How Vehicular Delay is Affected at Signalized Intersections with Light Rail Transit

by

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Abstract

This paper presents the results of research on how vehicular delay is affected at signalized intersections with light rail transit. This paper discusses both active and passive transit signal priority, which uses different methods to provide light rail transit with an unobstructed path through an intersection. This, while reducing delay for the light rail transit, causes delays for other roadway vehicles using the same intersection. Future intersection designs can balance the two out while getting the most out of the intersection by identifying the factors that affect vehicular delay at intersections with light rail transit. A literature review found that light rail transit frequency, traffic volume, and transit signal priority were the main factors that affect control delay at intersections with light rail transit. It was also found that other factors also affect delay but to a lesser extent. However, it was found that intersections with left-turning light rail transit with limited geometry that shares space with vehicular traffic were not directly addressed. To address this knowledge gap, simulations were conducted on an intersection that fits these parameters. With this model intersection, three alternatives were developed, simulated, and compared to existing intersection vehicular delays. With these comparisons, a recommendation was made. However, this recommendation was not to change the current intersection but to be used in future construction projects.

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Glossary

All-Red Interval: The amount of time an intersection displays a red signal for all approaches.

Cycle Length: The amount of time it takes for an intersection to go through all of its phases.

Effective Green: The amount of time vehicles typically pass through the intersection.

Effective Red: Determined as the Effective Green – the Cycle Length.

Green Interval: The green time an approach at an intersection receives.

Green Waveband: An intentional reoccurring event where a series of intersections are coordinated to allow a continuous flow of traffic through all coordinated intersections, typically in only one direction.

Light Rail Transit (LRT): An electric railway that operates single or short multi-car trains along aerial structures, subways, and or streets. This covers both trams and streetcars along with light rail with this definition.

North, East, South, and West Approach: The cardinal direction vehicles are arriving at an intersection from.

North, East, South, and Westbound: The direction of a vehicle's movement as it arrives at a point. An example of this is a vehicle eastbound is coming from the west.

Offset: The difference in time between a reference intersection's cycle to the same point in the downstream intersection's cycle. An example is when the reference intersection turns green for the main road; the offset is the amount of time until the downstream intersection turns green for the main road.

Permitted Left Turn: A permitted left turn is a left turn where the driver is given a flashing yellow left-turn arrow, or no arrow is provided for the driver. Thus, the driver must wait for a gap in oncoming traffic to make a left turn safely.

Phase: The green, yellow, and all-red intervals for an approach.

Preemption: A change in a traffic signal's typical phasing pattern allowing a transit vehicle to pass through the intersection during a green light with little to no delay.

Protected Left Turn: A protected left turn is where a diver is given a green left-turn arrow. This means that conflicting traffic is stopped for drivers wishing to make a left turn.

Red Time: The amount of time an approach at an intersection is given a red signal.

Yellow Interval: The yellow time an approach at an intersection receives before the signal turns red.

Chapter 1

Introduction, Background, and Literature Review

1.0. Introduction

1.0.1. Research Topic

As cities begin to build and expand light rail transit (LRT), a need for balance is required. This balance is between increasing efficiency in LRT and its impact on vehicular traffic. It is necessary to research any factors that affect this balance. These then can be used to formulate traffic solutions to obtain the highest flow of vehicles at an intersection. Thus, this paper aims to investigate how the vehicular delay is affected at signalized intersections with LRT.

1.1. Background

1.1.1. Transit Signal Priority

Transit Signal Priority (TSP) is a system that assigns priority to a transit system or vehicle at signalized intersections [1]. TSP is implemented at an intersection to reduce the delay of the transit vehicle. This is required to make the transit system a more reliable and faster alternative to other modes of transportation. Another benefit is that it assists with ensuring the system is profitable to the owner. Examples of transit vehicles would be buses and LRT [1]. There are two main types of transit signal priority: active priority and passive priority [2]. Active priority uses detectors, either overhead or in the roadway, ahead of the intersection to provide a green phase for the transit vehicle. This is achieved by extending the green phase, reducing the red phase (early green), or green phase insertion [3, 4, 5, 6]. A phase insertion is when a phase that has already been serviced is used again to allow a transit vehicle to pass through [1]. However, active priority typically results in heavy delays for other roadway users [7].

Passive priority does not use detectors and instead operates continuously regardless of the presence of a transit vehicle [2, 8]. Passive priority creates a green waveband for transit vehicles along their scheduled route. This is achieved by adjusting the order of phases at an intersection. This passive priority system typically has a lower impact on delays for roadway users [9, 10]. MAXBAND, MULTIBAND, and AM-BAND are three software programs used to optimize signal timing parameters -- including cycle length, offset, time per phase, and posted speed -- to maximize the green waveband [7]. A visual representation of how active TSP can reduce the delay for LRT is shown in Figure 1.

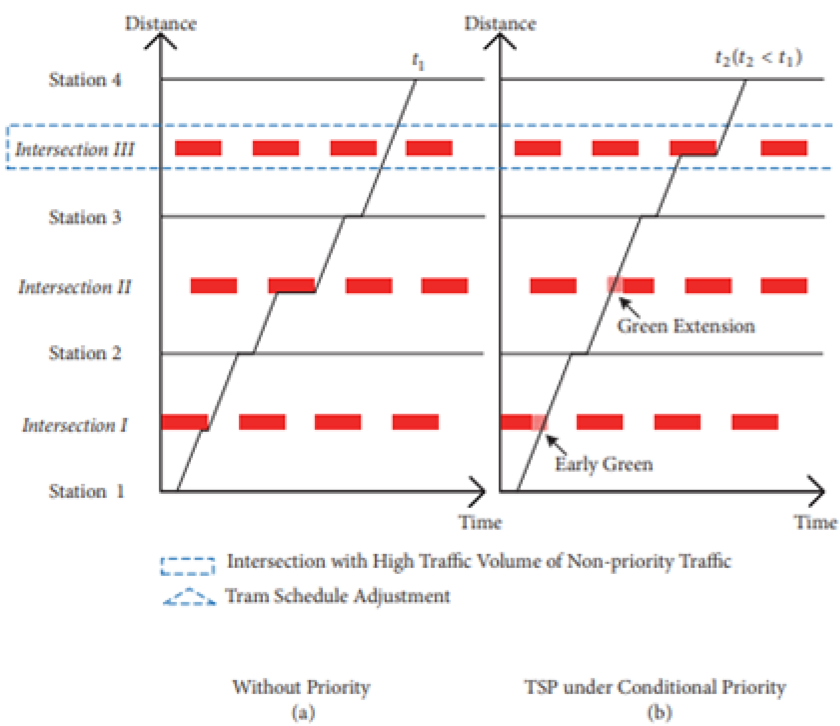

Figure 1: Benefits of TSP, Time-Space Diagram [11].

The time-space diagram shown in Figures 1a and 1b illustrates the relationship between time and the distance along a roadway. The slope of the line is the LRT's speed, and the red blocks are the effective red times of the three intersections the LRT is going through. Figure 1a is without TSP. Without TSP, the LRT must stop at two of the three intersections with significant delay. Figure 1b has TSP at the intersections; thus, when the LRT approaches the first intersection, the TSP provides the LRT with an early green allowing it to pass through the first intersection without delay. The LRT then reaches the second intersection, where the TSP extends the green time, allowing the LRT to pass through without delay. This enables the LRT to arrive at Station 4 earlier than without TSP [11].

1.2. Literature Review

1.2.1. Methods

Relevant research was conducted in October 2021 and January 2022 through the Milwaukee School of Engineering's (MSOE) Library Summon search engine, which searches the MSOE Library's database and other credible databases. All results were narrowed down to full text and scholarly/peer-reviewed literature. Additional information and research, which could not be found using the Summon search engine, were obtained using Google Scholar. The following were keywords used in the search: *delay, intersection, light rail, tram, streetcar, signalized intersection, vehicular, person delay, transit signal priority, and light rail transit.*

1.2.2. Reviewed Articles

The following are articles where TSP is used as part of a solution in optimizing a public transit system and how it affects vehicular traffic. Each article is summarized along with its main points and conclusions. It is then explained how the article relates to how vehicular delay is affected at signalized intersections with light rail transit. Lastly, areas not addressed by the article are discussed. Each article summary starts with the article's title and its location in the references.

1.2.2.1. *Traffic Signal Coordination for Tramlines with Passive Priority Strategy* [7]

This article features the passive priority function of TSP. The article's focus was on using MAXBAND, MULTIBAND, AM-BAND, and TRAMBAND to optimize the efficiency of the green waveband operating in both directions. The models also consider vehicular traffic allowing both the LRT and other vehicles to utilize the same green wavebands. A visual of this type of model is shown in Figure 2.

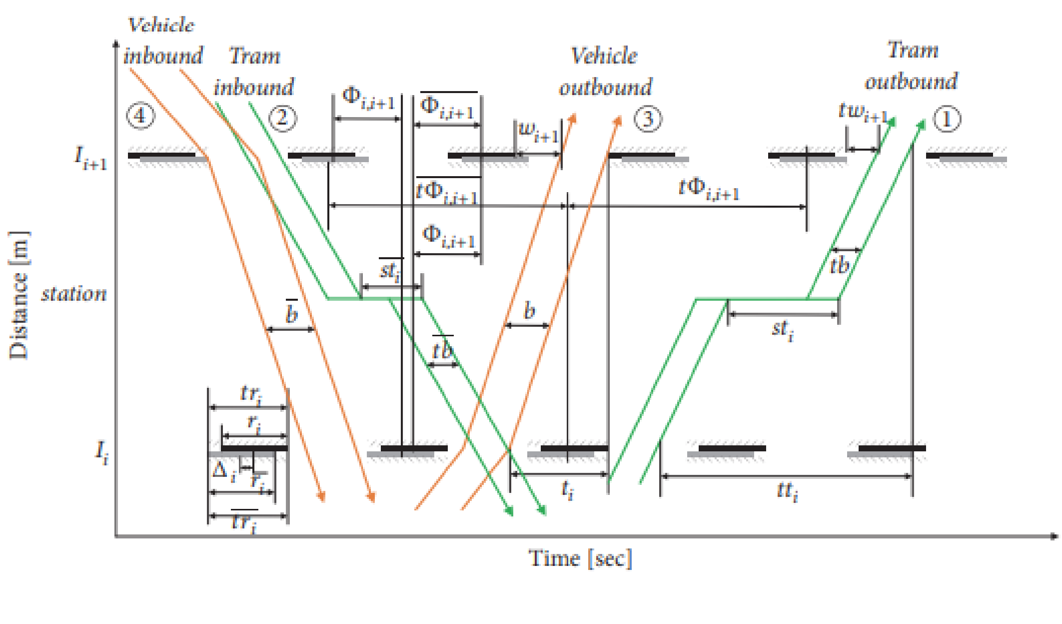

Figure 2: Green Waveband Model [7].

The article compares three models, including TRAMBAND (dynamic speed), TRAMBAND (constant speed), and the proposed model. The article indicates that prioritizing traffic signals for LRT would improve the service level of LRT operation at the cost of increased delays at intersections for vehicular traffic with conflicting movements. The proposed model developed for the article considers both the LRT and other vehicles. The proposed model was tested in China on an LRT system. Compared to the traditional TRAMBAND model, the proposed model reduced LRT average delays by 13.14 seconds per passenger in the LRT vehicle. It also reduced vehicular delays by 2.22% and allowed a 4.45% increase in traffic flow through affected intersections. It was also found that the proposed model's effectiveness is extremely sensitive to stopping times at stations, tram headways, and traffic volumes.

The article relates to how vehicular delay is affected at signalized intersections with light rail transit. This is done by showing that there are LRT systems that, when associated with TSP, can reduce vehicular delay at intersections for both LRT and other vehicles at affected intersections. It also identifies three factors that affect the proposed model. These factors are time spent by LRT at stations, LRT frequency, and traffic volume. The fact that these three factors affected the proposed model severely would also indicate that it would affect vehicular delay if the traffic signals were prioritized for the LRT over vehicular traffic. The article also explains how TSP operates, and since TSP is a tool used in maintaining the efficiency of LRT systems, this article is a valuable reference.

However, there are some issues with the article. The intersections used in this model do not address intersections where the LRT system makes left or right turns. Instead, the LRT system proceeds straight through the intersection used in the model. A visual of this issue is shown in Figure 3.

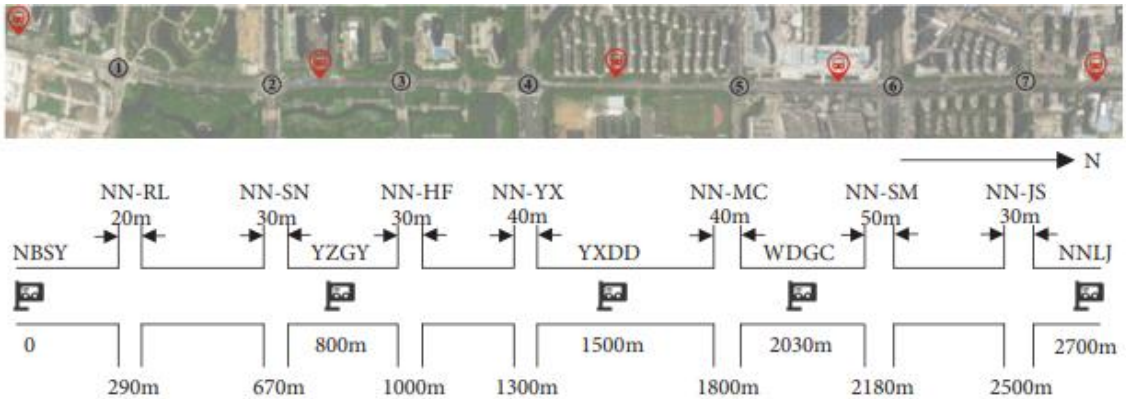

Figure 3: Intersection Locations [7].

Thus, potential factors are not addressed that could affect the model if the LRT system made a left/right turn.

1.2.2.2. *Integrated Optimization of Tram Schedule and Signal Priority at Intersections to Minimize Person Delay* [11]

This article focuses on the active priority function of TSP, along with modifications to LRT's schedule. Figure 4 illustrates how modifying the LRT's schedule, and active TSP, can reduce delay for LRT.

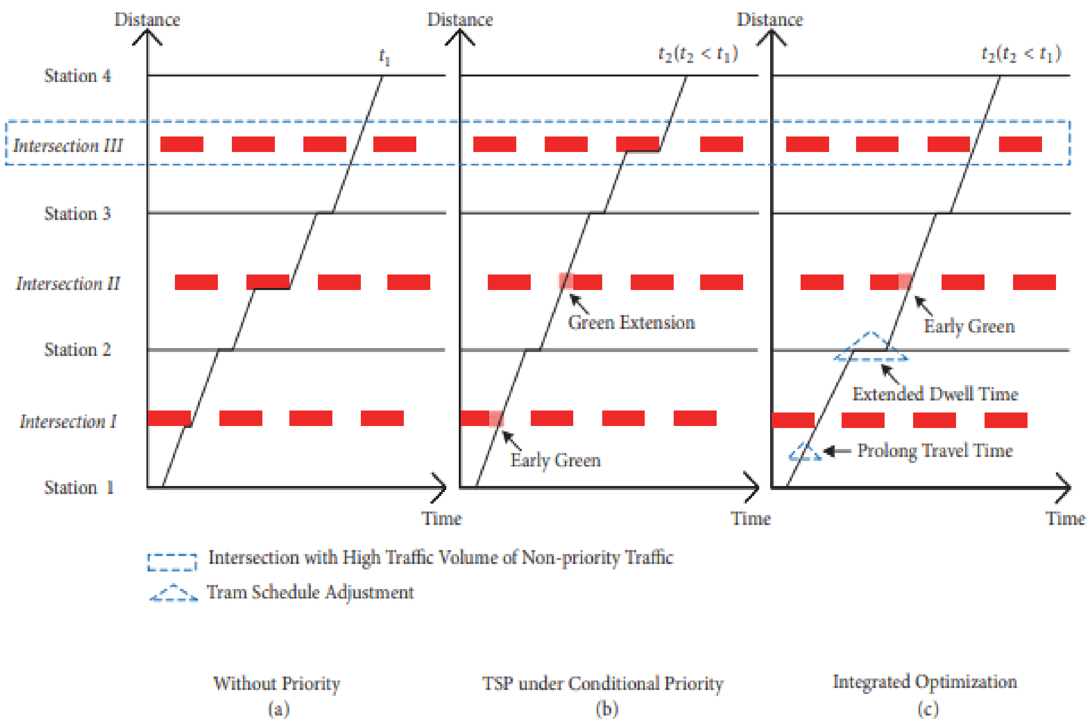

Figure 4: Active TSP and Modified LRT Schedule Example [11].

Figures 4a and 4b illustrate the relationship between time and the distance along a roadway. The slope of the line is the LRT's speed, and the red blocks are the effective red times of the three intersections the LRT is going through. Figure 1a is without TSP. Without TSP, the LRT must stop at two of the three intersections with significant delay. Figure 1b has TSP at the intersections; thus, when the LRT approaches the first intersection, the TSP provides the LRT with an early green allowing it to pass through the first intersection without delay. The LRT then reaches the second intersection, where the TSP extends the green time, allowing the LRT to pass through without delay. This enables the LRT to arrive at Station 4 earlier than without TSP. However, Figure 4c implements both TSP and modifications to the LRT's schedule. The adjustment to the LRT's schedule allows it to reach the first intersection during a green phase by traveling slower and thus prolonging the travel time. The LRT’s schedule is then adjusted again where it waits at Station 2 longer than usual to arrive at Intersection 2, where the TSP is activated, providing the LRT with an early green. This allows the LRT to pass through Intersections 2 and 3 during a green signal. Figure 1c is the suggested solution because while the LRT in Figures 1b and 1c reached Station 4 at the same time as in Figure 1c, the LRT did not have to stop at any intersections. This methodology was then used to formulate a model for an LRT system that passes through seven intersections. The article found that TSP is an effective tool for reducing the delay of LRT systems. The article also found that providing priority for the LRT imposes extra delays for other vehicles. Thus, the findings in the article were used to modify the LRT’s schedule and to use TSP to reduce the effect LRT had on delays for other vehicles. However, the article states that neither an optimal solution nor a near-optimal solution could be developed when the methodology was applied to an LRT system operating through multiple intersections. The reason for this is that the number of model intersections was too large.

The article relates to how vehicular delay is affected at signalized intersections with LRT. This is accomplished by showing there is potentially a way where LRT systems, when associated with with active TSP and a modified schedule, can reduce delay for the LRT and reduce the effect the system has on the delay of other vehicles. The article also describes how delay for vehicles is calculated. This description provides several factors that affect vehicular delays, such as time spent by LRT at stations, LRT frequency, cycle length, green time, red time, traffic volume, lane capacity, and traffic flow.

However, there are some issues with the article. The intersections used in this model do not address intersections where the LRT system makes a left or right turn. Instead, the LRT system proceeds straight through all intersections used in the model. A visual of this issue is shown in Figure 5.

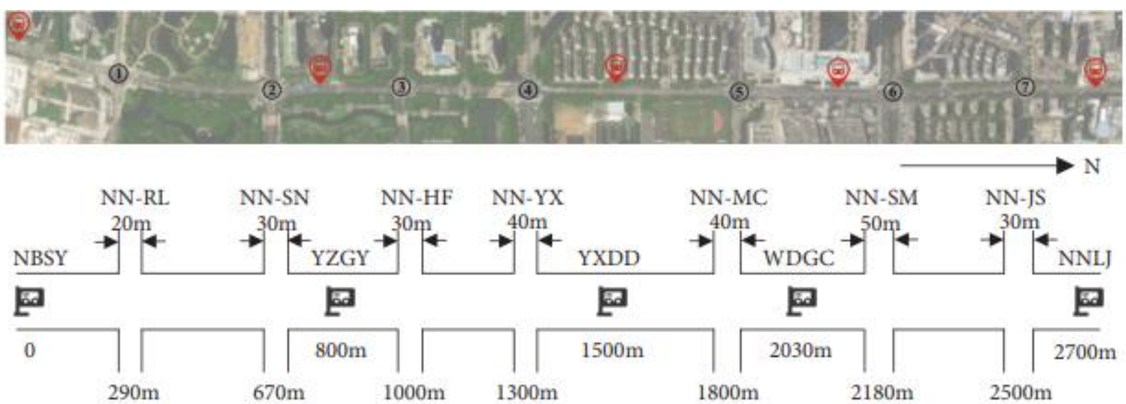

Figure 5: Intersection Locations [11]. Both Figure 3 and Figure 5 depict the same intersection models. This is because both studies feature the same model intersections.

Therefore, if potential factors were to affect the model, had LRT made a left/right turn, those factors were not addressed.

1.2.2.3. *An Exact Modeling of the Uniform Control Traffic Delay in Undersaturated Signalized Intersections* [12]

This article focuses on revising the equation used by the highway capacity manual for calculating uniform delay for vehicles. The purpose of this is to formulate an equation for calculating uniform delay that more accurately depicts field conditions. The original equation for calculating uniform delay is shown in Equation (1), adopted by the Highway Capacity Manual 2010 (HCM2010) [12]:

$$D_1 = \frac{0.5C\left(1-\frac{g}{C}\right)^2}{1-\frac{\lambda}{\mu}} = \frac{\lambda\mu r^2}{2(\mu-\lambda)} \times \frac{1}{\lambda C} = \frac{\mu r^2}{2C(\mu-\lambda)} \quad . \qquad (1)$$

This equation calculates uniform delay based on the following factors: effective green, effective red, cycle length, arrival flow rate, and departure flow rate. The new equation proposed by the article does not introduce any new factors affecting delay. Instead, it changes the relationship between factors to better represent what is observed in the field.

The article relates to how vehicular delay is affected at signalized intersections with light rail transit because, while the article has nothing to do with LRT or TSP, it provides factors that affect vehicular delay. Thus, any changes to a signalized intersection that affects these factors subsequently affect vehicular delay at the intersection.

Aside from the article not discussing LRT or TSP, it provides valuable information on how changes to intersection timing can affect vehicular delay.

1.2.2.4. *Light Rail Preemption of Traffic Signals: A Question of Balance* [13]

This article focuses on providing priority for busses without disrupting intersection coordination, essentially an early form of active TSP. Three TSP priority controls are queue jump maneuver, green time extension, and phase reservice. Visuals of these are shown in Figures 6, 7, and 8. Figure 6 depicts a queue jump maneuver, where the TSP system gives the bus a green signal before the rest of the traffic. This allows the bus to jump the queue, hence the name. Figure 7 depicts an extended green time, where the TSP system extends the green time of the phase so that the bus may pass through the intersection uninterrupted. Lastly, Figure 8 depicts a phase reservice. The TSP system reservices the phase required to give the bus preemption through the intersection.

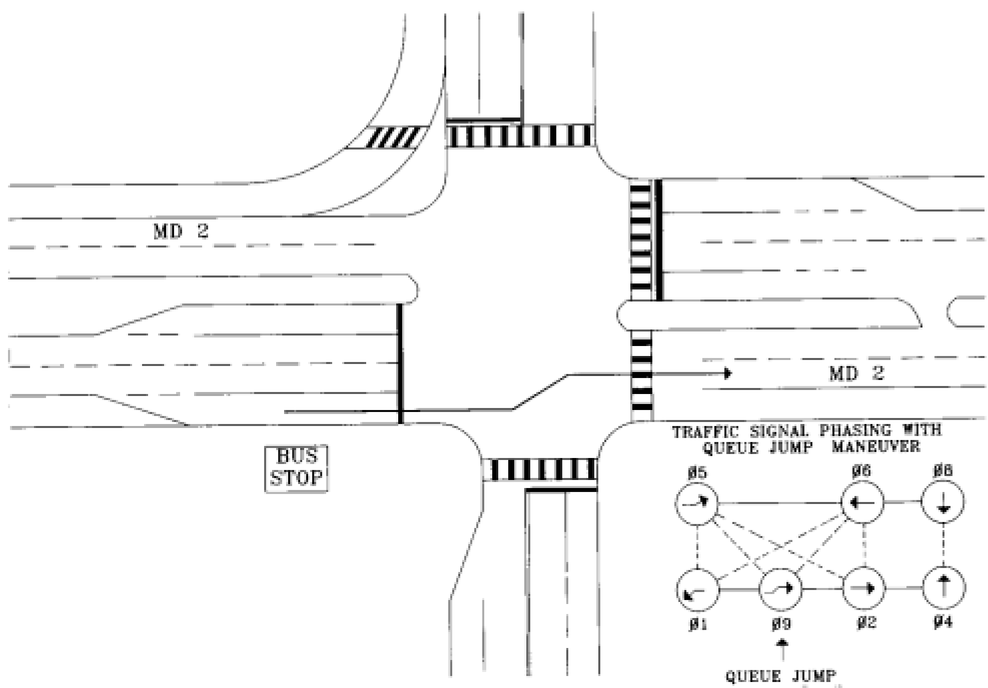

Figure 6: Queue Jump Maneuver [13].

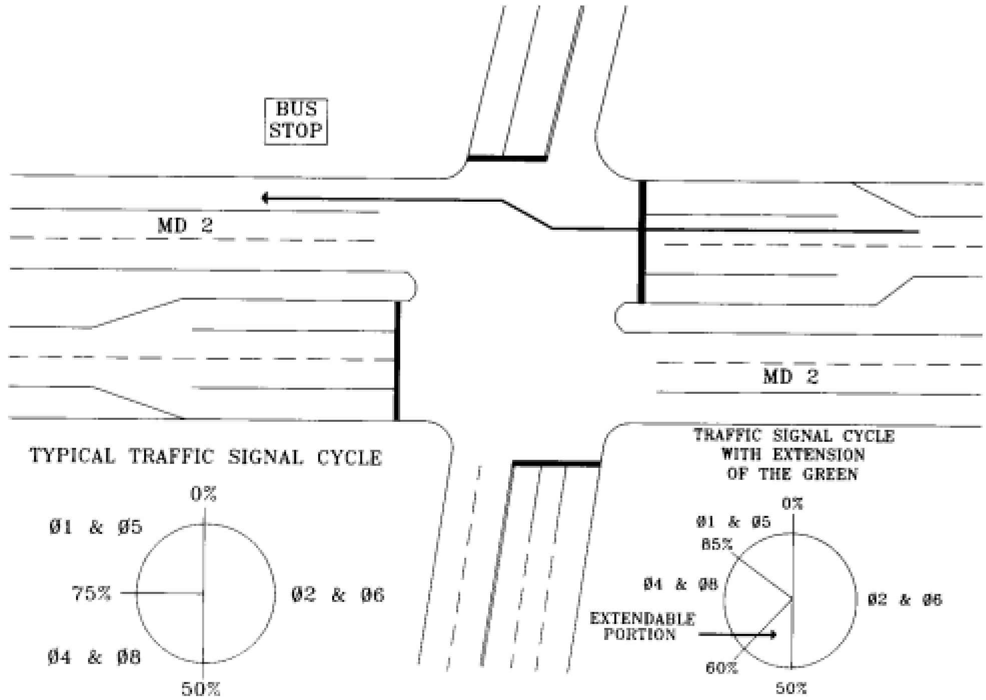

Figure 7: Extending the Green Time [13].

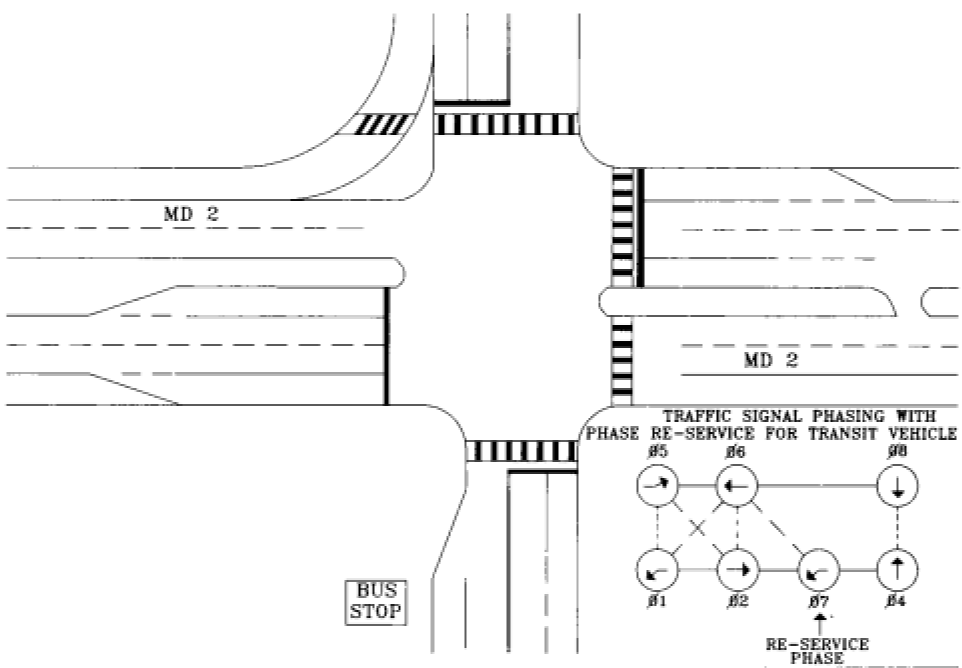

Figure 8: Phase Reservice [13].

The three TSP priority controls determined that bus travel times were reduced by 14% to 18%. This was achieved because all three TSP priority controls didn't affect the coordination with other intersections. The article also discusses human factors because part of the concern for developing the three TSP priority controls is whether other drivers would understand and accept the different and changing movements and traffic signal displays.

The article relates to how vehicular delay is affected at signalized intersections with light rail transit. It relates because it shows three early TSP priority controls. It also illustrates that drivers must understand and accept solutions to transportation-related issues. If other drivers do not understand the system, the solution that works, in theory, would only cause further problems in the field due to driver confusion. This article also addresses an issue the previous articles didn't address, specifically, a transit route that turns left/right (see Figure 9.) Figure 9 demonstrates that there are solutions to transit vehicles turning left/right that reduce transit vehicle delays.

However, this article focuses on buses rather than LRT; while this isn't an issue, the mobility of the transit vehicle may change with the change in vehicle type. Another problem is that the article does not review what factors involving the TSP system affect vehicular delay. The article also has an "unresolved issues" section on whether the system's benefits outweigh the increased delays to vehicular traffic.

1.2.2.5. *Traffic Impacts of Light Rail Transit* [14]

This article focuses on the traffic impacts caused by the San Diego Trolley. The article reviews key intersections that would be affected by the LRT systems and analyzes them under worst-case scenarios. These scenarios included peak volumes and 7.5-minute times between transit vehicles. Greenshield's model and a demonstration project determined that queues accumulated from the LRT crossing would dissipate after a single cycle length. The dissipation of the queue would take from 6 to 33 seconds. This was also confirmed in the demonstration project.

The article relates to how vehicular delay is affected at signalized intersections with light rail transit. This is because it demonstrates that any vehicular delay caused by LRT crossing is limited to the cycle length in which they occur.

However, this article does not address the traffic signal timing of the intersections, which may affect delays for vehicles. It also does not provide factors that influences the differences in the time it takes to dissipate the queue generated by the LRT crossing.

1.2.2.6. *Delay Impacts of Light Rail Transit Grade Crossings* [15]

This article focuses on factors that affect vehicular delay caused by LRT at grade crossings. This is accomplished by using the NETSIM simulation model to test four scenarios with LRT. The scenarios are: 1. LRT at an isolated crossing; 2. An adjacent intersection crossing; 3. A series of coordinated intersections with preemption; 4. A case study based on a corridor in Houston, Texas. The simulation determined that the volume to capacity (v/c) ratio significantly affects vehicular delay at an isolated crossing with LRT. For an adjacent intersection crossing with LRT, it was determined that the distance between the intersection and the crossing, along with the v/c ratio, has a significant effect on vehicular delay from the LRT crossing. It was also determined that traffic moving parallel with the LRT is barely affected by the LRT crossing. There was little impact on vehicular delay for a series of coordinated intersections with preemption. Lastly, for the case study in Houston, Texas, the vehicular delay was focused on LRT crossings. It was found to have no effect on vehicular delays at nearby intersections.

The article relates to how vehicular delay is affected at signalized intersections with light rail transit. It relates because not only does it provide two factors that directly affect the vehicular delay caused by LRT, it shows how the location of LRT crossings affects vehicular delay.

However, the article does not have any simulations in which the LRT shares lanes with other vehicles. This does not address other factors that might affect vehicular delay.

1.2.2.7. ***Effects of Light Rail Transit on Traffic Congestion* [16]**

This article focuses on how LRT crossings affect average vehicular delay. This was accomplished using VISSIM 3.70 simulation model. With VISSIM, four scenarios were examined: 1. Isolated crossings of a two-lane road; 2. Isolated crossings of a four-lane road; 3. A case in which LRT is located in the median of a street; 4. A more extensive network that includes four crossings. In the two scenarios with isolated crossings, the effects of traffic volumes and LRT crossing frequency were examined. In the scenarios where LRT is in the median of a street and the more extensive network that includes four crossings, the effects of LRT crossing frequency and TSP were examined. The results from the first two simulations found that both traffic volumes and LRT crossing frequency have a significant impact on the average increase in vehicular delays. It was found that when the roadway is over-saturated, meaning the arrival volume of vehicles is greater than the departure volume, the total vehicular delay continues to increase, but additional delay attributed to LRT is not as high as it would be if the roadway were under capacity. The scenarios where the LRT is in the median of a street and the more extensive network, including four crossings, determined that TSP for the LRT affects vehicular delay for all approaches. These, however, only involve movements that conflict with the crossing of the LRT. Other movements that do not conflict with the LRT's movement result in a reduction in vehicular delay due to additional green time. The article concludes that individual results are most likely dependent on traffic volume and roadway capacity at a given location.

The article relates to how vehicular delay is affected at signalized intersections with light rail transit because it provides three factors that affect vehicular delay. These factors are traffic volumes, LRT crossing frequency, and TSP.

However, the scenarios in this article do not include LRT sharing lanes with other vehicles. Thus, potential factors that might affect vehicular delay could be eliminated.

1.2.2.8. *Microscopic Traffic Characterization of Light Rail Transit Systems at Level Crossings* [17]

This article focuses on the impact of LRT level crossings on vehicular delay using the VISSIM 2020 microsimulation software. VISSIM 2020 was used to evaluate a variety of scenarios. It was determined that increasing LRT arrivals and traffic volume increases vehicular delays. It also determined that the geometry of the intersection is a factor in vehicular delay times.

The article relates to how vehicular delay is affected at signalized intersections with light rail transit because it provides three factors that affect vehicular delay. These factors are LRT arrival frequency, traffic volume, and intersection geometry.

However, the article does not have scenarios where the LRT shares lanes with other vehicles. It also does not address left-turning LRT interactions. Thus, other potential factors that might affect vehicular delay could be left out.

1.2.3. Conclusions

In conclusion, based on a review of literature, it can be determined that the following are the main factors for vehicular delay at intersections with LRT: The frequency of the LRT vehicles, traffic volume, and TSP. These factors are repeatedly stated throughout several articles; other factors that are not as significant are the relationship between effective green and red times, cycle length, and intersection geometry. The relationship between effective green and red times and cycle length are components for calculating control delay at a typical intersection. Lastly, intersection geometry is a theme directly addressed in a few articles and may affect delays for vehicles.

1.2.4. Additional Research

Of the eight articles reviewed, one article addresses left turns for TSP. The articles also do not address intersections where the LRT shares space with vehicular traffic. Most have the LRT in the median. Lastly, none of the articles discuss limited geometry intersections. Most intersections featured in these articles have multiple lanes per approach, with the LRT traveling through the intersection and in the road’s median. Thus, a knowledge gap exists in the literature, and therefore, research should be conducted on a limited geometry signalized intersection with a left/right turning LRT that shares space with vehicular traffic.

Chapter 2

Model Intersection

2.0. General Overview

The signalized intersection used for this capstone research is East Ogden Ave. and North Jackson St., located in Milwaukee, Wisconsin. This four-legged intersection with the north approach serves a commercial development, East Pointe Marketplace. The intersection is also a change in direction for Milwaukee's streetcar, The Hop. Figure 9 is a satellite photograph from Google Maps that provides a visual representation of the intersection. The decision to use the intersection of East Ogden Ave. and North Jackson St. was chosen as the model intersection because it satisfies the description of a limited geometry signalized intersection with a left-turning LRT that shares space with vehicular traffic. An intersection is considered a limited geometry intersection when it has the following: One lane for most approaches. It cannot be enlarged due to surrounding buildings. It is making use of the entire area allowed for the intersection. Further details on how the intersection satisfies this description are explained in the geometry section describing the intersection.

Figure 9: Satellite photograph of East Ogden Ave. and North Jackson St.

2.1. Intersection Geometry

The north approach has three lanes for vehicles, two lanes southbound and one lane northbound. The east approach has two lanes, one eastbound and one westbound. Vehicular traffic and the Hop share both lanes. The east approach also has street parking located on both sides of the roadway. The south approach has two lanes of traffic, one northbound and one southbound. Vehicular traffic and The Hop share both lanes, with parking only on the east side near the intersection. The west approach has two lanes, one eastbound and one westbound, with parking on both sides of the roadway. The Hop turns at the intersection from northbound on North Jackson to eastbound on East Ogden, where it stops after clearing the intersection at Ogden/Jackson Eastbound. The Hop also makes a left turn from westbound on East Ogden to southbound on North Jackson, where it stops at Ogden/Jackson Westbound after clearing the intersection. Thus, this intersection fits the limited geometry part of the description due to the low number of lanes per approach. The intersection fits the left turning LRT part of the description due to the Hop making both left and right turns at the intersection. Lastly, the intersection is signaled, and the details of the intersection's signalization are discussed in the following section.

2.2. Intersection's Traffic Signal Timing

Appendix A features information and data on the timing for the intersection of East Ogden Ave. and North Jackson St. The traffic signal timing data used for this report was received from Joseph C. Blakeman, a traffic control engineer for the City of Milwaukee, on September 14, 2021 [18].

Beginning with the order of phases for the intersection, the intersection starts with both approaches on North Jackson St., followed by the west approach, then lastly, the east approach on East Ogden Ave. Thus, this intersection has split phasing due to the approaches on East Ogden Ave. being split into two phases. The minimum and maximum green time, the yellow interval, and the red interval for each approach are shown in Table 1. Figure 10 shows a visual of both the order and timing of each phase for the intersection.

Table 1: Intersection Approach Timings (seconds) [18].

Phase	North Approach ↑	East Approach ←	South Approach ↓	West Approach →
Min Green	12	12	12	12
Max Green	22	26	22	26
Yellow	4	4	4	4
All-Red	1.5	1.5	1.5	1.5

Figure 10: Intersection Order and Timing [18].

In the traffic signal timing data, there are notes on the intersection's timing. In this section, the traffic signal timing data state there are four preemption cycles. Two of these preemptions are for emergency vehicles. The other two preemptions are for The Hop. However, the intersection timing data do not state anywhere what the phasing or order of these preemptions is. Thus, visual timing for these preemptions was taken manually. These times were recorded on April 1, 2022, during the afternoon and into the evening; the conditions were dry and clear. Table 2 shows the green time for each phase for ten preemption cycles for both left and right turn Hop movements. When recording these times, the times were rounded to the nearest half-second since this is done when calculating green times for intersections. The ten recorded preemption cycles were taken and averaged to find the preemption timing for the preemption cycles. It was also discovered that these preemption cycles maintain the 4-second yellow interval and 1.5-second all-red interval. The first phase for each Hop movement is the phase in which the

Hop maneuvers through the intersection. Figures 11 and 12 show a visual of the order and timing of the preemption cycles using the averaged time from Table 2.

Table 2: Recorded Preemption Green Times.

	Right Turn Hop Movement			Left Turn Hop Movement			
Preemption Cycle	↕	→	←	←	→	←	↕
1	22	48	35.5	22.5	48	53.5	34
2	22	48.5	33	20	47.5	53	34
3	25	48	43	29.5	48.5	53.5	27
4	26.5	48.5	29.5	24	48.5	53.5	23
5	22	48	29.5	23.5	48	53	30.5
6	22.5	48	32.5	24	48.5	53.5	28
7	24	48.5	33	20.5	48	53	27.5
8	22	48	33	22	48.5	53	34
9	26	48.5	42	21.5	48	53.5	30
10	23	48	29.5	28	48.5	53	29
Average	23.5	48	34	23.5	48	53	30

Note: All values are in seconds.

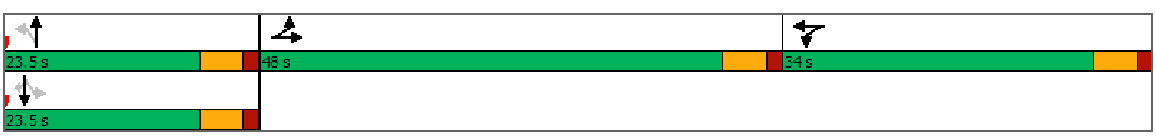

Figure 11: Intersection Preemption Order and Timing for Right Turn Hop Movement.

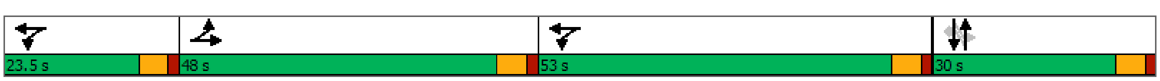

Figure 12: Intersection Preemption Order and Timing for Left Turn Hop Movement.

2.3. Intersection Traffic

On Wednesday, February 16, 2022, traffic volumes were collected from 4 pm CST. The weather conditions at the time were cloudy with light rain. However, the assumption was made that the presence of rain did not affect roadway or traffic volume conditions. Volumes for each movement for all four approaches were counted for 30 minutes. A 30-minute count was conducted due to time constraints. A 30-minute count is still acceptable as the volumes counted can be multiplied by two to get an hour-long traffic volume. Figure 13 shows the traffic volumes and movements over one hour for each approach. These values (vehicles per hour) are calculated from the 30-minute count by multiplying the values by two.

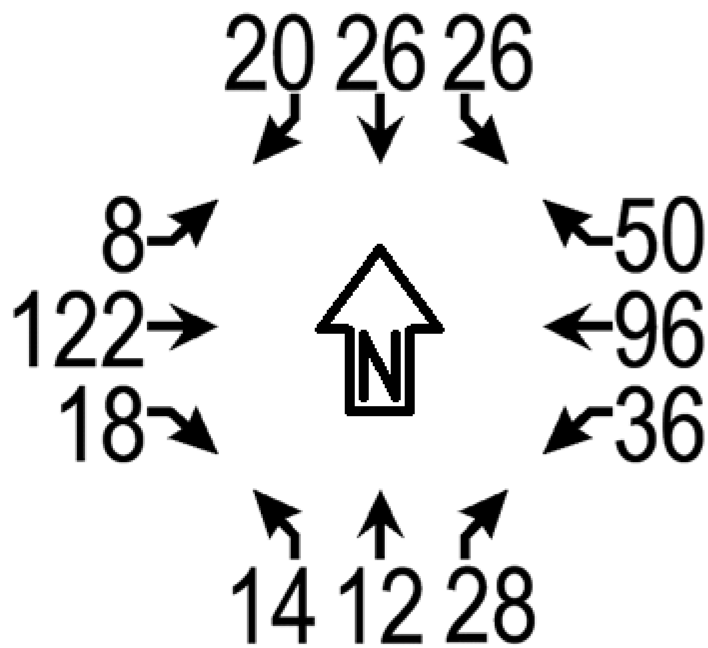

Figure 13: Intersection Traffic Movements per Approach – Vehicles per Hour (vph).

The average vehicular delay experienced by drivers was also observed and calculated. This was completed by conducting a delay study per the Highway Capacity Manual (HCM) procedure obtained from Appendix A in the manual [19]. Two delay studies were conducted on both East Ogden Ave. approaches, one on February 9 and the other on March 9, 2022. Both studies took place between 4:00 and 5:30 pm during light rain. The assumption was made that the rain did not have a noticeable effect on traffic flow or vehicular delay on both days. During this time, the number of vehicles stopped at the intersection was recorded in 20-second intervals. This was conducted for 14 cycles of the intersection. Data were collected for 56 cycles. The raw data for these delay studies can be found in Appendix B.

The following calculations were made for each page of data collected for the delay study. All the vehicles stopped in each 20-second interval were summed as the total vehicles in queue. The highest total number of vehicles that had to stop for each cycle was summed as the stopped-vehicle count. Lastly, the total vehicles were summed as the total vehicles arriving. The remainder of the equations can be found at the bottom of each page of the delay study. These equations were used to determine the control delay for each page. Control delay is the average delay experienced by vehicles passing through an intersection over a given period. It is also the value used to determine the level of service for an intersection. Table 3 shows the control delay times for all eight pages from the delay study.

Table 3: Summary of Control Delay from Delay Study.

	West Approach (sec/veh) →	East Approach (sec/veh) ←
	38.60	25.31
	19.68	26.07
	36.54	25.18
	26.30	19.07
Average	30.3	23.9

Chapter 3

Simulations

3.0. Software Constraints

The initial approach in this capstone project was to utilize PTV VISSIM to simulate the intersection of East Ogden Ave. and North Jackson St. PTV VISSIM was chosen because it could simulate LRT. However, while LRT simulations were part of the education version, it could not model actuated traffic signals, including TSP. Based on these limitations, the decision was made to continue with simulations utilizing Synchro 10. While Synchro 10 has the same limitations as PTV VISSIM, the reason for utilizing Synchro 10 over PTV VISSIM is due to the amount of experience that the author of this report has had with each program. The way Synchro 10's issues were worked around is by having three models for each alternative: A model for no Hop movement; model for left turn Hop movement; and a model for right turn Hop movements. The average control delay between these models is calculated by a weighted averaging. The weighted average is as follows: two for the no-Hop model, one for the left turn model, and one for the right-turn model. This weighted average gives the no-Hop movement model the same weight as the left and right turn models combined. The reason for the assumption is to reduce complexity.

3.1. Calibration Model

The purpose of the calibration model is to represent the intersection as close as possible to the current situation at the intersection. This model is then used to calibrate traffic flow rates for other alternative models. Figure 14 shows the calibration model intersection's geometry and the volumes from Figure 13. Figures 15, 16, and 17 show the traffic signal timing for the three calibration models.

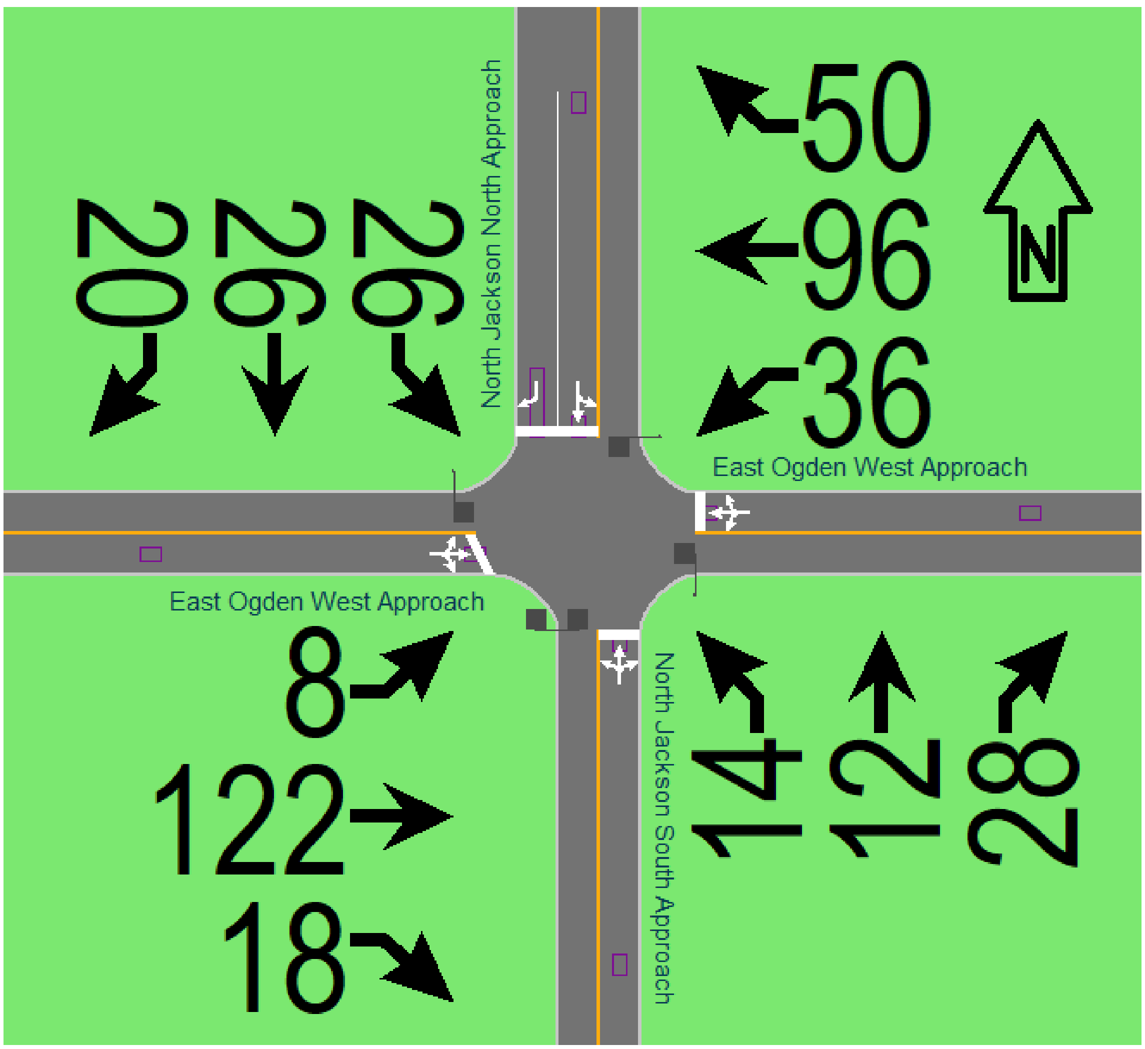

Figure 14: Calibration Model Geometry.

Figure 15: Calibration Model No Hop Movement Traffic Signal Timing.

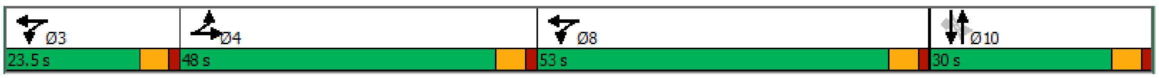

Figure 16: Calibration Model Left Turn Hop Movement Traffic Signal Timing.

Figure 17: Calibration Model Right Turn Hop Movement Traffic Signal Timing.

Figures 15, 16, and 17 have the exact timing as those from Figures 10, 11, and 12. This is because the calibration model must have the precise traffic signal timing as that which is occurring at the intersection. These models also use the same yellow and all-red intervals of 4 seconds for the yellow interval and 1.5 seconds for the all-red interval.

The models were calibrated by changing the saturation flow rate for the approaches on East Ogden Ave. The weighted average between the three models aligned with the average collected from the delay study. The saturation flow rate for an approach is the maximum number of vehicles that can pass through the intersection from that approach in one hour, given continuous green time. Synchro sets the default saturation flow rate for all approaches to 1900 vehicles per hour. Table 4 shows the control delay for both approaches on East Ogden under both the default and calibrated saturation flow rates. The optimal calibrated value for saturation flow rate was found to be 1360 vehicles per hour green per lane (vphgpl) for the west approach and 1570 vphgpl for the east approach.

Table 4: Control Delay for Calibration Model Before and After Calibration.

Hop Movement	East Ogden Ave Approaches	1900 vphgpl default value (sec/veh)	Calibrated Value (sec/veh)
No Hop	West	22.0	25.0
	East	21.3	23.3
Left Turn	West	45.1	49.1
	East	14.7	15.5
Right Turn	West	20.5	22.2
	East	31.2	36.6
Average	West	27.4	30.3
	East	22.1	23.9

The calibrated values of 1360 vphgpl for the west approach and 1570 vphgpl for the east approach resulted in the average control delay for the west approach being 30.3 seconds and 23.9 seconds for the east approach. These averaged control delays match the average values from Table 3 and subsequently mean that the saturation flow rates are calibrated correctly.

For all alternatives, the traffic volumes for the intersection are the same as those depicted in Figure 13. The west approach uses a saturation flow rate of 1360 vphgpl. The east approach uses a saturation flow rate of 1570 vphgpl. All alternative models use 4 seconds for the yellow interval and 1.5 seconds for the red interval. Lastly, the intersection is coordinated with the intersection of East Juneau Ave. and North Jackson St. Thus, all alternatives are restricted to 90-second cycle lengths. Alternatives 1 and 2 use the same intersection geometry shown in Figure 14. Alternative 3 features differing geometry.

3.2. Alternative 1: Timing Change

The purpose of Alternative 1 is to reduce control delay by changing only the timing of the phases for the intersection while maintaining the split phasing. For Alternative 1, it was determined that the timing for the intersection for no-Hop movement is already optimized. Thus, the intersection retains the same timings found in Figures 10 and 15. Therefore, the only remaining way to optimize the intersection is the preemption phasing. The changed green times for the preemptions are shown in Table 5. A visual of the changed green times are also shown in Figures 18 and 19. After the changed green times, the cycle length for The Hop's right turn preemption is 90 seconds, and the left-hand turn is now 90 seconds from its original 120 seconds.

Table 5: Alternative 1 Preemption Green Times.

	Right Turn Hop Movement			Left Turn Hop Movement			
Preemption Cycle	↕	→	←	←	→	←	↕
Green	23.5	26	24	23.5	22	22	22.5

Note: All values are in seconds

Figure 18: Alternative 1 Model Right Turn Hop Movement Traffic Signal Timing.

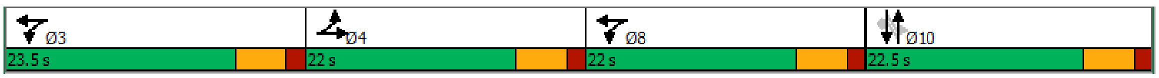

Figure 19: Alternative 1 Model Left Turn Hop Movement Traffic Signal Timing.

The next step was to evaluate the control delay for both east and west approaches. This is due to the significant difference in traffic volumes on East Ogden Ave. compared to North Jackson St. Table 6 shows the summary and weighted average of the control delay for Alternative 1.

Table 6: Alternative 1 Control Delay.

Hop Movement	East Ogden Ave Approaches	Control Delay (sec/veh)
No Hop	West	25.0
	East	23.3
Left Turn	West	46.1
	East	10.3
Right Turn	West	24.5
	East	25.5
Average	West	30.2
	East	20.6

With Alternative 1, the west approach's control delay is now 30.2 sec/veh, a 0.1 sec/veh reduction in control delay from the original intersection. The east approach now has an average control delay of 20.6 sec/veh, a reduction of 3.3 sec/veh.

3.3. Alternative 2: Phasing and Timing Change

The purpose of Alternative 2 was to reduce the control delay by changing both the timing and phasing of the intersection. For Alternative 2, a more traditional two-phase traffic signal was used. The green time for the intersection was divided based on the percentage of total volume per roadway, with East Ogden Ave. having an hourly volume of 330 vph and North Jackson St. having 126 vph. Thus, with East Ogden Ave. having 72% of the traffic volume, East Ogden Ave. will receive 57 seconds of green time of the 79 seconds allowed by the 90-second cycle length. Seventy-nine seconds was calculated by subtracting the 5.5 seconds per roadway for yellow and all-red intervals from the 90-second cycle length. The remaining 22 seconds is for North Jackson St. This provides a 57-second green time for East Ogden Ave. and 22-second green time for North Jackson St. when The Hop is not affecting the intersection. During these green times, left turns are permitted on East Ogden Ave. instead of operating protected. When The Hop turns left, a protected left-turn phase and traffic from the east approach are allowed to travel. After the protected left-turn has finished, the left turn becomes a permitted left turn. This is what is called a protected permitted left turn. The time of 23.5 seconds was chosen for this protected left turn because it is the average time given to The Hop for left turn preemption from Table 2. When The Hop turns right, the green time for North Jackson is extended. For Alternative 2, the green time was set to 23.5 seconds as it was the average green time given to right turn preemption from Table 2. Figures 20, 21, and 22 show the timing and phasing patterns for Alternative 2. Table 7 immediately afterward shows the summary and weighted average of the control delay for Alternative 2.

Figure 20: Alternative 2 Model no Hop Movement Traffic Signal Timing.

Figure 21: Alternative 2 Model Left Turn Hop Movement Traffic Signal Timing.

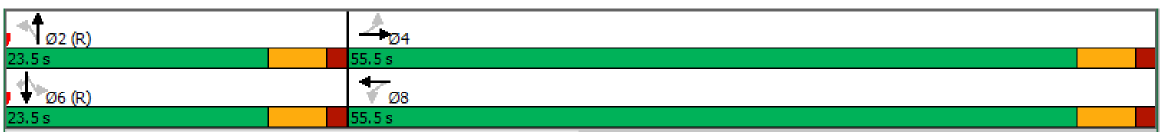

Figure 22: Alternative 2 Model Right Turn Hop Movement Traffic Signal Timing.

Table 7: Alternative 2 Control Delay.

Hop Movement	East Ogden Ave Approaches	Control Delay (sec/veh)
No Hop	West	5.4
	East	4.7
Left Turn	West	20.1
	East	4.6
Right Turn	West	6.1
	East	5.3
Average	West	9.8
	East	4.8

With Alternative 2, the west approach's average control delay is now 9.8 sec/veh, which is a 20.5 sec/veh reduction in control delay from the original intersection. The east approach now has an average control delay of 4.8 sec/veh, a reduction of 19.1 sec/veh.

3.4. Alternative 3: Phasing and Timing Change with Minor Changes to Intersection Geometry

The purpose of Alternative 3 was to apply the phasing and timing from Alternative 2 to a more favorable intersection geometry. However, Alternative 3 is still limited by the right of way imposed by the surrounding buildings. Thus, Alternative 3 features the removal of street parking to add lanes to the intersection. As stated earlier, Alternative 3 utilized phasing and timing from Alternative 2, and only the intersection's geometry will be displayed before discussing the control delay times. The only places that make sense to add additional lanes are on East Ogden. Additional lanes on the south approach would put vehicles to the right of a streetcar turning right. To change this would require reconstruction of the rail lines and thus is not feasible. There are already two approach lanes for the north approach, and there is no room for additional lanes. Therefore, the only option is the East Ogden Ave. approaches. For the west approach, a right-turn lane was added. The length of this lane was 70 feet to prevent removing all parking from this side of the street. All street parking was removed and replaced with a thorough/right turn lane for the east approach. This makes the existing lane a left turn only lane. Figure 23 shows the geometry and volumes from Figure 13 for the intersection -- note there would not be a median on East Ogden. The median shown in Figure 23 is a limitation of the software.

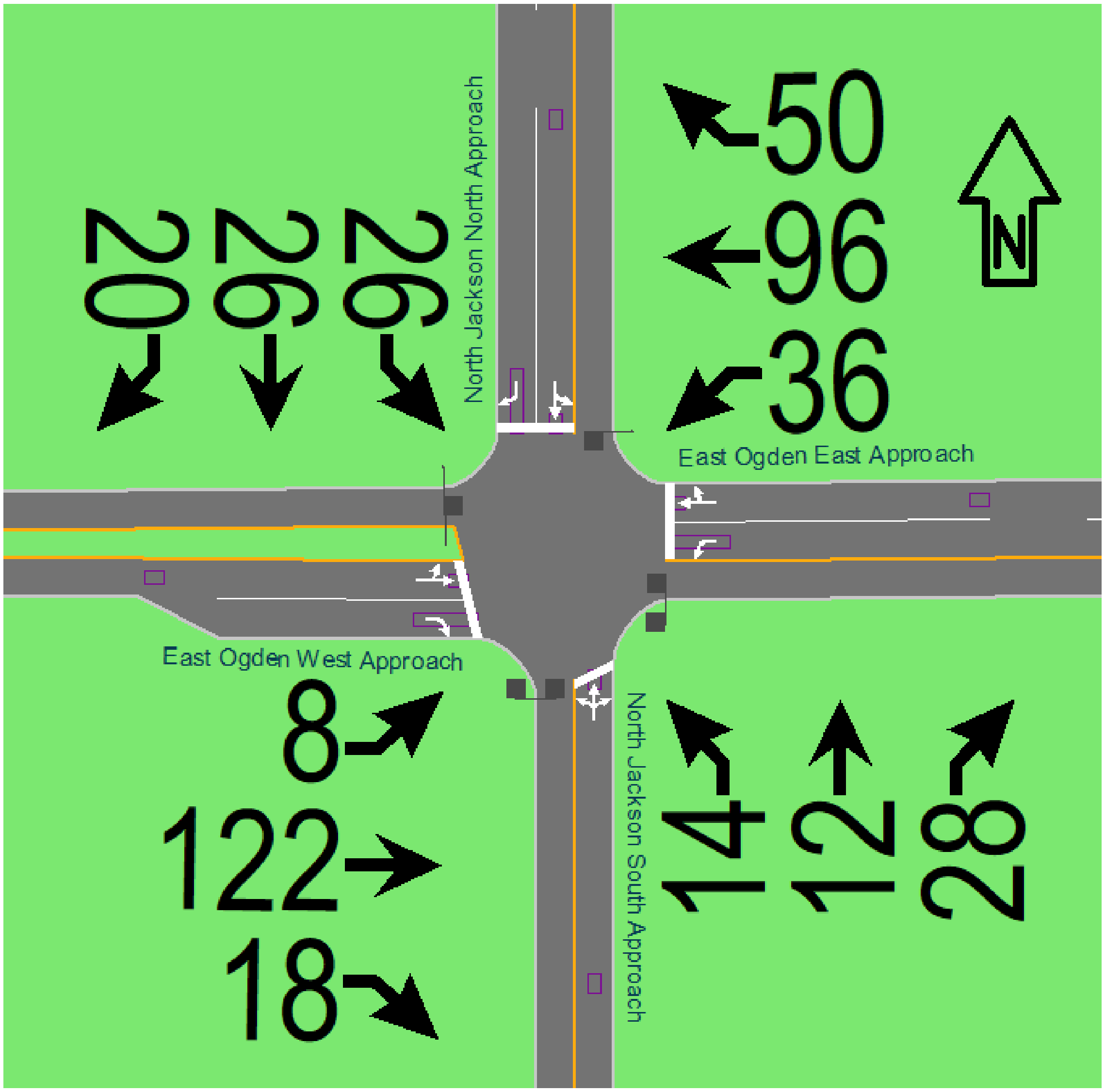

Figure 23: Alternative 3 Intersection Geometry.

Because of the addition of a lane on both approaches on East Ogden Ave., the control delay is split between the two lanes. Thus, the control delay listed in Table 8 is the weighted average based on volume per lane. This type of control delay is called approach delay because it is the weighted average of control delay for all lanes based on traffic volume per lane.

Table 8: Alternative 3 Control Delay.

Hop Movement	East Ogden Ave Approaches	Control Delay (sec/veh)
No Hop	West	5.3
	East	4.2
Left Turn	West	18.1
	East	4.2
Right Turn	West	5.9
	East	4.6
Average	West	8.7
	East	4.3

With Alternative 3, the west approach's average control delay is now 8.7 sec/veh, which is a 21.6 sec/veh reduction in control delay from the original intersection. The east approach now has an average control delay of 4.3 sec/veh, a reduction of 19.6 sec/veh.

3.5. Night Operation

Typically, an intersection experiences extremely low traffic volume late at night. When this occurs, the signalized intersection may be programmed to flash at night. The signalized intersection may operate flashing red for all approaches or flashing yellow for one roadway and flashing red for the other. The intersection of East Ogden Ave. and North Jackson St. was a 4-way stop before the implementation of The Hop. Therefore, it would make sense that the intersection outside of The Hop's operating hours would operate a flashing operation. Two-night flash models were developed for the intersection.

One was flashing red for all approaches. The other model had flashing red for the approaches on North Jackson St. and flashing yellow for the approaches on East Ogden Ave. While these models are not crucial to the results of the alternatives, they could be considered if the intersection were to be redone.

Chapter 4

Results and Discussion

4.0. Summary of Results

Table 9 is a summary of all control delays for each alternative. This table also lists, from highest to lowest, what impact cost each alternative would have.

Table 9: Summary of Simulation Results.

Hop Movement	East Ogden Ave Approaches (sec/veh)	Calibrated Model (sec/veh)	Alternative 1 (sec/veh)	Alternative 2 (sec/veh)	Alternative 3 (sec/veh)
No Hop	West	25.0	25.0	5.4	5.3
	East	23.3	23.3	4.7	4.2
Left Turn	West	49.1	42.2	20.1	18.1
	East	15.5	10.8	4.6	4.2
Right Turn	West	22.2	24.5	6.1	5.9
	East	36.6	25.5	5.3	4.6
Average	West	30.3	30.2	9.8	8.7
	East	23.9	20.6	4.8	4.3
Difference from Calibration Model	West	0	-0.1	-20.5	-21.6
	East	0	-3.3	-19.1	-19.6
Impact cost			Low	Medium	High

Overall, all alternatives reduced vehicular delay at the intersection for East Ogden Ave. approaches. The advantages and disadvantages of each alternative are summarized here. Alternative 1 is the easiest of the three alternatives to implement. However, it is also the least effective at reducing vehicular delay. Alternative 2 is associated with a moderate impact on implementation, requiring some traffic lights to be changed along with the timing for the intersection. However, compared to Alternative 1, Alternative 2 features a massive reduction in vehicular delay. Alternative 3 is associated with the largest cost impact requiring changes to both the roadway and traffic lights. However, the difference this makes from Alternative 2 is minimal. Thus, Alternative 2 is the recommended alternative because it is a good balance between having a low to medium cost impact while maintaining a considerable reduction in vehicular delay.

4.1. Recommendations

The recommendation in this capstone project is Alternative 2, in addition to one of the night operations; the reasoning behind this decision is that Alternative 2 significantly reduces vehicular delay compared to Alternative 1. While Alternative 3 has a greater vehicular delay reduction than Alternative 2, the impact cost is greater. The difference in the reduced vehicular delay between Alternatives 1 and 2 does not justify the increased cost to implement. For Alternative 2, the cost of implementation consists of changing traffic signal heads at the intersection and changing the traffic signal timing. The implementation cost of Alternative 3 is the same as Alternative 2 with the addition of roadway reconstruction. This could involve blocking access to this portion of East Ogden Ave. It also consists of removing street parking, which nearby businesses would likely fight to keep. Thus, the recommendation in this report is Alternative 2 if the intersection is redone.

While the intersection could be more efficient, this is not a pressing issue. Therefore, while Alternative 2 is recommended, immediate construction is not recommended. However, the implementation of one of the night operations would be preferred. Instead, it is recommended that this report be used as a pilot study to provide insight on potential solutions for future construction projects with similar circumstances.

4.2. What Could Have Been Done Differently

Some minor things that could have been done differently in this capstone project include conducting the delay study and traffic counts in favorable conditions. Collecting a full hour of traffic counts could have also been completed. Conducting a delay study for both North Jackson St. approaches and calibrating said approaches could also have been done. Would these have massively affected the outcome of the simulations? Unlikely; however, they would have increased the accuracy of simulated models. The primary thing that could have been done differently was acquiring full access to PTV VISSIM software. This would have allowed models to be modeled in an extremely accurate manner with respect to real-world conditions.

4.3. Future Research

The alternatives and the calibration model they are based on are not a full-depth analysis. They were built to demonstrate potential alternatives to the current intersection design. Future research could be conducted in validating these possible alternatives by conducting an in-depth analysis of each alternative to optimize further. It is further recommended that in future research, a fully licensed version of PTV VISSIM software be employed.

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Appendix A.

Traffic Signal Timing for the Intersection of North Jackson St & East Ogden Ave

N. JACKSON ST. & E. OGDEN AV.

DRAWING NO: B-19-667-T **SUPERCEDES:** B-18-787-T **TIME IN SERVICE:** 7/10/19 @1430

Date:	7/3/19
Signal No:	1102
Service:	
Master:	LOCAL
Cabinet/Controller:	P1 CABINET, COBALT SHELF MOUNT CONTROLLER- SOFTWARE VERSION 2.65
Auxiliary Equipment:	TRANSIT SIGNAL PRIORITY EQUIPMENT OPTICOM CONF. LIGHTS
Flash Program:	NONE- EMERGENCY ALL RED
Program Notes:	DAY PLAN 1: WEEKEND (SAT, SUN), DAY PLAN 2: WEEKDAY (MON-FRI) ACTION PLAN 1: OFFPEAK, ACTION PLAN 4: 1500-1800, ACTION PLAN 7: 0600-0900 PE 5: ON WB STREETCAR. DISPLAYS WB/WBLT PE6: ON NB STREETCAR. DISPLAYS NB/SB GREEN AND OMITS EXW PE 3: SB FIRE CALL. DISPLAYS NB/SB GREEN, MAX DELAY 19.5 SEC, DET DIST > 1300 FT PE 4: WB FIRE CALL. DISPLAYS WBLT/WB GREEN, MAX DELAY 19.5 SEC, DET DIST > 1300 FT

Phase and Overlap Descriptions

Phase	1	2	3	4	5	6	7	8
Description		SB WXW		WB/WBLT NXW		NB EXW		EB/EBLT SXW
Overlap	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Description				PE CONF				

Controller Sequence (MM)1-1-1
All Sequences (1-16) B B REMEMBER TO COPY SEQUENCE 1 TO ALL SEQUENCES

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Ring 1		2														
Ring 2		6	8	4												

Phases In Use / Exclusive PED (MM)1-2

Phase	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Phases in Use		X		X		X		X								
Exclusive PED																

Load Switch Assignments (MMU Channel) (MM)1-3

Switch	Phase/ Overlap	Type	Dimming				Flash		
			Red	Yellow	Green	Dark	Power	Auto	Together
1	4	O				+	R	R	
2	2	V				+	R	R	X
3						+			
4	4	V				+	R	R	
5						-			
6	6	V				-	R	R	X
7						-			
8	8	V				-	R	R	
9	2	P				+			X
10	4	P				+			
11	6	P				-			X
12	8	P				-			
13	0					+			
14	0					-			
15	0					+			
16	0					-			

Ethernet (MM)1-5-1
Controller IP: 10.70.10.51
Subnet Mask: 255.0.0.0
Default Gateway IP: 10.70.10.1
Server IP: 10.70.10.1
Link Speed/Duplex: Auto
Drop-out Time: 10

SDLC Port 1 Config (MM)1-4-1
Term & Facility: "X" FOR BIU 1 AND 2
Detector Rack: "X" FOR BIU 1

Enable MMU Extended Status: Yes
Enable SDLC Stop Time: No
Enable 3 Crit. RFEs Lockup: Yes
MMU to CU SDLC Ext. Start: Enabled

ECPIP (MM)1-5-6
Controller Address: 0

Color Check Enable (MM) 1-4-3
ENABLE COLOR CHECK: 'X'

MMU/LOAD SWITCH	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
RED		X		X		X		X								
YELLOW		X		X		X		X								
GREEN		X		X		X		X	X	X	X	X				

Designed By: KAP **Checked By:** VMAJ **Approved By:** SCR

N. JACKSON ST. & E. OGDEN AV.

DRAWING NO: B-19-667-T **SUPERCEDES:** B-18-787-T **TIME IN SERVICE:** 7/10/19 @1430

Controller Timing Plan (MM)2-1
All Timing Plans (1-4) REMEMBER TO COPY TIMING PLAN 1 TO ALL TIMING PLANS

Phase	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Min Green		12		12		12		12								
BK Min Green																
CS Min Green																
Delay Green																
Walk		7		7		7		7								
Walk 2																
Walk Max																
Ped Clear		10		10		10		10								
Ped Clear 2																
Ped Clear Max																
Ped CO																
Vehicle Ext																
Vehicle Ext 2																
Max 1		22		26		22		26								
Max 2																
Max 3																
DYM Max																
DYM Stp																
Yellow		4		4		4		4								
Red Clear		1.5		1.5		1.5		1.5								
Red Max																
Red Revert																
ACT B4																
SEC/ACT																
Max Int																
Time B4																
Cars Wt																
STPT Duc																
Time To Reduce																
Min Gap																

Vehicle Overlaps (MM)2-2

Vehicle/Pedestrian Overlaps (MM)2-3

Included	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16

Guaranteed Minimum Time Data (MM)2-4

Phase	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Min Green		12		12		12		12								
Walk																
Ped Clear		10		10		10		10								
Yellow		4		4		4		4								
Red Clr		1.5		1.5		1.5		1.5								
OVL Green																

N. JACKSON ST. & E. OGDEN AV.

DRAWING NO: B-19-667-T **SUPERCEDES:** B-18-787-T **TIME IN SERVICE:** 7/10/19 @1430

Controller Start/Flash (MM) 2-5

Start Up

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Phase		W				W										
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
Overlap																

Flash > Mon: No Flash Time: 10 All Red: 6 Pwr Start Seq: 1 MUTCD: Yes

Y>G: Yes

Automatic Flash

Phase	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Entry				X												
Exit		X				X										
Overlap	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**K**	**L**	**M**	**N**	**O**	**P**
Exit																

Flash > Mon: No Exit Flash: W Min Flash: 8 Min Recall: Yes Cycle Thru Phase: Yes

Controller Options (MM)2-6-1

Phase	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Dual Entry		X				X										

Act Pre-Time (MM)2-7

Pre-Time Mode Enable: YES

Free Input Enables Pre-Timed: NO

Phase	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Pre-Timed Phase				X				X								

Phase Recall Options (MM)2-8

All Timing Plans (1-4) **MANUALLY CHANGE FOR PLANS 2-4**

Phase	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Lock Detector																
Vehicle Recall		X		X		X		X								
Ped Recall		X		X		X		X								
Max Recall																
Soft Recall																
No Rest																
AI Calc																

Coordination Options (MM)3-1

Manual Pattern:	Auto
System Source:	TBC
Splits In:	Seconds
Transition:	ADDONLY
Dwell/Add Time:	90
Dly Coord Wk-Lz:	YES
Offset Reference:	YEL
Pedestrian Recall:	YES
Local Zero Override:	No
Re-Sync Count:	3

ECPI Coordination:	Yes
System Format:	STD
Offset In:	Seconds
Max Select:	Max1
Enable Man Sync:	No
Force Off:	Fixed
Cal Use Ped Tm:	No
Ped Reserve:	No
Fo Add Ini Grn:	Yes
Multisync:	No

N. JACKSON ST. & E. OGDEN AV.

DRAWING NO: B-19-667-T **SUPERCEDES:** B-18-787-T **TIME IN SERVICE:** 7/10/19 @1430

Pattern Data (MM)3-2

Coordinator Pattern – 1 - OFFPEAK

COPY PATTERN 1 TO ALL PATTERNS AND MANUALLY CHANGE 4 AND 7

Split Pattern	1
Cycle	90
Offset Value	6
Actuated Coord	Yes
Actuated Walk Rest	Yes
Phase Reservice	No
Max Select	None

Std (COS)	0
Dwell/Add Time	0
Timing Plan	1
Sequence	1
Action Plan	1
Force Off	Fixed

Coordinator Pattern – 4 - PM

Split Pattern	4
Cycle	90
Offset Value	14
Actuated Coord	Yes
Actuated Walk Rest	Yes
Phase Reservice	No
Max Select	None

Std (COS)	0
Dwell/Add Time	0
Timing Plan	1
Sequence	1
Action Plan	4
Force Off	Fixed

Coordinator Pattern – 7 - AM

Split Pattern	7
Cycle	90
Offset Value	86
Actuated Coord	Yes
Actuated Walk Rest	Yes
Phase Reservice	No
Max Select	None

Std (COS)	0
Dwell/Add Time	0
Timing Plan	1
Sequence	1
Action Plan	7
Force Off	Fixed

Split Pattern Data (MM)3-3

Split Pattern – 1 - OFFPEAK

COPY SPLIT PATTERN 1 TO ALL PATTERNS AND MANUAL CHANGE 4 AND 7

Phase	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Splits (seconds)		28		31		28		31	0	0	0	0	0	0	0	0
Coordinated Phases		X				X										
Vehicle Recalls																
Ped Recalls																
Max Recalls																
Phase Omit									X	X	X	X	X	X	X	X

Split Pattern – 4 - PM

Phase	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Splits (seconds)		28		31		28		31	0	0	0	0	0	0	0	0
Coordinated Phases		X				X										
Vehicle Recalls																
Ped Recalls																
Max Recalls																
Phase Omit									X	X	X	X	X	X	X	X

Split Pattern – 7 - AM

Phase	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Splits (seconds)		28		31		28		31	0	0	0	0	0	0	0	0
Coordinated Phases		X				X										
Vehicle Recalls																
Ped Recalls																
Max Recalls																
Phase Omit									X	X	X	X	X	X	X	X

N. JACKSON ST. & E. OGDEN AV.

DRAWING NO: B-19-667-T **SUPERCEDES:** B-18-787-T **TIME IN SERVICE:** 7/10/19 @1430

Action Plan (MM)5-2 COPY ACTION PLAN 1 TO ALL PLANS AND MANUALLY CHANGE 4, 7, AND 99 (IF NECESSARY)

Action Plan – 1 - OFFPEAK

Pattern	1	Override System	No
Timing Plan	1	Sequence	1
Veh Det Plan	1	Detector Log	None
Flash	No	Red Rest	No
Veh Det Diag Plan	1	Ped Det Diag Plan	1
Diming Enable	No		

Action Plan – 4 - PM

Pattern	4	Override System	No
Timing Plan	1	Sequence	1
Veh Det Plan	1	Detector Log	None
Flash	No	Red Rest	No
Veh Det Diag Plan	1	Ped Det Diag Plan	1
Diming Enable	No		

Action Plan – 7- AM

Pattern	7	Override System	No
Timing Plan	1	Sequence	1
Veh Det Plan	1	Detector Log	None
Flash	No	Red Rest	No
Veh Det Diag Plan	1	Ped Det Diag Plan	1
Diming Enable	No		

Action Plan – 99 – NIGHT FLASH (NOT USED)

Pattern	1	Override System	No
Timing Plan	1	Sequence	1
Veh Det Plan	1	Detector Log	None
Flash	No	Red Rest	No
Veh Det Diag Plan	1	Ped Det Diag Plan	1
Diming Enable	No		

Day Plan (MM)5-3

Day Plan – 1 – SAT, SUN

Event	Action Plan	Start Time
1	1	00:00
2	0	00:00

Day Plan – 2 – MON-FRI

Event	Action Plan	Start Time
1	7	06:00
2	1	09:00
3	4	15:00
4	1	18:00
5	0	00:00

Exception Day Program (MM)5-5

Day	Fixed/Float	Month	Day of Week/ Month	Week of Month/ Year	Day Plan
1	FIXED	1	1	0	1
2	FIXED	12	24	0	1
3	FIXED	12	25	0	1
4	FIXED	7	4	0	1
5	FLOAT	5	2	4	1
6	FLOAT	9	2	1	1
7	FLOAT	11	5	4	1
8	FLOAT	11	6	4	1

N. JACKSON ST. & E. OGDEN AV.

DRAWING NO: B-19-667-T **SUPERCEDES:** B-18-787-T **TIME IN SERVICE:** 7/10/19 @1430

Preempt Plan (MM)4-1 (Note: Engineering Department to set minimum entrance times)Remember to remove "override flash", add exit to coord

Preempt Plan 3 - Enable: Yes

Phase	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Enable Trailing	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Dwell Vehicle		X				X										
Dwell Overlap																

Preempt Plan 4 - Enable: Yes

Phase	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Enable Trailing	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Dwell Vehicle				X												
Dwell Overlap																

Preempt Plan 5 - Enable: YES EXIT OPT: XPH

Phase	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Enable Trailing	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Dwell Vehicle				X												
Dwell Ped				X												
EXIT PHASE								X								

Preempt Plan 6 - Enable: YES EXIT OPT: XPH

Phase	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Enable Trailing	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Dwell Vehicle		X				X										
Dwell Ped		X														
EXIT PHASE								X								

Vehicle Detector Assignment Plan (MM)6-1
All Plans

Detector	Call Phase	Call Phase																Type
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	
1		.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	N
2		.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	N
3		.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	N
4		.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	N
5		.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	N
6		.	.	.	.	.	..	.	.	.	.	.	.	.	.	.	.	N
7		.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	N
8		.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	N
9		.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	N
10		.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	N
11		.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	N
12		.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	N
13		.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	N
14		.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	N
15		.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	N
16		.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	N

Ped Detector Options (MM)6-3

Detector	Call Phase															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	X	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
2	.	X	.	.	.	X	.	.	.	.	.	.	.	.	.	.
3	.	.	X	.	.	.	.	.	.	.	.	.	.	.	.	.
4	.	.	.	X	.	.	.	.	.	.	.	.	.	.	.	.
5	.	.	.	.	X	.	.	.	.	.	.	.	.	.	.	.
6	.	X	.	.	.	X	.	.	.	.	.	.	.	.	.	.
7	.	.	.	.	.	.	X	.	.	.	.	.	.	.	.	.
8	.	.	.	.	.	.	.	X	.	.	.	.	.	.	.	.
9	.	.	.	.	.	.	.	.	X	.	.	.	.	.	.	.
10	.	.	.	.	.	.	.	.	.	X	.	.	.	.	.	.
11	.	.	.	.	.	.	.	.	.	.	X	.	.	.	.	.
12	.	.	.	.	.	.	.	.	.	.	.	X	.	.	.	.
13	.	.	.	.	.	.	.	.	.	.	.	.	X	.	.	.
14	.	.	.	.	.	.	.	.	.	.	.	.	.	X	.	.
15	.	.	.	.	.	.	.	.	.	.	.	.	.	.	X	.
16	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	X

Logic Processor Statement Control (MM)1-8-1

	1	2	3	4	5	6	7	8	9	0	1	2	3	4	5
LP 1-15	E	E	D	.	.	.	.	.	.	.	.	.	.	.	.
LP 16-30	D	D	.	.	.	.	.	.	.	.	.	.	.	.	.
LP 31-45	D	.	.	.	.	.	.	.	.	.	.	.	.	.	.
LP 46-60	D	D	.	.	.	.	.	.	.	.	.	.	.	.	.
LP 61-75	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
LP 76-90	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
LP 91-100	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.

LP 16: ON NB TSP, OMIT PED PHASE 6 (EXW)
LP 17: IF 2 OR 6 FDW ON FORCE OFF TSP 2
LP 31: IF CTR PHASE TIMING 7 (WBLT), THEN OMIT PHASE 8 (EB)
LP 46: IF TSP 1 ON, CALL PHASE 7
LP 47: IF TSP 2 ON, CALL PHASE 6

N. JACKSON ST. & E. OGDEN AV.

DRAWING NO: B-19-667-T **SUPERCEDES:** B-18-787-T **TIME IN SERVICE:** 7/10/19 @1430

(MM)4-3 TSP/SCP SPLIT PLAN

TSP/SCP PLAN	1	2	3	4	5	6	
SP/SCP ENA	NO	NO					
SIGNAL TYPE							
DET LOCK							ONLY USED IF SET TO "P"
DELAY TIME							TIME TO DELAY AFTER CHECKIN TO SERVE
MAX PRESENCE							MAX TIME TO HOLD CALL ACTIVE
PMT ENA RESVR							ALLOWS FOR TSP AFTER PREEMPT
NO DELAY IN TSP							NO DELAY COUNT IF TSP IS GREEN
ACT SF INHIBIT							SPECIFY SPEC. FUNCTIONS TO INHIBIT TSP
RESERVICE CYCLS							# OF CYCLES BETWEEN RESERVING
BUS HEADING							UNUSED UNLESS METRO RAPID
TSP OR SCP:	TSP						
FREE DEFAULT PLAN:	120						

TSP/SCP PHASE

Phase	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
TSP/SCP 1-WB																
TSP/SCP 2-NB																

(MM)4-4 TSP SPLIT PATTERN MODIFIER

TSP Split Pattern –1,4,7

Phase	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
MAX RDTN																
MIN GRN																

(MM)4-2 PREEMPT FILTERING & TSP/SCP

FILTERED INPUT	SOLID	PULSING
1	BYPASSED	BYPASSED
2	BYPASSED	BYPASSED
3	PREEMPT 3	BYPASSED
4	PREEMPT 4	BYPASSED
5	BYPASSED	PREEMPT 5
6	BYPASSED	PREEMPT 6

P1 CABINET

LOCATION

N. JACKSON ST.
&
E. OGDEN AV.

SHADED COMBINATIONS ARE PERMITTED

PHASE	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
DIRECTION	PE. CONF. LIGHTS	SB JACKSON	SPARE	WB/WBLT OGDEN	SPARE	NB JACKSON	SPARE	EB/EBLT OGDEN	W. X-WALK	N. X-WALK	E. X-WALK	S. X-WALK	.	.	.	.
	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	
	3	4	5	6	7	8	9	10	**11**	**12**	13	14	15	16		
	4	5	6	7	8	**9**	10	11	12	13	14	15	16			
	5	**6**	7	8	9	10	11	**12**	13	14	15	16				
	6	7	8	9	10	**11**	12	13	14	15	16					
	7	8	9	**10**	11	12	13	14	15	16						
	8	**9**	10	11	12	13	14	15	16							
	9	10	11	12	13	14	15	16								
	10	**11**	12	13	14	15	16									
	11	12	13	14	15	16										
	12	13	14	15	16											
	13	14	15	16												
	14	15	16													
	15	16														
	16															

DETECTOR RACK

	SW 1	SW 2	SW 3	SW 4	SW 5	SW 6	SW 7	SW 8	SW 9	SW 10
BIU 1									PE5	PE3
									PE6	PE4

LOAD SWITCH LOCATIONS

1	2	3	4	5	6
7	8	9	10	11	12

	PE	SB	-	WB	-	NB
	-	R	-	R	-	R
NB/SB CONF.	PE3	Y	-	Y	-	Y
EB/WB CONF.	PE4	G	-	G	-	G

-	EB	WXW	NXW	EXW	SXW
-	R	DW	DW	DW	DW
-	Y	-	-	-	-
-	G	W	W	W	W

MMU PROGRAM (MM)1-4-2

```
MMU PROGRAM [    MANUAL]    ERROR          v
     CH 6 5 4 3 2 1 0 9 8 7 6 5 4 3 2
      1 . . . . X X X X X . X . X . X
      2 . . . . . X . X . . X . . .
      3 . . . . . . . . . . . . .
      4 . . . . . . X . . . . .
      5 . . . . . . . . . . .
      6 . . . . . X . X . .
      7 . . . . . . . . .
      8 . . . . X . _ .
      9 . . . . . X .
     10 . . . . X .
     11 . . . . .
     12 . . . .
     13 . . .
     14 . .
```

NOTE: SET MINIMUM FLASH TIME IN MMU TO 8 SEC

NOTE: DISABLE DUAL INDICATION MONITORING FOR LOAD SWITCH 1 (PE CONF LIGHTS)

DRG. NO: B-19-667-T

Appendix B.

Delay Study Raw Data

①

EXHIBIT A16-1. INTERSECTION CONTROL DELAY WORKSHEET

INTERSECTION CONTROL DELAY WORKSHEET

General Information

Analyst	Anthony Lukowitz
Agency or Company	MSOE
Date Performed	2/4/2022
Analysis Time Period	PM

Site Information

Intersection	E Ogden & N Jackson
Area Type	■ CBD ☐ Other
Jurisdiction	Milwaukee
Analysis Year	2022

Input Initial Parameters

Number of lanes, N	1	Total vehicles arriving, V_{tot}	33
Free-flow speed, FFS (mi/h)	30	Stopped-vehicle count, V_{stop}	28
Survey count interval, I_s (s)	20	Cycle length, C (s)	90

Input Field Data

total vehicals	Clock Time	Cycle Number	Number of Vehicles in Queue — Count Interval 1	2	3	4	5	6	7	8	9	10
2	3:59	1	0	2	2	0	0					
0		2	0	0	0	0						
3		3	0	2	2	0	0					
2		4	1	2	0	0						
0		5	0	0	0	0	0					
2		6	0	1	0	0						
☆ 5		7	0	2	2	2	5					
4		8	6	7	1	1						
1		9	1	1	0	1	1					
2		10	3	0	0	0						
3		11	0	2	2	0	1					
3		12	2	2	0	0						
3		13	1	1	3	0	0					
3		14	1	3	0	0						
	Total		15	25	12	4	7					63

Computations

Total vehicles in queue, ΣV_{iq} =	63	Number of cycles surveyed, N_c =	14
Time-in-queue per vehicle, $d_{vq} = (I_s * \frac{\Sigma V_{iq}}{V_{tot}}) * 0.9$	34.36 s	Fraction of vehicles stopping, FVS = $\frac{V_{stop}}{V_{tot}}$	0.85
No. of vehicles stopping per lane each cycle = $\frac{V_{stop}}{(N_c \times N)}$	2.35	Accel/Decel correction delay, d_{ad} = FVS * CF	4.24 s
Accel/Decel correction factor, CF (Ex. A16-2)	5	Control delay/vehicle, $d = d_{vq} + d_{ad}$	38.60 s

EXHIBIT A16-1. INTERSECTION CONTROL DELAY WORKSHEET

INTERSECTION CONTROL DELAY WORKSHEET

General Information

Analyst: Anthony Lukowitz
Agency or Company: MSOE
Date Performed: 2/9/2022
Analysis Time Period: PM

Site Information

Intersection: E Ogden & N Jackson
Area Type: ■ CBD ☐ Other
Jurisdiction: Milwaukee
Analysis Year: 2022

Input Initial Parameters

Number of lanes, N: 1
Free-flow speed, FFS (mi/h): 30
Survey count interval, I_s (s): 20

Total vehicles arriving, V_{tot}: 31
Stopped-vehicle count, V_{stop}: 14
Cycle length, C (s): 90

Input Field Data

total vehicals	Clock Time	Cycle Number	Number of Vehicles in Queue — Count Interval 1	2	3	4	5	6	7	8	9	10
3	4:28	1	0	1	1	2	0					
1		2	0	0	0	0						
☆ 2		3	0	0	0	0	0					
3		4	0	0	0	0						
3		5	0	2	2	2	3					
1		6	0	0	0	0						
1		7	0	0	1	1	0					
☆ 5		8	0	1	2	0						
2		9	0	0	0	0	0					
2		10	0	0	0	1						
4		11	0	1	3	3	0					
0		12	0	0	0	0						
1		13	0	1	1	1	0					
☆ 3		14	0	1	0	0						
	Total		0	7	10	10	3					30

Computations

Total vehicles in queue, ΣV_{iq} = 30

Time-in-queue per vehicle, $d_{vq} = (I_s * \frac{\Sigma V_{iq}}{V_{tot}}) * 0.9$ = 17.42 s

No. of vehicles stopping per lane each cycle = $\frac{V_{stop}}{(N_c \times N)}$ = 1

Accel/Decel correction factor, CF (Ex. A16-2) = 5

Number of cycles surveyed, N_c = 14

Fraction of vehicles stopping, $FVS = \frac{V_{stop}}{V_{tot}}$ = 0.45

Accel/Decel correction delay, $d_{ad} = FVS * CF$ = 2.26 s

Control delay/vehicle, $d = d_{vq} + d_{ad}$ = 19.68 s

(11)

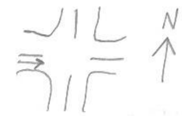

EXHIBIT A16-1. INTERSECTION CONTROL DELAY WORKSHEET

INTERSECTION CONTROL DELAY WORKSHEET

General Information

Analyst: Anthony Lukowitz
Agency or Company: MSOE
Date Performed: 3/9/2022
Analysis Time Period: PM

Site Information

Intersection: E Ogden & N Jackson
Area Type: ■ CBD ☐ Other
Jurisdiction: Milwaukee
Analysis Year: 2022

Input Initial Parameters

Number of lanes, N: 1
Free-flow speed, FFS (mi/h): 30
Survey count interval, I_s (s): 20
Total vehicles arriving, V_{tot}: 32
Stopped-vehicle count, V_{stop}: 25
Cycle length, C (s): 90

Input Field Data

	total vehicals	Clock Time	Cycle Number	Number of Vehicles in Queue – Count Interval 1	2	3	4	5	6	7	8	9	10
☆	2	3:57	1	0	0	0	0	2					
	1		2	0	0	0	2						
	4		3	2	3	3	0	1					
	2		4	1	2	0	0						
	1		5	0	0	0	0	0					
	2		6	1	2	0	0						
☆	2		7	0	1	0	0	0					
	2		8	1	2	2	2						
	6		9	0	0	0	1	1					
	3		10	1	2	0	1						
	5		11	1	4	5	0	0					
	2		12	0	1	0	0						
	2		13	1	1	1	0	0					
☆	4		14	3	4	4	0						
		Total		11	22	15	6	4					58

Computations

Total vehicles in queue, ΣV_{iq} = 58
Time-in-queue per vehicle, $d_{vq} = (I_s * \frac{\Sigma V_{iq}}{V_{tot}}) * 0.9$ = 32.63 s
No. of vehicles stopping per lane each cycle = $\frac{V_{stop}}{(N_c \times N)}$ = 1.78
Accel/Decel correction factor, CF (Ex. A16-2) = 5
Number of cycles surveyed, N_c = 14
Fraction of vehicles stopping, $FVS = \frac{V_{stop}}{V_{tot}}$ = 0.78
Accel/Decel correction delay, d_{ad} = FVS * CF = 3.91 s
Control delay/vehicle, $d = d_{vq} + d_{ad}$ = 36.54 s

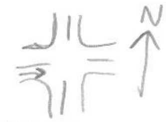

EXHIBIT A16-1. INTERSECTION CONTROL DELAY WORKSHEET

INTERSECTION CONTROL DELAY WORKSHEET

General Information

Analyst: Anthony Lukowitz
Agency or Company: MSOE
Date Performed: 3/9/2022
Analysis Time Period: PM

Site Information

Intersection: E Ogden & N Jackson
Area Type: ■ CBD ☐ Other
Jurisdiction: Milwaukee
Analysis Year: 2022

Input Initial Parameters

Number of lanes, N: 1
Free-flow speed, FFS (mi/h): 30
Survey count interval, I_s (s): 20
Total vehicles arriving, V_{tot}: 34
Stopped-vehicle count, V_{stop}: 24
Cycle length, C (s): 90

Input Field Data

total vehicals	Clock Time	Cycle Number	Number of Vehicles in Queue — Count Interval 1	2	3	4	5	6	7	8	9	10
3	4:21	1	1	2	3	0	2					
6		2	4	4	0	0						
3		3	1	1	1	0	0					
☆ 1		4	0	0	0	1						
2		5	0	0	0	0	1					
4		6	1	1	2	0						
☆ 1		7	0	1	0	0	0					
4		8	1	2	4	0						
0		9	0	0	0	0	0					
2		10	0	0	2	0						
0		11	0	0	0	0	2					
☆ 6		12	0	0	3	0						
2		13	0	0	1	1	1					
		14	0	0	0	0						
	Total		8	11	16	2	6					43

Computations

Total vehicles in queue, ΣV_{iq} = 43

Time-in-queue per vehicle, $d_{vq} = (I_s * \frac{\Sigma V_{iq}}{V_{tot}}) * 0.9$ = 22.76 s

No. of vehicles stopping per lane each cycle = $\frac{V_{stop}}{(N_c \times N)}$ = 1.71

Accel/Decel correction factor, CF (Ex. A16-2) = 5

Number of cycles surveyed, N_c = 14

Fraction of vehicles stopping, $FVS = \frac{V_{stop}}{V_{tot}}$ = 0.71

Accel/Decel correction delay, $d_{ad} = FVS * CF$ = 3.53 s

Control delay/vehicle, $d = d_{vq} + d_{ad}$ = 26.30 s

②

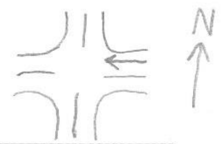

EXHIBIT A16-1. INTERSECTION CONTROL DELAY WORKSHEET

INTERSECTION CONTROL DELAY WORKSHEET

General Information		Site Information	
Analyst	Anthony Lukowitz	Intersection	E Ogden & N Jackson
Agency or Company	MSOE	Area Type	■ CBD ☐ Other
Date Performed	2/9/2022	Jurisdiction	Milwaukee
Analysis Time Period	PM	Analysis Year	2022

Input Initial Parameters

Number of lanes, N	1	Total vehicles arriving, V_{tot}	55
Free-flow speed, FFS (mi/h)	30	Stopped-vehicle count, V_{stop}	30
Survey count interval, I_s (s)	20	Cycle length, C (s)	90

Input Field Data

total vehicles	Clock Time	Cycle Number	1	2	3	4	5	6	7	8	9	10	
2	4:53		0	0	0	0	0						RLR
1			0	0	0	0							
6			0	3	4	0	0						
7			1	1	0	0							
3			0	2	0	0	0						
1			0	1	0	0							
7			0	2	4	0	2						
6			3	4	0	0							
☆↱ 0			0	1	2	2	3						
7			3	3	6	6							
0			0	0	1	1	2						
6			2	2	0	0							
5			0	0	3	0	0						
4			2	3	0	0							
	Total		11	22	20	9	7					69	

(Number of Vehicles in Queue, by Count Interval 1–10)

Computations

Total vehicles in queue, ΣV_{iq} =	69	Number of cycles surveyed, N_c =	14
Time-in-queue per vehicle, $d_{vq} = (I_s * \frac{\Sigma V_{iq}}{V_{tot}}) * 0.9$	22.58 s	Fraction of vehicles stopping, $FVS = \frac{V_{stop}}{V_{tot}}$	0.55
No. of vehicles stopping per lane each cycle = $\frac{V_{stop}}{(N_c \times N)}$	2.14	Accel/Decel correction delay, d_{ad} = FVS * CF	2.73 s
Accel/Decel correction factor, CF (Ex. A16-2)	5	Control delay/vehicle, $d = d_{vq} + d_{ad}$	25.31 s

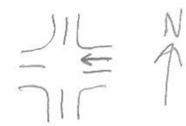

EXHIBIT A16-1. INTERSECTION CONTROL DELAY WORKSHEET

INTERSECTION CONTROL DELAY WORKSHEET

General Information

Analyst	Anthony Lukowitz
Agency or Company	MSOE
Date Performed	2/9/2022
Analysis Time Period	PM

Site Information

Intersection	E Ogden & N Jackson
Area Type	■ CBD ☐ Other
Jurisdiction	Milwaukee
Analysis Year	2022

Input Initial Parameters

Number of lanes, N	1	Total vehicles arriving, V_{tot}	57
Free-flow speed, FFS (mi/h)	30	Stopped-vehicle count, V_{stop}	38
Survey count interval, I_s (s)	20	Cycle length, C (s)	90

Input Field Data

total Vehicals	Clock Time	Cycle Number	Number of Vehicles in Queue — Count Interval 1	2	3	4	5	6	7	8	9	10	
☆ 2	5:16		0	0	0	0	1						
☆ 6			1	2	2	2							
7			3	5	0	0	2						
5			3	4	0	0							
8			1	3	8	0	0						
5			0	2	0	0							
1			0	0	0	0	0						
☆ 5			2	4	0	0							
6			2	3	0	0	1						RLR
4			1	2	0	0							
0			0	0	0	0	0						
4			0	0	0	0							
9			4	4	9	0	0						
3			0	1	0	0							RLR
	Total		17	30	19	2	4					72	

Computations

Total vehicles in queue, ΣV_{iq} =	72	Number of cycles surveyed, N_c =	14
Time-in-queue per vehicle, $d_{vq} = (I_s * \frac{\Sigma V_{iq}}{V_{tot}}) * 0.9$	22.74 s	Fraction of vehicles stopping, $FVS = \frac{V_{stop}}{V_{tot}}$	0.67
No. of vehicles stopping per lane each cycle = $\frac{V_{stop}}{(N_c \times N)}$	2.71	Accel/Decel correction delay, d_{ad} = FVS * CF	3.33 s
Accel/Decel correction factor, CF (Ex. A16-2)	5	Control delay/vehicle, $d = d_{vq} + d_{ad}$	26.07 s

22

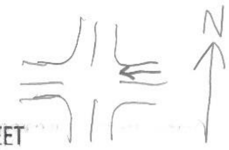

EXHIBIT A16-1. INTERSECTION CONTROL DELAY WORKSHEET

INTERSECTION CONTROL DELAY WORKSHEET

General Information

Analyst: Anthony LuKavitz
Agency or Company: MSOE
Date Performed: 3/9/2022
Analysis Time Period: PM

Site Information

Intersection: E Ogden & N Jackson
Area Type: ■ CBD ☐ Other
Jurisdiction: Milwaukee
Analysis Year: 2022

Input Initial Parameters

Number of lanes, N: 1
Free-flow speed, FFS (mi/h): 30
Survey count interval, I_s (s): 20
Total vehicles arriving, V_{tot}: 70
Stopped-vehicle count, V_{stop}: 43
Cycle length, C (s): 90

Input Field Data

total Vehicals	Clock Time	Cycle Number	Number of Vehicles in Queue – Count Interval 1	2	3	4	5	6	7	8	9	10	
2	4:49	1	1	1	1	0	0						
5		2	0	1	0	0							
★↙ 8		3	1	2	6	0	0						
6		4	3	4	0	0							
3		5	1	1	2	0	1						
3		6	1	1	0	0							
3		7	0	0	0	0	1						
6		8	4	4	0	0							
★↗ 0		9	0	0	0	0	2						Vehical Stoppe in intersection
10		10	4	10	10	0							
1		11	0	0	2	3	4						
7		12	4	0	0	1							
8		13	3	7	0	0	0						
8		14	0	0	0	0							
	Total		22	31	21	4	8					86	

Computations

Total vehicles in queue, ΣV_{iq} = 86
Time-in-queue per vehicle, $d_{vq} = (I_s * \frac{\Sigma V_{iq}}{V_{tot}}) * 0.9$ = 22.11 s
No. of vehicles stopping per lane each cycle = $\frac{V_{stop}}{(N_c \times N)}$ = 3.07
Accel/Decel correction factor, CF (Ex. A16-2) = 5
Number of cycles surveyed, N_c = 14
Fraction of vehicles stopping, FVS = $\frac{V_{stop}}{V_{tot}}$ = 0.61
Accel/Decel correction delay, d_{ad} = FVS * CF = 3.07 s
Control delay/vehicle, $d = d_{vq} + d_{ad}$ = 25.18 s

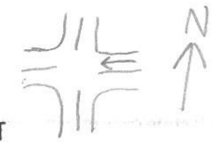

EXHIBIT A16-1. INTERSECTION CONTROL DELAY WORKSHEET

INTERSECTION CONTROL DELAY WORKSHEET

General Information

Analyst: Anthony Lukowitz
Agency or Company: MSOE
Date Performed: 3/9/2022
Analysis Time Period: PM

Site Information

Intersection: E Ogden & N Jackson
Area Type: ■ CBD ☐ Other
Jurisdiction: Milwaukee
Analysis Year: 2022

Input Initial Parameters

Number of lanes, N: 1
Free-flow speed, FFS (mi/h): 30
Survey count interval, I_s (s): 20
Total vehicles arriving, V_{tot}: 68
Stopped-vehicle count, V_{stop}: 29
Cycle length, C (s): 90

Input Field Data

total vehicals	Clock Time	Cycle Number	Number of Vehicles in Queue, Count Interval 1	2	3	4	5	6	7	8	9	10
3	5:19	1	0	0	0	0	0					
6		2	4	4	0	0						
☆ 8		3	2	2	4	0	0					
4		4	0	0	0	0						
6		5	1	1	4	0	0					
7		6	1	1	0	0						
6		7	0	2	2	0	0					
4		8	0	0	0	0						
☆ 0		9	1	2	2	5	5					
8		10	6	0	0	0						
1		11	1	1	1	0	0					
7		12	1	2	0	0						
5		13	1	2	4	0	0					
3		14	1	1	0	0						
	Total		19	18	17	5	5					64

RLR

Computations

Total vehicles in queue, ΣV_{iq} = 64
Time-in-queue per vehicle, $d_{vq} = (I_s * \frac{\Sigma V_{iq}}{V_{tot}}) * 0.9$ = 16.94 s
No. of vehicles stopping per lane each cycle = $\frac{V_{stop}}{(N_c \times N)}$ = 2.07
Accel/Decel correction factor, CF (Ex. A16-2) = 5
Number of cycles surveyed, N_c = 14
Fraction of vehicles stopping, FVS = $\frac{V_{stop}}{V_{tot}}$ = 0.43
Accel/Decel correction delay, d_{ad} = FVS * CF = 2.13 s
Control delay/vehicle, $d = d_{vq} + d_{ad}$ = 19.07 s

Civil Engineering

Capstone Report Approval Form

Master of Science in Civil Engineering – MSCVE

Milwaukee School of Engineering

This capstone report, titled "How Vehicular Delay is Affected at Signalized Intersections with Light Rail Transit," submitted by the student Anthony G. Lukowitz, has been approved by the following committee:

Faculty Advisor: ______________________________ Date: _May 13, 2022____

Dr. Mitzi Dobersek, PhD.

Faculty Member: ______________________________ Date: _May 13, 2022____

Dr. Jera Sullivan, PhD.

Faculty Member: ______________________________ Date: _May 13, 2022_____

Dr. Todd Davis, PhD.