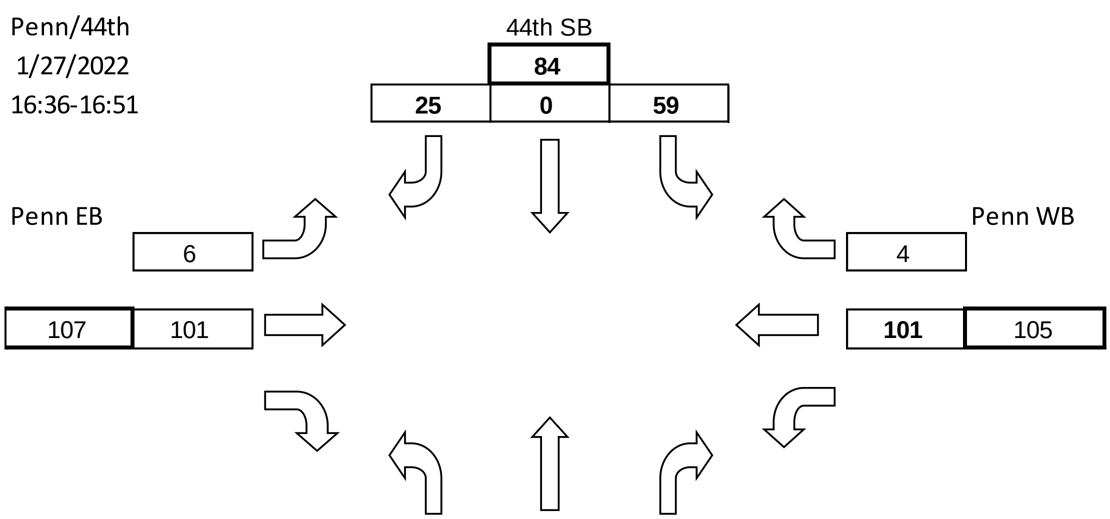


Figure 60 Penn/44th Vehicle Counts 1/27/22

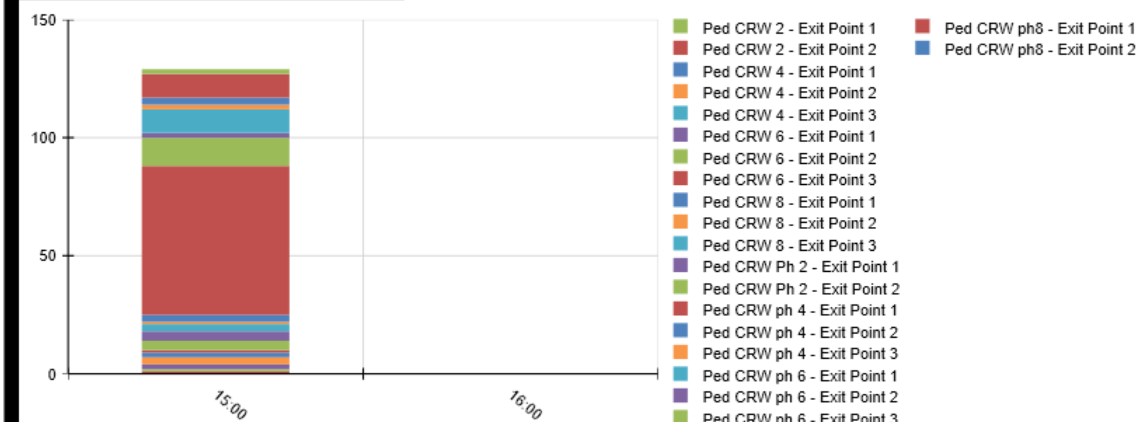
Appendix D Pedestrian Count Validation

GRIDSMART

Pedestrian Crosswalk Counts

Intersection Penn Ave & 40th st
Date 1/6/2022

	Exit Point 1	Exit Point 2	Exit Point 3	Total
Ped CRW 2	2	10		12
Ped CRW 4	3	2	10	15
Ped CRW 6	2	12	63	77
Ped CRW 8	3	1	3	7
Ped CRW Ph 2	4	4		8
Ped CRW ph 4	1	2	3	6
Ped CRW ph 6		2	1	3
Ped CRW ph8	1			1
Total	**16**	**33**	**80**	**129**



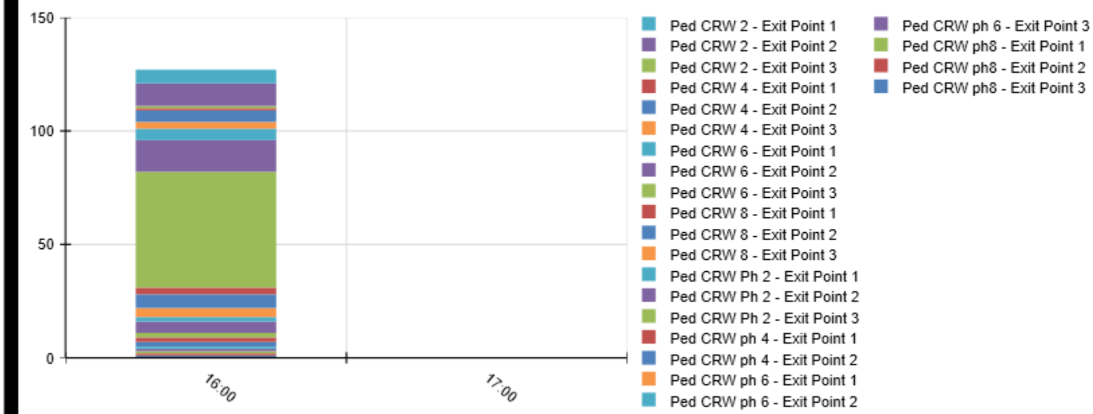
	Ped CRW 2		Ped CRW 4			Ped CRW 6			Ped CRW 8			Ped CRW Ph		Ped CRW ph 4			Ped CRW ph 6			Ped CRW ph8	
	Exit	Exit	Exit	Exit	Exit	Exit	Exit	Exit	Exit	Exit	Exit	Exit	Exit	Exit	Exit	Exit	Exit	Exit	Exit	Exit	Exit
15:00	2	10	3	2	10	2	12	63	3	1	3	4	4	1	2	3		2	1	1	
16:00																					
Total	**2**	**10**	**3**	**2**	**10**	**2**	**12**	**63**	**3**	**1**	**3**	**4**	**4**	**1**	**2**	**3**		**2**	**1**	**1**	

Figure 61 GRIDSMART Ped Count 1500-1600

GRIDSMART Pedestrian Crosswalk Counts

Intersection Penn Ave & 40th st
Date 1/6/2022

	Exit Point 1	Exit Point 2	Exit Point 3	Total
Ped CRW 2	6	10	1	17
Ped CRW 4	1	5	3	9
Ped CRW 6	5	14	51	70
Ped CRW 8	3	6	4	13
Ped CRW Ph 2	2	5	2	9
Ped CRW ph 4	2	2		4
Ped CRW ph 6		1	1	2
Ped CRW ph8	1	1	1	3
Total	**20**	**44**	**63**	**127**



	Ped CRW 2			Ped CRW 4			Ped CRW 6			Ped CRW 8			Ped CRW Ph 2			Ped CRW ph		Ped CRW ph 6			Ped CRW ph8		
	Exit	Exit	Exit	Exit	Exit	Exit	Exit	Exit	Exit	Exit	Exit	Exit	Exit	Exit	Exit	Exit	Exit	Exit	Exit	Exit	Exit	Exit	Exit
00:00	6	10	1	1	5	3	5	14	51	3	6	4	2	5	2	2	2		1	1	1	1	1
17:00																							
Total	**6**	**10**	**1**	**1**	**5**	**3**	**5**	**14**	**51**	**3**	**6**	**4**	**2**	**5**	**2**	**2**	**2**		**1**	**1**	**1**	**1**	**1**

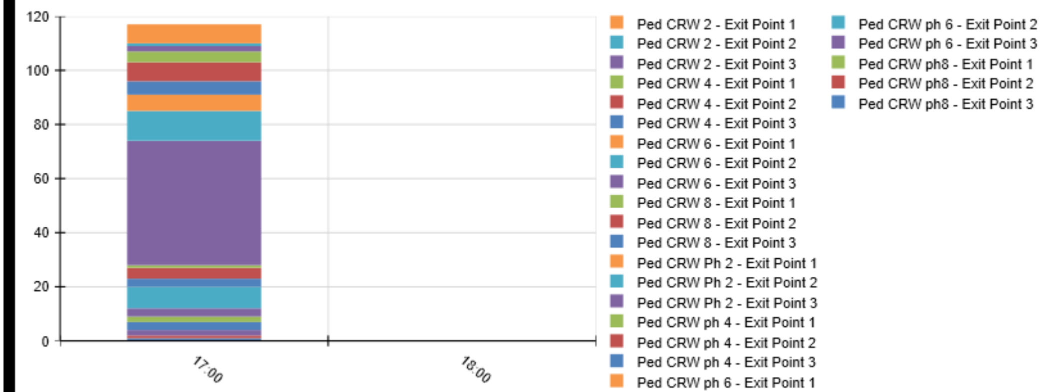
Figure 62 GRIDSMART Ped Count 1600-1700

GRIDSMART

Pedestrian Crosswalk Counts

Intersection Penn Ave & 40th st
Date 1/6/2022

	Exit Point 1	Exit Point 2	Exit Point 3	Total
Ped CRW 2	7	1	2	10
Ped CRW 4	4	7	5	16
Ped CRW 6	6	11	46	63
Ped CRW 8	1	4	3	8
Ped CRW Ph 2		8	3	11
Ped CRW ph 4	2		3	5
Ped CRW ph 6			2	2
Ped CRW ph8		1	1	2
Total	**20**	**32**	**65**	**117**



	Ped CRW 2			Ped CRW 4			Ped CRW 6			Ped CRW 8			Ped CRW Ph 2			Ped CRW ph 4			Ped CRW ph 6			Ped CRW ph8		
	Exit	Exit	Exit	Exit	Exit	Exit	Exit	Exit	Exit	Exit	Exit	Exit	Exit	Exit	Exit	Exit	Exit	Exit	Exit	Exit	Exit	Exit	Exit	Exit
00:00	7	1	2	4	7	5	6	11	46	1	4	3		8	3	2		3			2		1	1
18:00																								
Total	**7**	**1**	**2**	**4**	**7**	**5**	**6**	**11**	**46**	**1**	**4**	**3**		**8**	**3**	**2**		**3**			**2**		**1**	**1**

Figure 63 GRIDSMART Ped Count 1700-1800

Appendix E Pedestrian Phase Analysis

Table 26 Unused Pedestrian Phases

Time	Ped Phase	Reason
15:01:22	15	Manual Call - Ped crossed immediately during all-red
15:04:59	15	Auto Call - 2 Peds crossed during all-red
15:08:22	15	False Call - Large shuttle bus incorrectly detected
15:15:07	15	False Call - Ped accessing nursing home. Call made during Phase 2. Provided ped phase during next cycle Phase 2.
15:21:34	13/15	Auto Call - 2 peds waiting to cross using 14 and 16. Provided 13 and 15 in next phase.
15:23:01	15	Auto Call - Ped phase provided after ped used Ped Phase 14 correctly. Unclear why it was given when Ped Phase 15 was already provided based on this ped detection
15:24:14	15	Manual Ped call during Phase 4. Ped crossed 14 without ped phase and then continued through 13 during all-red. Ped Phase 15 provided during next vehicle phase. Ped Phase 14 provided during next vehicle phase. Ped already well past intersection
15:24:55	14	
15:27:50	*15*	*False Call - Ped accessing nursing home after crossing 15 during Phase 2. Provided Ped Phase 15 during next cycle Phase 2. Separate ped used 13 (not given) while Ped Phase 15 was active.*
15:35:28	15	False Call - Ped accessing nursing home. Call made during all-red.
15:36:40	15	Auto Call - Ped left wait zone and did not cross.
15:40:39	15	Unclear where ped call came from. No detection seen or pedestrians in area.
15:45:50	14	Auto Call - Ped detection. Ped crossed during Phase 2 illegally. Ped through intersection before Phase 4 but ped phase provided anyway.
15:50:39	14	Manual and Auto Call - 2 Peds used Ped Phase 15 provided. Ped Phase 14 followed in next vehicle phase but peds already through intersection
15:53:54	16	Auto Call - Ped waiting to cross 16. Ped crossed 16 during all-red after Phase 2. Ped Phase 16 provided during Phase 4.
15:55:19	13	Unclear where ped call came from. No detection seen or pedestrians in area. Previous cycle provided Ped Phase 13 from detection correctly.
16:03:06	15	Manual Call - Call made in Phase 2. Ped crossed immediately and Ped Phase 15 provided during next cycle Phase 2.
16:06:55	13	Unclear where ped call came from. No detection seen or pedestrians in area. Previous cycle provided Ped Phase 13 followed by Ped Phase 16 from detection.
16:19:02	13	Unclear where ped call came from. Previous cycle provided Ped Phase 13 correctly. Ped Phase 13 provided during next cycle Phase 2.
16:22:57	15	Auto Call - Ped waiting to cross 16 during Phase 4. Ped Phase 15 provided during next vehicle phase 2.
16:28:07	15	Auto and Manual Call - Ped detected during Phase 2. Ped made Manual Call and used Ped Phase 16 during next Phase 4. Ped Phase 15 provided during next cycle Phase 2 despite no ped presence.
16:33:55	13	Auto Call - Ped Phase 13 provided during previous cycle from detection. Ped used Ped Phase 16 correctly during next Phase 4. Ped Phase 13 provided again during next vehicle phase 2 despite no ped presence.
16:35:24	13/15	Auto Call - 2 Peds during Phase 2 that crossed immediately. False Call for 13 during same phase. Ped Phase 13 and 15 provided during next cycle Phase 2 despite no ped presence.

Table 26 continued

Time	Ped Phase	Reason
16:38:45	13	Auto Call - Ped during Phase 2. Ped crossed immediately. Provided Ped Phase 13 during next cycle Phase 2 despite no ped presence.
16:40:44	13	Manual Call - Call made during permissive Phase 2. Ped crossed immediately during all-red. Provided Ped Phase 13 during next cycle Phase 2.
16:43:08	*13*	*Auto Call - Ped below detected after manual call. Ped Phase 13 provided during next vehicle Phase 2. Another ped crossed during Ped Phase 13 DW.*
16:43:47	14	Manual Call - Ped waiting to use 14 made call during all-red. Crossed after Phase 2 during all-red before Ped Phase 14 provided during Phase 4.
16:44:35	13	Unclear where ped call came from. No detection seen or pedestrians in area. Previous cycle provided Ped Phase 13 from detection correctly.
16:46:03	13	Auto Call - Call made during Phase 4. Ped crossed during all-red. Provided Ped phase 13 during next vehicle phase 2.
16:50:15	15	False Call - Ped accessing nursing home. Call made during Phase 2. Provided ped phase during next cycle Phase 2.
17:00:03	13	Auto and Manual Call - Ped waiting to cross 16 during all-red. Provided Ped Phase 13 during next vehicle phase 2. Ped made Manual Call and crossed during next vehicle phase 4.
17:04:51	13	Auto and Manual Call - Ped waiting to cross 16 during Phase 4. Provided Ped Phase 13 during next vehicle phase 2. Ped made 2 Manual Calls and crossed during next vehicle phase 4.
17:06:04	13/15	False Call - Previous ped detected exiting 16 during Phase 4. Ped Phase 13 and 15 provided during next Phase 2.
17:08:38	15	False Call - Multiple detection errors provided Ped Phase 15 for multiple cycles.
17:09:47	15	
17:11:12	13	False Call - Detection error during Phase 2. Provided Ped Phase 13 during next cycle Phase 2.
17:18:39	15	Auto Call - Call made during Phase 2. Ped crossed immediately. Ped Phase 15 provided during next cycle Phase 2.
	13	False Call - Detection error during Phase 4. Provided Ped Phase 13 during next vehicle phase 2.
17:20:07	13	False Call - Detection error during Phase 4. Provided Ped Phase 13 during next vehicle phase 2.
17:22:17	13	Auto Call - Call made during Phase 4. Ped incorrectly crossed 13 immediately. Ped Phase 13 provided during next vehicle phase 2.
17:25:07	13	Manual Call - Ped waiting to cross 14 during Phase 2. Ped crossed during Ped Phase 14 during next Phase 4. Ped Phase 13 provided during next cycle Phase 2 despite no ped presence.
17:27:45	13	False Call - Multiple detection errors during Phase 4. Provided Ped Phase 13 during next vehicle phase 2.
	15	False Call - Detection error during Phase 2. Provided Ped Phase 15 during next cycle Phase 2.
RAIN STARTS		
17:30:30	13	False Call- Multiple detection errors during Phase 4. Provided Ped Phase 13 during next vehicle phase 2.
17:32:01	13	False Call - Detection error during Phase 4. Provided Ped Phase 13 during next vehicle phase 2.
	15	Auto and Manual Call- Ped waiting to cross 14 during Phase 2. Ped made manual call during next Phase 2 after Ped Phase 14 not provided. Ped Phase 14 provided during next Phase 4. Ped Phase 15 provided during next Phase 2.
17:34:33	13	False Call - Multiple detection errors during Phase 2 and Phase 4. Provided Ped Phase 13 during next cycle Phase 2.
17:37:20	15	Unclear where ped call came from. No detection seen or pedestrians in area. Previous cycle provided Ped Phase 15 correctly from detection.
17:44:30	15	False Call - Ped paused near wait zone during Phase 4. Another ped across the street made Manual Call to cross 14 during Phase 4. Provided Ped Phase 15 during next Phase 2. Could have been from either call.
17:45:41	15	Unclear where ped call came from. Previous ped crossed 14 correctly during Phase 4. Provided Ped Phase 15 during next Phase 2.
17:59:20	13	False Call - Detection error during Phase 4. Provided Ped Phase 13 during next vehicle phase 2.

Appendix F Vehicle Delay Results

Table 27 GEH Statisic Calculation for Network Movements

Penn/Main	SIM	FIELD	GEH	Penn/ 45th	SIM	FIELD	GEH
EB LEFT	32	26	1.114	EB LEFT	35	33	0.343
EB RIGHT	36	39	0.490	EB THRU	509	562	2.290
EB THRU	326	364	2.046	EB RIGHT	153	150	0.244
SB RIGHT	12	13	0.283	NB LEFT	82	88	0.651
SB THRU	93	95	0.206	NB THRU	173	156	1.325
SB LEFT	52	56	0.544	NB RIGHT	119	132	1.160
NB LEFT	52	68	2.066	WB THRU	403	415	0.593
NB THRU	125	139	1.219	WB RIGHT	116	109	0.660
NB RIGHT	116	119	0.277	WB LEFT	29	28	0.187
WB THRU	442	453	0.520	SB RIGHT	24	24	0.000
WB RIGHT	35	42	1.128	SB THRU	65	60	0.632
WB LEFT	109	112	0.285	SB LEFT	51	40	1.631
Penn/44th	**SIM**	**FIELD**	**GEH**	**Liberty/40th**	**SIM**	**FIELD**	**GEH**
EB THRU	468	509	1.855	SB RIGHT	6	6	0.000
EB LEFT	21	30	1.782	SB LEFT	135	160	2.058
WB RIGHT	13	20	1.723	EB LEFT	49	46	0.435
WB THRU	491	507	0.716	EB THRU	616	572	1.805
SB LEFT	231	236	0.327	WB RIGHT	278	273	0.301
SB RIGHT	96	100	0.404	WB THRU	346	381	1.836

Table 28 Vehicle Delay Results for Manual Pedestrian Volume

Manual Ped Volume	Full Actuation			Ped Recall			Min Recall			Max Recall		
	Total Sim Volume	Avg Sim VPH	Avg Delay	Total Sim Volume	Avg Sim VPH	Avg Delay	Total Sim Volume	Avg Sim VPH	Avg Delay	Total Sim Volume	Avg Sim VPH	Avg Delay
NB LEFT	404	80.8	20.844	406	81.2	19.216	407	81.4	21.084	409	81.8	18.263
NB RIGHT	215	43	25.919	216	43.2	17.114	218	43.6	24.658	220	44	22.132
NB THRU	994	198.8	24.117	989	197.8	17.931	992	198.4	23.158	998	199.6	21.126
WB THRU	1555	311	17.033	1554	310.8	17.043	1551	310.2	17.573	1548	309.6	24.495
WB LEFT	104	20.8	23.323	103	20.6	22.925	104	20.8	25.833	103	20.6	34.373
WB RIGHT	1020	204	16.367	1022	204.4	17.928	1022	204.4	17.876	1020	204	22.034
EB THRU	1028	205.6	15.447	1026	205.2	17.196	1030	206	16.228	1022	204.4	21.010
EB RIGHT	137	27.4	14.416	136	27.2	15.193	137	27.4	15.721	136	27.2	20.041
EB LEFT	26	5.2	22.388	26	5.2	14.490	26	5.2	15.018	26	5.2	26.498
SB RIGHT	296	59.2	19.695	300	60	17.232	297	59.4	20.375	300	60	25.517
SB LEFT	893	178.6	27.061	889	177.8	25.987	891	178.2	26.199	892	178.4	27.541
SB THRU	564	112.8	20.506	562	112.4	17.175	561	112.2	19.924	570	114	25.338
APPROACH	NB	322.6	23.538		322.2	18.145		323.4	22.838		325.4	20.542
	WB	535.8	17.024		535.8	17.607		535.4	18.009		534.2	23.936
	EB	238.2	15.480		237.6	16.908		238.6	16.143		236.8	21.019
	SB	350.6	23.708		350.2	21.659		349.8	23.197		352.4	26.484
	Intersection	1447.2	19.841		1445.8	18.593		1447.2	20.035		1448.8	23.317

Table 29 Vehicle Delay Results for ManualPlus Pedestrian Volume

ManualPlus Ped Volume	Full Actuation			Ped Recall			Min Recall			Max Recall		
	Total Sim Volume	Avg Sim VPH	Avg Delay	Total Sim Volume	Avg Sim VPH	Avg Delay	Total Sim Volume	Avg Sim VPH	Avg Delay	Total Sim Volume	Avg Sim VPH	Avg Delay
NB LEFT	404	80.8	20.006	406	81.2	21.288	406	81.2	20.683	410	82	17.999
NB RIGHT	213	42.6	28.201	216	43.2	20.208	217	43.4	29.068	220	44	22.147
NB THRU	979	195.8	25.668	991	198.2	19.176	988	197.6	25.652	998	199.6	20.653
WB THRU	1566	313.2	17.293	1554	310.8	17.755	1563	312.6	16.476	1548	309.6	24.522
WB LEFT	106	21.2	25.382	103	20.6	25.278	105	21	22.839	103	20.6	35.039
WB RIGHT	1020	204	18.111	1026	205.2	18.799	1020	204	17.509	1020	204	22.564
EB THRU	1036	207.2	15.564	1030	206	16.649	1029	205.8	15.868	1022	204.4	21.021
EB RIGHT	137	27.4	13.573	136	27.2	15.927	137	27.4	14.916	136	27.2	20.286
EB LEFT	26	5.2	18.761	27	5.4	19.903	26	5.2	15.434	26	5.2	27.070
SB RIGHT	300	60	20.583	300	60	17.235	300	60	21.765	300	60	25.648
SB LEFT	890	178	28.128	881	176.2	27.339	889	177.8	29.692	892	178.4	27.571
SB THRU	556	111.2	21.974	561	112.2	16.788	560	112	21.873	570	114	25.578
APPROACH	**NB**	319.2	24.573		322.6	19.846		322.2	24.860		325.6	20.186
	WB	538.4	17.921		536.6	18.443		537.6	17.116		534.2	24.180
	EB	239.8	15.406		238.6	16.640		238.4	15.749		236.8	21.069
	SB	349.2	24.872		348.4	22.201		349.8	25.829		352.4	26.599
	Intersection	1446.6	20.650		1446.2	19.364		1448	20.719		1449	23.362

Table 30 Vehicle Delay for Peak Pedestrian Volume

Peak Ped Input	Full Actuation			Ped Recall			Min Recall			Max Recall		
	Total Sim Volume	Avg Sim VPH	Avg Delay	Total Sim Volume	Avg Sim VPH	Avg Delay	Total Sim Volume	Avg Sim VPH	Avg Delay	Total Sim Volume	Avg Sim VPH	Avg Delay
NB LEFT	404	80.8	21.496	406	81.2	18.802	402	80.4	22.313	408	81.6	17.373
NB RIGHT	215	43	31.599	214	42.8	20.534	215	43	29.172	217	43.4	24.623
NB THRU	990	198	25.339	985	197	19.184	986	197.2	25.545	995	199	22.641
WB THRU	1561	312.2	17.982	1553	310.6	18.901	1557	311.4	19.027	1548	309.6	25.025
WB LEFT	104	20.8	26.494	103	20.6	27.991	104	20.8	26.348	103	20.6	36.506
WB RIGHT	1027	205.4	21.097	1022	204.4	20.880	1028	205.6	21.445	1020	204	26.251
EB THRU	1036	207.2	16.201	1029	205.8	17.341	1033	206.6	16.307	1022	204.4	21.017
EB RIGHT	137	27.4	17.542	136	27.2	18.854	137	27.4	18.683	136	27.2	22.832
EB LEFT	27	5.4	24.215	26	5.2	18.861	27	5.4	27.269	26	5.2	27.036
SB RIGHT	296	59.2	23.824	300	60	18.457	299	59.8	24.015	300	60	27.177
SB LEFT	881	176.2	28.828	889	177.8	27.418	884	176.8	29.420	892	178.4	27.317
SB THRU	558	111.6	23.100	562	112.4	17.926	559	111.8	22.621	569	113.8	26.111
APPROACH	**NB**	321.8	25.210		321	19.267		320.6	25.221		324	21.580
	WB	538.4	19.499		535.6	20.006		537.8	20.234		534.2	25.936
	EB	240	16.534		238.2	17.547		239.4	16.826		236.8	21.358
	SB	347	26.132		350.2	22.836		348.4	26.310		352.2	26.903
	Intersection	1447.2	21.868		1445	20.122		1446.2	22.239		1447.2	24.447

Appendix G Pedestrian Delay Results

Table 31 Manual Pedestrian Delay Results

Detection Time	Time Ped Phase	Delay	Detection Time	Time Ped Phase	Delay	Detection Time	Time Ped Phase	Delay
15:04:40	15:04:53	00:13	16:20:24	16:20:44	00:20	17:06:47	17:07:20	00:33
15:05:21	15:05:52	00:31	16:21:16	16:21:29	00:13	17:09:02	17:09:47	00:45
15:08:00	15:08:22	00:22	16:22:31	16:22:57	00:26	17:13:09	17:13:22	00:13
15:14:11	15:15:07	00:56	16:22:31	16:23:37	01:06	17:15:23	17:16:07	00:44
15:21:29	15:22:14	00:45	16:23:53	16:24:23	00:30	17:15:58	17:16:07	00:09
15:21:29	15:21:34	00:05	16:25:29	16:25:35	00:06	17:16:34	17:16:50	00:16
15:23:53	15:24:54	01:01	16:27:17	16:27:33	00:16	17:17:47	17:18:39	00:52
15:24:34	15:25:40	01:06	16:31:47	16:32:27	00:40	17:18:11	17:18:39	00:28
15:26:31	15:26:38	00:07	16:32:27	16:33:10	00:43	17:22:01	17:22:17	00:16
15:29:08	15:29:09	00:01	16:34:25	16:35:24	00:59	17:22:18	17:23:35	01:17
15:38:53	15:39:22	00:29	16:34:27	16:35:24	00:57	17:22:38	17:23:35	00:57
15:41:43	15:42:02	00:19	16:37:52	16:38:45	00:53	17:24:18	17:24:19	00:01
15:44:59	15:45:07	00:08	16:43:03	16:43:08	00:05	17:26:47	17:27:45	00:58
15:45:15	15:45:50	00:35	16:43:03	16:43:48	00:45	17:27:30	17:27:45	00:15
15:46:21	15:46:38	00:17	16:45:52	16:46:04	00:12	17:28:36	17:29:13	00:37
15:49:21	15:49:57	00:36	16:48:02	16:48:45	00:43	17:29:35	17:31:13	01:38
15:53:48	15:54:34	00:46	16:48:18	16:48:45	00:27	17:38:11	17:38:34	00:23
15:56:31	15:56:34	00:03	16:49:19	16:50:15	00:56	17:38:32	17:38:34	00:02
15:59:42	16:00:07	00:25	16:58:20	16:58:41	00:21	17:44:10	17:45:10	01:00
16:01:50	16:02:04	00:14	16:58:40	16:58:41	00:01	17:48:16	17:49:26	01:10
16:05:05	16:06:10	01:05	16:59:47	17:00:46	00:59	17:48:56	17:49:26	00:30
16:05:14	16:05:30	00:16	17:00:18	17:01:34	01:16	17:51:31	17:51:57	00:26
16:09:34	16:10:39	01:05	17:02:27	17:02:33	00:06	17:54:55	17:55:45	00:50
16:15:19	16:16:22	01:03	17:04:45	17:05:31	00:46	**AVERAGE DELAY**		**00:34**
16:17:39	16:17:44	00:05	17:05:36	17:06:04	00:28			

Table 32 Pedestrian Delay for Manual Pedestrian Volume

Manual Ped Volume	Full Actuation			Ped Recall			Min Recall			Max Recall		
	Total Sim Volume	Avg Sim VPH	Avg Delay	Total Sim Volume	Avg Sim VPH	Avg Delay	Total Sim Volume	Avg Sim VPH	Avg Delay	Total Sim Volume	Avg Sim VPH	Avg Delay
14NB	9	1.8	29.038	9	1.8	20.189	9	1.8	30.259	9	1.8	31.300
12EB	24	4.8	31.404	24	4.8	18.753	24	4.8	31.463	24	4.8	42.165
18NB	17	3.4	28.890	17	3.4	21.805	18	3.6	33.411	18	3.6	47.544
14SB	21	4.2	24.600	22	4.4	33.165	22	4.4	27.475	22	4.4	42.881
16WB	48	9.6	30.004	48	9.6	30.673	48	9.6	25.648	48	9.6	33.667
18SB	19	3.8	32.809	18	3.6	25.023	19	3.8	31.508	19	3.8	32.933
16EB	31	6.2	30.204	31	6.2	23.472	31	6.2	31.223	31	6.2	41.482
12WB	26	5.2	25.298	26	5.2	23.625	26	5.2	22.177	25	5	41.351
APPROACH		**12**	28.229			21.287			26.634			41.750
		14	25.932			29.398			28.283			39.519
		16	30.083			27.847			27.836			36.734
		18	30.958			23.460			32.434			40.041
		Overall	29.130			25.624			28.465			39.053

Table 33 Pedestrian Delay for ManualPlus Pedestrian Volume

ManualPlus Ped Volume	Full Actuation			Ped Recall			Min Recall			Max Recall		
	Total Sim Volume	Avg Sim VPH	Avg Delay	Total Sim Volume	Avg Sim VPH	Avg Delay	Total Sim Volume	Avg Sim VPH	Avg Delay	Total Sim Volume	Avg Sim VPH	Avg Delay
14NB	9	1.8	27.814	9	1.8	32.554	10	2	32.422	10	2	32.825
12EB	32	6.4	33.426	33	6.6	22.985	33	6.6	34.508	32	6.4	49.270
18NB	19	3.8	32.413	19	3.8	37.207	19	3.8	34.551	19	3.8	43.261
14SB	20	4	35.241	22	4.4	29.706	22	4.4	36.780	23	4.6	49.062
16WB	74	14.8	30.168	75	15	27.969	73	14.6	28.480	72	14.4	35.997
18SB	21	4.2	33.217	21	4.2	25.068	21	4.2	33.383	21	4.2	38.924
16EB	46	9.2	26.018	46	9.2	23.526	46	9.2	30.441	45	9	42.091
12WB	39	7.8	31.246	39	7.8	34.291	39	7.8	35.360	39	7.8	37.098
APPROACH		**12**	32.229			29.109			34.969			42.584
		14	32.936			30.533			35.418			44.142
		16	28.577			26.280			29.238			38.341
		18	32.835			30.834			33.938			40.984
		Overall	30.715			28.241			32.274			40.633

Table 34 Pedestrian Delay for Peak Pedestrian Volume

Peak Ped Volume	Full Actuation			Ped Recall			Min Recall			Max Recall		
	Total Sim Volume	Avg Sim VPH	Avg Delay	Total Sim Volume	Avg Sim VPH	Avg Delay	Total Sim Volume	Avg Sim VPH	Avg Delay	Total Sim Volume	Avg Sim VPH	Avg Delay
14NB	37	7.4	33.780	37	7.4	31.495	37	7.4	38.572	37	7.4	34.740
12EB	147	29.4	32.543	145	29	26.585	147	29.4	31.958	145	29	31.383
18NB	75	15	32.441	76	15.2	31.546	75	15	33.682	77	15.4	34.295
14SB	70	14	35.124	72	14.4	31.562	70	14	34.179	70	14	32.373
16WB	186	37.2	29.825	187	37.4	28.874	187	37.4	29.360	188	37.6	30.063
18SB	63	12.6	33.842	67	13.4	31.875	63	12.6	29.573	65	13	36.567
16EB	123	24.6	28.468	123	24.6	28.816	123	24.6	28.172	123	24.6	31.346
12WB	132	26.4	25.486	130	26	27.303	132	26.4	25.627	131	26.2	31.924
APPROACH		**12**	29.204			26.925			28.962			31.640
		14	34.659			31.539			35.698			33.191
		16	29.285			28.851			28.889			30.570
		18	33.081			31.700			31.806			35.335
		Overall	30.577			29.055			30.270			32.068

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