University of Nevada, Reno

Strategies for Signal Timing and Coordination for Bicycle Progression

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by

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FOR BICYCLE PROGRESSION

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ABSTRACT

Current signal timing practices in the United States typically give vehicles the highest priority which can make travel by other modes challenging or time consuming. Bicycles are an example of these other modes that are not often prioritized. Due to their generally slow speeds, cyclists typically cannot keep up with timing plans designed for vehicle speeds. This can lead to increased stops and delays, souring the cycling experience.

In places that do accommodate cyclists like the Netherlands, standard practice is to coordinate signals by designing for bicycle speeds. In the US, cities like Portland, OR and San Francisco, CA have adopted this practice in places, lowering speed limits and coordinating for bikes, and have become known for their relatively high numbers of cyclists. The other approach to this problem is to keep vehicles at their own speeds, but to also consider bicycle progression. Due to its complexity, this approach is much less popular. At the time of this research, there are few papers or case studies taking this approach.

This research looks into the second approach of coordinating with vehicles and bicycles traveling at different speeds. The effort of this research can be divided into a conceptual

method and an empirical method. The first method uses the relationship between vehicle and bicycle speeds to determine optimal cycle lengths or split lengths to create bandwidth for both speeds. This conceptual method calculates precise timing parameters that can provide ideal results. However, the calculated parameters may not reasonably serve intersection demand and thus, this method is limited by whether road segment lengths and mode speeds produce useable values.

The second method is a brute force approach that takes timing plans and empirically grades them on potential for vehicle and bicycle progression based on timing inputs and expected travel results. This grade is representative of the overall quality of a plan for both vehicle and bicycle progression and can quickly be compared with other plans. The grading was calibrated with simulation done using Vissim for the Center St corridor in Reno, Nevada.

Previous signal timing practices typically coordinated for one mode and then adjusted where possible to improve progression for the other, making the second an afterthought in terms of the timing and performance. This research provides a method for designing signal timing while looking at both modes simultaneously for fairer treatment. Provided the calculated timing parameters are sufficient for demand, the first method gives values that can guarantee similar vehicle and bicycle progression, but the second method is more widely applicable and can be used if the requirements for the first method are not met. It is recommended to use the first method, the TTD-Cycle method, if applicable but the second, TSD Performance Estimator, serves as a generally applicable backup.

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CHAPTER ONE

THE STATE OF CYCLING IN AMERICA

1.1 Introduction

The coordination of traffic signals along a corridor can greatly improve the efficiency of those signals and the system. By properly offsetting the timing of the downstream signals, traffic engineers can ensure that the downstream signals turn green with the arrival of the upstream platoon of vehicles (known as a green wave), thus minimizing delays caused by red lights as well as driver frustrations, pollution from idling, and congestion and stress on the system. Most places in the United States are designed around driving and a large percentage of the population gets around using personal vehicles; data from the National Personal Transportation Survey in 1990 and the National Household Travel Surveys in 2001 and 2009, summarized in Chapter 8 of a report from the Office of Transportation Policy Studies, showed that over 80% of participants relied on either single occupancy vehicles or high occupancy vehicles for their commutes (Blumenberg et al., 2013). However, this tremendous focus on maximizing system efficiency around personal vehicles often comes at the expense of other modes of transportation such as walking, cycling, and transit.

Looking at the United States as a whole, the number of cyclists and the percentage they occupy as a primary mode of transport have gradually grown over the past two decades (*The State of Bike Commuting*, 2021). Additionally, research conducted in 2016 by the National Association of City Transportation Officials (NACTO) in seven cities showed a positive correlation between building bicycle infrastructure and increases in cycling, and more importantly, a reduction in risk (*High-quality bike facilities,* 2016). There are many advantages to bicycles and cycling. From a personal standpoint, the initial and maintenance costs tend to be much lower for bicycles compared to vehicles and cycling contributes to a healthy lifestyle. From a societal standpoint, bicycles produce less emissions, occupy less roadway and parking space, and can encourage the development of neighborhoods as desirable places to live. Bicycles as transport work best in places that are also walkable – places with high-density housing that tend to have close and easy access to shopping, schools, and parks. It has been shown that neighborhoods that are perceived to have higher walkability tend to have higher property values (Cortright, 2009); people want to live in places where driving is optional rather than mandatory. The promotion of walking and cycling, and the construction of their supporting infrastructure is the development of prosperous neighborhoods.

There is another benefit to the tighter density of walkable neighborhoods. More closely packed neighborhoods means that people can cut down on their daily travel because their needs are closer. Combined with the fact that bicycles are much smaller than vehicles and utilize less roadway space, an increase in cyclists and a decrease in drivers naturally lends itself to helping reduce roadway congestion. By cutting down on the ubiquity of vehicles and spreading out and investing into bicycles and other infrastructure systems, we can develop cities that are denser, and thus faster to travel around, healthier, wealthier, and more environmentally friendly.

1.2 Cycling as Transportation

In the United States, interest in cycling as a mode of transportation has picked up in the past few decades with notable cities like New York, NY; Portland, OR; San Francisco, CA; Boulder, CO; and others building infrastructure like dedicated bike lanes. While design of bicycle infrastructure in the past had largely been experimental and at a municipal level, the release of the Urban Bikeway Design Guide, developed by NACTO in 2012 and endorsed by the Federal Highway Administration (FHWA) in 2013, has set the standard for which bicycle infrastructure in North American cities will most likely be built.

However, even with the infrastructure to support cycling, current signal timing coordination methods can make cycling as a form of transportation difficult. In a lot of cities, cyclists are treated as vehicles, riding on the roadway and following roadway rules including obeying signals. One of the difficulties for cyclists is stopping at intersections due to red lights. On major roadways with heavy traffic and closely packed intersections, signals are coordinated to help move vehicles through all intersections without stopping. This is done by delaying or offsetting the green at downstream intersections so that they start as vehicles begin to approach. If done for all intersections, a window of opportunity, or bandwidth is created where staying within the band guarantees uninterrupted progression along a corridor. However, a problem arises with bicycles. They tend to travel much slower than vehicles and lag out of the band. In many cities, the lowest speed limits, generally small roads in and around residential neighborhoods, range from 25-35 mph. Most cycling blogs and websites generally agree that beginner cyclist travels in the range of 10-15 mph, with more experienced cyclists managing to achieve above 20 mph (*Average cycling speed,* n.d.). Other factors can affect those speeds such as terrain, weather, and traffic control devices, but using the average cyclist speeds, even on the lowest speed roads, vehicles are two to three times faster than bicycles. This difference means that with a vehicle and a bicycle starting at the same location, a gap inevitably forms with that gap growing larger over time and exceeding the bandwidth; when it comes to current signal timing methods designed around vehicles, whether or not a cyclist reaches an intersection during a red or green is largely up to luck and in the worst case, they reach each intersection as it turns red and are forced to come to a stop at every intersection for maximum stops and delay. To truly promote cycling, signal timing methods should also accommodate bicycles.

1.3 Research Goals and Questions

To promote cycling as a form of transportation, cities need to maximize convenience for cyclists along corridors that have bicycle infrastructure (e.g., cycle tracks and bicycle signal heads) by ensuring that such infrastructure is being used effectively. This research especially looks at reducing stops and travel time for cyclists through the signal timing, preferably without too heavily impacting vehicle progression.

1.3.1 Research Goals

Bicycle signal heads allow for dedicated bike phases that ensure a period in which cyclists are allowed to cross an intersection. The goal of this research is to develop a methodology for designing signal timing that accounts for both vehicles and bicycles. Ideally, there is a relationship between vehicle and bicycles speeds that produces some value that can be set as some timing variable and results in good progression for both vehicles and bicycles.

1.3.2 Research Questions

These questions provide the basis for the research goal:

- Is there a relationship between vehicle and bicycle speeds, and some timing parameter that produces "good" progression for both modes?
    - How is that relationship used?
    - Are there conditions necessary to achieve this?
- Presuming such a relationship does not exist or results in parameters that are unusable, what method should be used to design signal timing that accounts for both vehicle and bicycle progression?
    - How do we judge the quality of a signal timing plan that may result in good progression for one mode, but not for the other?

1.4 Organization of Study

The study is organized into six chapters. Chapter One discusses the state of cycling as a form of transportation in the United States. Chapter Two looks at existing literature and previous studies done for the coordination of traffic signals for bicycle progression. Chapter Three discusses the methodology and design of the progression strategies. Chapter Four covers the first main question mentioned above and propose methods for tackling the challenge of bicycle progression from the standpoint of adjusting timing parameters in order to guarantee progression for both modes. Chapter Five covers the second main question mentioned above and proposes a method for tackling the issue of balancing the needs of both vehicles and bicycles when there is no clear solution for progressing both. The Chapter Six summarizes the major findings and recommends a course of action for signal coordination for bicycle progression.

1.5 Terms and Definitions

This following section defines terms and abbreviations commonly used in this thesis and in the field of signal timing:

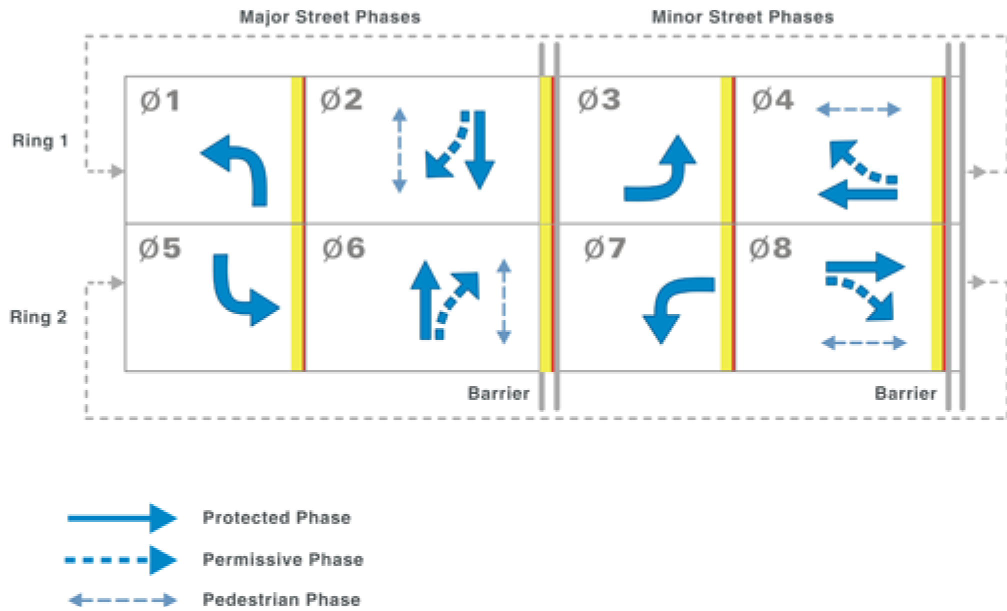
Bandwidth: Window of time when a vehicle traveling from the starting intersection is able to make it past the target intersection without stopping due to the alignment of the greens. Link bandwidth refers to the window between two adjacent intersections while thru bandwidth looks at the window for the whole corridor. The thru band is less than or equal to the smallest link band and may possibly not exist on a timing plan meaning at least one stop needs to be made at an intersection.

Bike Signal Head: A separate signal head at intersections dedicated for bicycle usage. The separate signal head allows for bicycles to have a dedicated phase.

Cycle Track: A physically separated segment of the roadway dedicated for bicycle usage. The physical separation with barriers such bollards or an elevated track differentiates cycle tracks from bike lanes, which are marked only with paint, and contributes to an increase in safety.

Cycle (Length): Total time it takes to service all movements at an intersection. After servicing all movements, the cycle repeats. Signals in coordination typically share the same cycle length so that every cycle has the same progression pattern. Figure 1 shows an example ring-barrier diagram, a typical representation of a cycle. The cycle is divided between two horizontal rings that show phases that are allowed to run concurrently (no conflicts) and with a vertical barrier to separate the major street movements from the minor street.

Figure 1: Example Ring-Barrier Diagram



Source: FHWA *Traffic Signal Timing Manual* Chapter 4, 2008

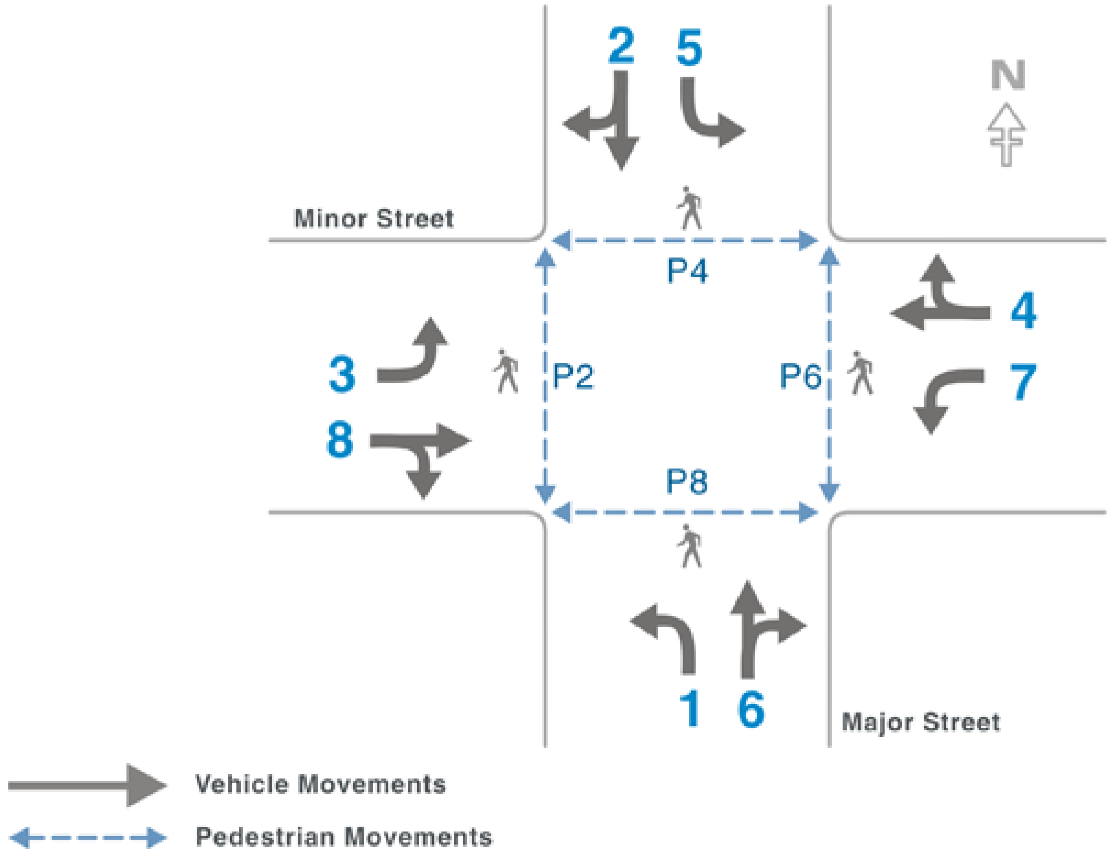
Green wave: The coordination of a group of consecutive traffic signals to allow for continuous flow between several intersections. This is commonly seen when driving when hitting multiple green lights in a row.

Offset: Reference point for an intersection; based off a master clock. An offset determines when the cycle at its intersection "begins" and is key in coordinating multiple signals for green waves. Points for reference include the start of green, end of green/start of yellow, end of yellow/start of red, and end of barrier. Typically, the coordinated phase is used as the reference phase.

Phase/Split: Portion of time within a cycle allotted to its assigned movement. This time is the sum of a phase's green, yellow, and red times. In standard NEMA phasing, typical 4-leg intersections will use 8 phases with each leg having separate left-turn and through movement phases. Figure 2 shows a 4-leg intersection with NEMA phasing. Phase and split are used interchangeably in this paper to refer to either the movement or the time assigned to the movement.

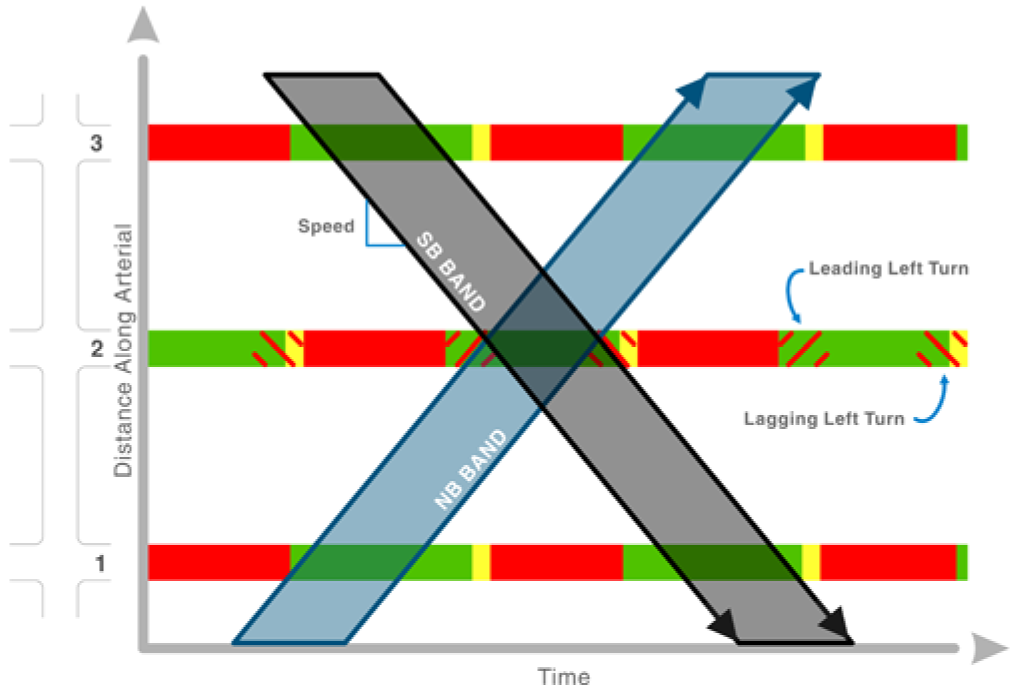
Time Space Diagram (TSD): Visual representation of signal timing and progression along a corridor. Figure 3 shows an example TSD. The X-axis represents time, and the Y-axis represents position along a given corridor. Travel is represented solely on the Y-axis along the corridor of interest, regardless of the curvature or direction of the roadway; movement along the X-axis is strictly forward in time, or to the right. The slopes of the bands are defined by the speed limit; travelling at the speed limit results in staying parallel to the edges and allows a vehicle to stay within the band.

Figure 2: Standard NEMA Phasing at 4-Leg Intersection



Source: FHWA *Traffic Signal Timing Manual* Chapter 4, 2008

Figure 3: Time Space Diagram Example



Source: FHWA Traffic Signal Timing Manual Chapter 6, 2008

Protected Turn: Indicated by a green arrow rather than a flashing yellow or solid green ball. Guarantees the turning movement has an opportunity to go rather than being forced to yield and find a gap.

Sequence: Order phases appear within the cycle. Phases are allowed to move within their ring and barrier without conflict for standard phasing.

CHAPTER TWO

LITERATURE REVIEW: CURRENT STATE OF BICYCLE PROGRESSION TECHNIQUES AND CASE STUDIES

2.1 Introduction

Current strategies for bicycle progression can generally be grouped into two categories. The first strategy is to prioritize bicycles and design signal coordination around bicycle speeds. As stated previously, the problem with bicycle progression is that signal coordination is typically designed for vehicle speeds, which even at lower speed limits is much higher than speeds achievable by average cyclists and thus, by the time cyclists have reached the next intersection, the green is no longer guaranteed. By reducing the speed limit and the design speed, the issue of bicycles lagging behind and falling out of the bandwidth is avoided and thus any coordination plan is able to serve both vehicles and bicycles. The second strategy attempts to accommodate both vehicles and bicycles moving at different speeds. Usually in this case, the coordination plan is first designed around vehicles and then small adjustments are made where possible, such as extending the duration of a split or shifting an offset over a few seconds, to allow bicycles to make it past without stopping.

2.2 Bicycle Green Wave

The coordination of traffic signals to allow for smooth progression at bicycles speeds is generally known as a “bicycle green wave”. In Copenhagen, Denmark, where cycling is a much more common mode of transportation, many streets are already timed for bicycle green waves. In the United States, cities such as Portland, Oregon and San Francisco, California, as well as others, have tested and implemented bicycle green waves along some of their streets.

The strength of bicycle green waves lies in its simplicity; changing the design speed has no significant impact on the coordination design process. In this case, bicycle movements are controlled by their vehicle counterparts' phase. For example, a northbound moving cyclist should follow the same signals of the northbound vehicle movements. This method has the added benefit of not requiring separate bicycle signal heads and phasing; however, a separate bike signal head would allow adding in a brief bicycle-only period to help avoid potential conflicts with right-turning vehicles. In the U.S., even in cities with higher-than-average number of cyclists, vehicle traffic is much higher than bicycle traffic. As a result, cyclists generally only utilize a small portion of the bandwidth and split lengths determined by vehicle volumes are sufficient for bicycles.

Bicycle green waves generally work well in downtown or commercial areas, where the high volume of vehicles can end up resulting in average speeds much lower than the posted speed limit. Alternatively, bicycle green waves may be employed as a traffic calming measure to increase walkability, safety, and encourage more engagement with local businesses.

On the other hand, slower speeds results longer travel time for vehicles. Streets with speed limits of 45 mph would see an expected three times increase in travel time if reduced to 13 mph assuming uninterrupted travel at both speeds. Many of the larger arterials that serve as major connectors and corridors tend to have higher speed limits and would see significant impacts if timed for bicycle green waves. Additionally, driver expectations along with street design can result in speeding which ends up producing stop-and-go movements at multiple intersections, adding to driver frustrations.

2.2.1 San Francisco Green Wave

Around the early 2010's, San Francisco started a temporary pilot for a green wave signal re-timing aimed at bicycle progression that was eventually more permanently implemented (Bialick, 2011). This signal re-timing was done for Valencia St from 16th to 25th St, a segment stretching roughly a mile. The speed limit was set to 13 mph as seen in Figure 4 below.

From the article, an initial San Francisco Municipal Transportation Agency (SFMTA) study was estimating decreases to vehicle travel times with the implementation of the bicycle green wave. This was because the corridor was already heavily congested, and speeds were much lower than the 25-mph speed limit. By reducing the speed limit, vehicles were expected to be able to stay within the band, improving corridor performance. On top of the improved performance, the article extols the increased safety provided by slower moving vehicles and cyclists more willing to obey convenient signal timing.

Figure 4: Green Wave Speed Limit Sign

Source: Bryan Goebel, 2011

2.3 Timing Adjustments

The other major approach of signal coordination for bicycle progression is modifying a coordination plan aimed at vehicle progression. For example, a minor intersection might have a larger cycle length than necessary (based on its demands) to match the critical intersection for coordination; the coordinated phase may only need a relatively short window of time each cycle to clear out the built-up vehicles, but with the excess time due to the larger cycle length, additional green time added to the coordinated phase would expand the green window, potentially allowing lagging cyclists to make it through the intersection before the red.

A conceptual paper by Taylor and Mahmassani proposes several different scenarios and accompanying methods for the adjustment of vehicle-based coordination timing to benefit bicycle progression (Taylor & Mahmassani, 2000). The strategies discussed in the paper can be summarized as varying bicycle speeds, varying vehicle speeds, allocation of excess green time, running half cycles for intersections upstream of critical ones, stop dispersal, increasing the cycle length, and prioritizing bicycle bandwidth. The paper is widely referenced by numerous studies and real-world projects that have attempted the challenge of designing coordination plans for both vehicle and bicycle progression.

The paper has limitations. The conceptual nature results in splits and cycles that are designed to demonstrate the various techniques discussed rather than being the techniques applied to splits and cycles defined by real-world constraints such as vehicle demand or roadway geometry. Additionally, the examples provided only ever look at one progression.

2.3.1 Vancouver Case Study

A case study was published in 2018 regarding the findings of adjusting the coordination of a downtown street in Vancouver, British Colombia for better bicycle progression (Do et al., 2018). The adjustments made to the Dunsmuir St Corridor were able to reduce cyclist delays and stops, while having minimal impact to the already existent vehicle coordination. It should be noted that the results of the study were from simulations using

Synchro 6; it does not appear that at the time the study was published that the timing was implemented into the field and the real-world changes observed.

Two main adjustments were made to the timing plans to improve bicycle progression—the vehicle speed limit was lowered from 60 km/h (37 mph) to 40 km/h (25 mph) and offsets were adjusted to maintain coordination for vehicles and accomodate bicycles. 20 km/h (12 mph) was used for calculating the bicycle bandwidth. Cycle lengths and phases were maintained to minimize the impact on neighboring intersections.

To briefly summarize the results of the adjustments, travel times for the corridor dropped by a range of approximately 14-30 seconds depending on the peak and direction. This cut a range of 185-197 seconds down to a range of 165-173 seconds. The largest time reduction was in the eastbound direction where presumably, moving against the direction of progression had previously caused cyclists much higher delays. Both the AM and PM westbound movements previously had 2 stops, while the eastbound movements had 3 stops (The PM EB is listed at 1 stop before, but the difference is listed as -2. The TSD also seems to indicate 3 stops). This case study seemed to take a trial-and-error approach with making adjustments to include bicycle progression.

2.3.2 Oregon Vehicle-to-Infrastructure Greenwave

This case study from the University of Oregon looked at enabling bicycle green waves through smartphone usage (Fickas & Schlossberg, 2019). The study initially looked at using an app to send requests to the upcoming signal controller to accommodate approaching cyclists, but the cost of the equipment needed to modify the controller made the method unfeasible. A second approach was developed based on Green Light

Optimized Speed Advisory (GLOSA) technology. Essentially, the app pulled real-time data for the timing of an upcoming intersection and advised cyclists if they needed to make speed changes to catch the green wave.

One of the challenges of timing signals for bicycles is that bicycles do not come with speedometers. In an example like the Valencia St case where the timing has been implemented for a while, engineers can rely on cyclists to eventually get a feel for the timing, but it is difficult to convey to cyclists how fast they should be moving. One solution is to buy a speedometer, but this does not inform cyclists if they are in the band. Light strips buried along cycle tracks that glow green or red depending on the location of the band have been implemented in some places, but smartphones are incredibly common in this day and age, and a smartphone app directing cyclists as necessary would be incredibly beneficial to getting cyclists through intersections without stopping.

CHAPTER THREE

METHODOLOGY AND DESIGN

3.1 Introduction

This research originally started with the proposal of a cycle track to be built along Center St in Reno, NV that would have linked up the University, Downtown, and Midtown areas. In addition to the cycle track, the original feasibility report by Headway Engineering contained traffic counts with some simple timing suggestions regarding the phasing sequence for the signalized intersections (Headway, 2020). One of the original goals of the project was to provide a signal timing coordination plan that worked for bicycle progression as much as it did for vehicle progression.

With that goal in mind, the first attempted method of solving this challenge was to determine if there was some cycle length that could be calculated to provide good progression for both vehicles and bicycles. Using the intersections along Center St that were proposed for the cycle track addition as the basis of initial tests, multiple timing plans with various cycles lengths were created and tested for bandwidth and progression using the posted speed limit of 30 mph and an assumed average cycling speed of 13 mph. After testing out various cycle lengths, it was deduced that a certain condition needed to be fulfilled along a roadway for vehicles and bicycles to have a similar progression bandwidth for the same timing plan, and that that condition was not present along Center St.

Chapter Four delves into this conceptual method of determining the required cycle length for ensuring both vehicle and bicycle progression, as well as another method based off the same calculation that can be used for determining phase lengths. For the ideal cycle length for dual progression, Sun Valley Blvd from 1st St to 8th St fulfilled the required condition and was used as the basis of tests.

It was concluded that there was no apparent and easy method of designing a timing plan that would satisfy both vehicle and bicycle progression for Center St. Instead, the focus of the research then moved towards determining a method of balancing vehicle needs versus bicycle needs. Chapter Five discusses an empirical approach of weighing the two modes using a single score and the justifications behind factors contributing to that score.

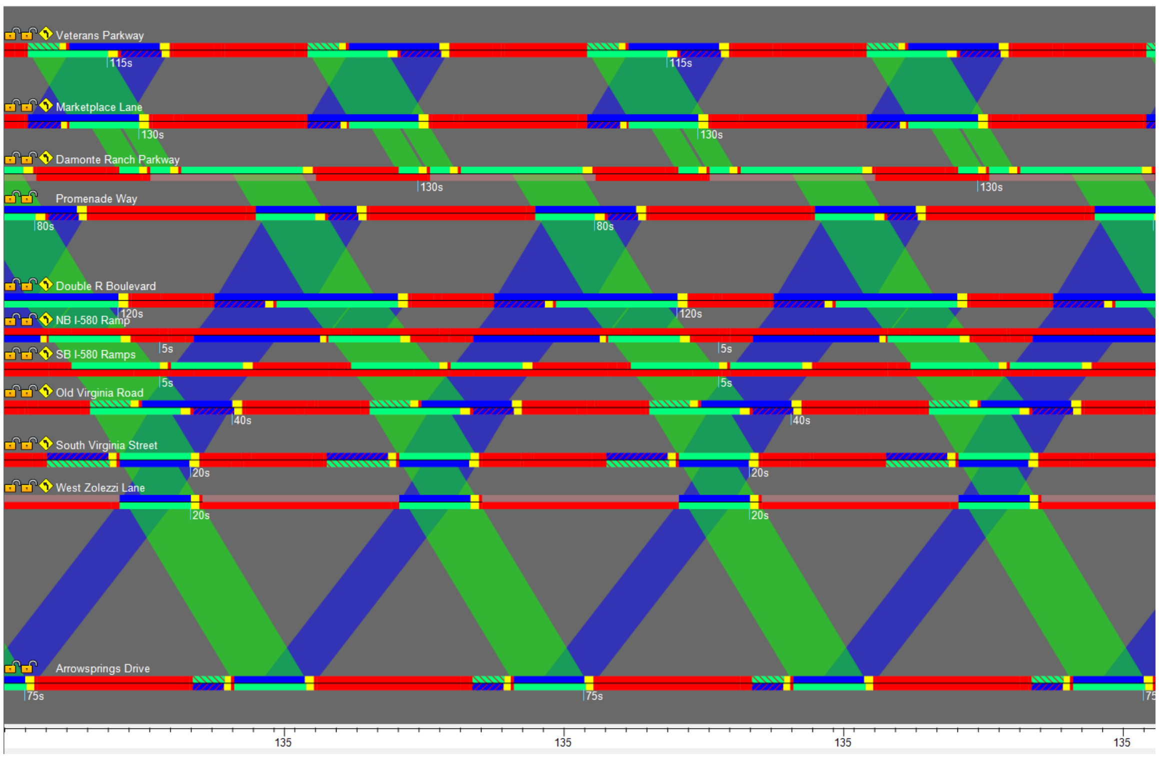
3.2 Tools

For this research, the two programs primarily used were TranSync and VISSIM.

<u>TranSync</u> – TranSync is a software provided by Trans Intelligence LLC that really focuses on the essential timing aspects of signal timing. Specifically, the desktop version of the application was used for this research. It differs from Synchro, a very commonly used program in signal timing, by ignoring vehicle volumes and lane configurations, instead focusing on performance by optimizing bandwidth and coordination. It takes basic parameters such as green, yellow, and red times; offsets; and cycle lengths, and produces a time space diagram (TSD) such as the one seen in Figure 5 below that can easily be manipulated manually or automatically to create large bands between intersections to guarantee non-stop progression. The advantage of TranSync over a program like Synchro is the ease and simplicity of generating timing plans, as well as

being able to quickly manipulate the TSD and see the effects of those changes on bandwidth and progression. On the other hand, it is unable to determine intersection level of service (LOS) based on the Highway Capacity Manual (HCM) standards and does not generate simulation runs.

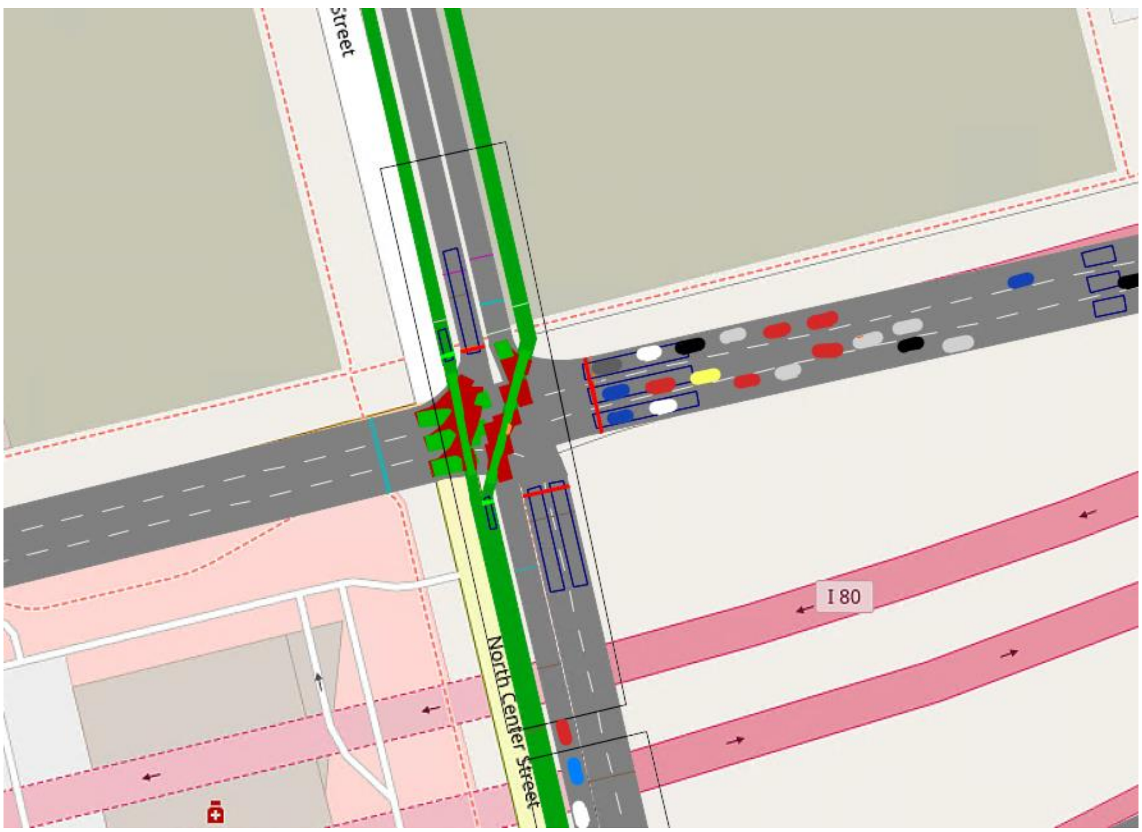
Figure 5: Example Time Space Diagram from TranSync



TranSync was used to design the timing plans used in this research. It was also used for visual comparison when comparing TSDs between vehicle and bicycle progression or for different plans.

PTV Vissim – Vissim is a traffic simulation software from the PTV group. Vissim requires volumes and land configurations in addition to timing configurations and provides an in-depth visual simulation of a corridor. Vissim was chosen over Synchro because of the flexibility it offered with regards to roadway design and multiple modes of transportation. Figure 6 below shows the model of the Center and 8th intersection. Vissim provided the flexibility needed to simulate the cycle track along Center St, as well as at 8th where the cycle track diverges between travel directions north of the intersection.

Figure 6: Screenshot of the Center St Model in Vissim



Because the Center St cycle track has been postponed at the time of this research, the simulation from Vissim was used to provide the performance results used to calibrate the weights and scores for the timing plans.

3.3 Methodology

With the conceptual approach, the goal was to discover the conditions necessary to provide some timing parameter that could be calculated or was apparent and would provide good progression for both modes. No simulation was used for this conceptual, ideal method. This method assumed sufficient time needed to satisfy demand conditions and looked solely at ensuring similar progression potential between vehicles and bicycles based off bandwidth. For those reasons, the primary method of evaluation was comparison between vehicle and bicycle speeds, and the bandwidth that those speeds produced on the same timing plans.

For the empirical approach, the goal of this research was to provide a method of quickly evaluating a timing plan while considering factors that are not readily apparent or difficult to compare, or in this case, comparing timing plans that are aimed at progressing two very different modes of transportation. Without such a method, it can be difficult to justify favoring one over the other. Due to the added complexity of an additional mode, field implementation or simulation would likely be needed to provide the additional data for justifying the choice of timing plan. However, both options would require significant time and resources to collect the necessary data. A grading sheet is used to pull the significant factors from either the basic timing parameters (i.e., split length) or the TSD (i.e., bandwidth, number of stops) to provide an overall grade for the timing plan.

Weights for the influencing factors have been calibrated using the results of the simulation. The goal of the grading sheet is to skip the lengthy processes of building and running a simulation for every individual corridor.

CHAPTER FOUR

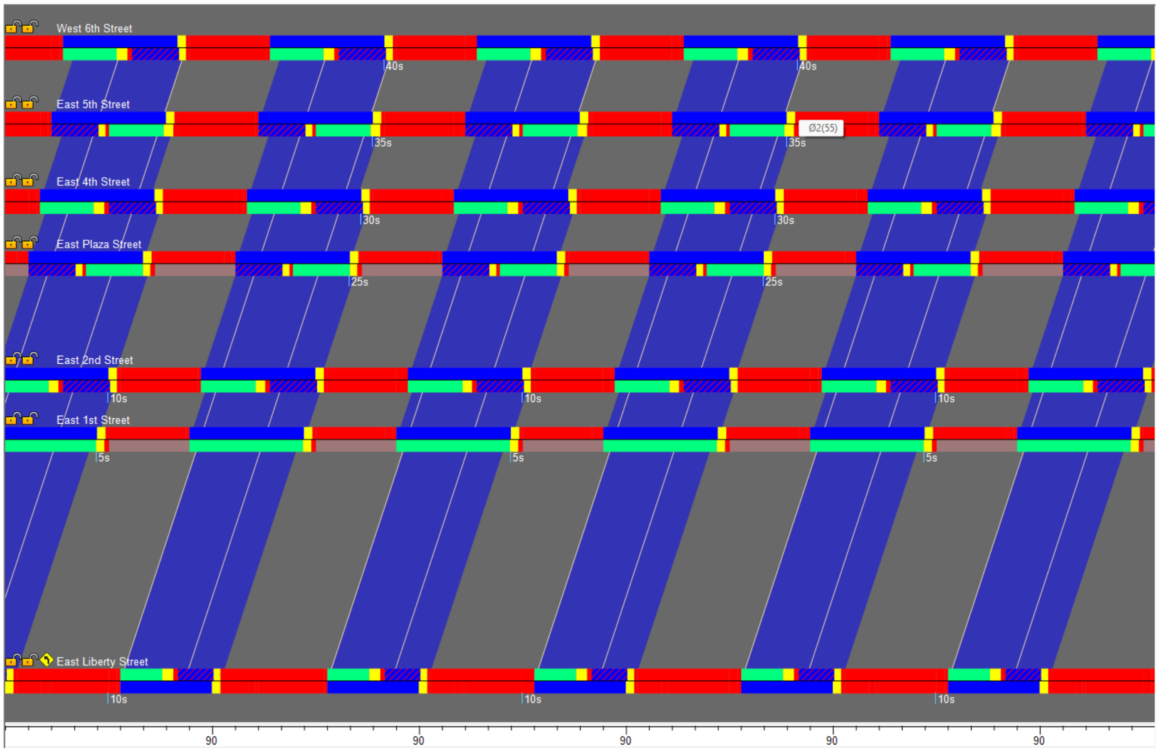
TRAVEL TIME DIFFERENCE: ADJUSTING CYCLE LENGTH AND SPLIT PARAMETERS

4.1 Introduction

The significant barrier in designing a timing plan that has good progression for both vehicles and bicycles is the difference in speeds between the two modes of transport. Normally when designing for vehicle progression, the offset at subsequent intersections is set so that they turn green around the time vehicles from the previous intersection begin to arrive. For well-designed corridors, this results in large bands across multiple intersections such as the one seen below in Figure 7 where vehicles traveling at the design speed can easily stay within the band and travel past multiple intersections without stopping.

However, bicycles, due to human limitations, generally travel much slower than the design speed or speed limit, and thus inevitably fall out of the bandwidth. They may be forced to stop for a red every few intersections, or in the worst case, they fall out of the bandwidth between every intersection and achieve the maximum number of reds. It became clear that this difference between the two and the resulting gap would be important for calculating some timing parameter to allow for progression for both modes.

Figure 7: TSD with Wide Bandwidth

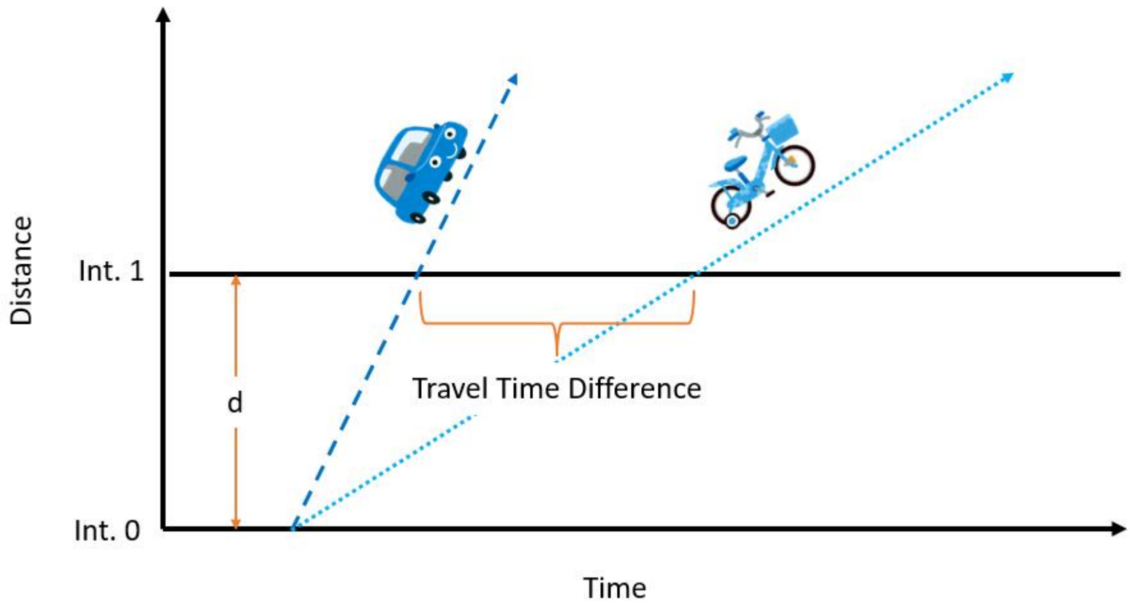


4.2 Travel Time Difference

Travel time difference, or TTD, is an important value proposed by this research for designing "ideal" timing plans for both vehicle and bicycle progression. The TTD is an incredibly simple concept and can be defined as the difference between the time it takes for a vehicle to travel from one intersection to another and the time it takes for a bicycle to travel the same distance as seen in (1). Figure 8 demonstrates the TTD visually.

$$TravelTimeDifference = TravelTime_{veh} - TravelTime_{bike} \qquad (1)$$

Figure 8: Travel Time Difference



Note. Vehicles and bicycles starting at the same time and location form a gap after a distance.

The TTD is dependent on three variables–vehicle speed, bicycle speed, and the distance between intersections. Changing any of these variables results in a different TTD for a potentially infinite number of combinations. However, speed limits generally are within a given range and in increments of five, bicycles have an expected speed based on human limitations, and there are reasonable limits for distance between intersections when it comes to coordination. With these restrictions, TTDs can be quickly calculated. Table 1 below lists some TTDs based on vehicle speeds of 30 to 35 mph and bike speeds of 12 to 13 mph.

Table 1: Sample Table Showing TTD Variations

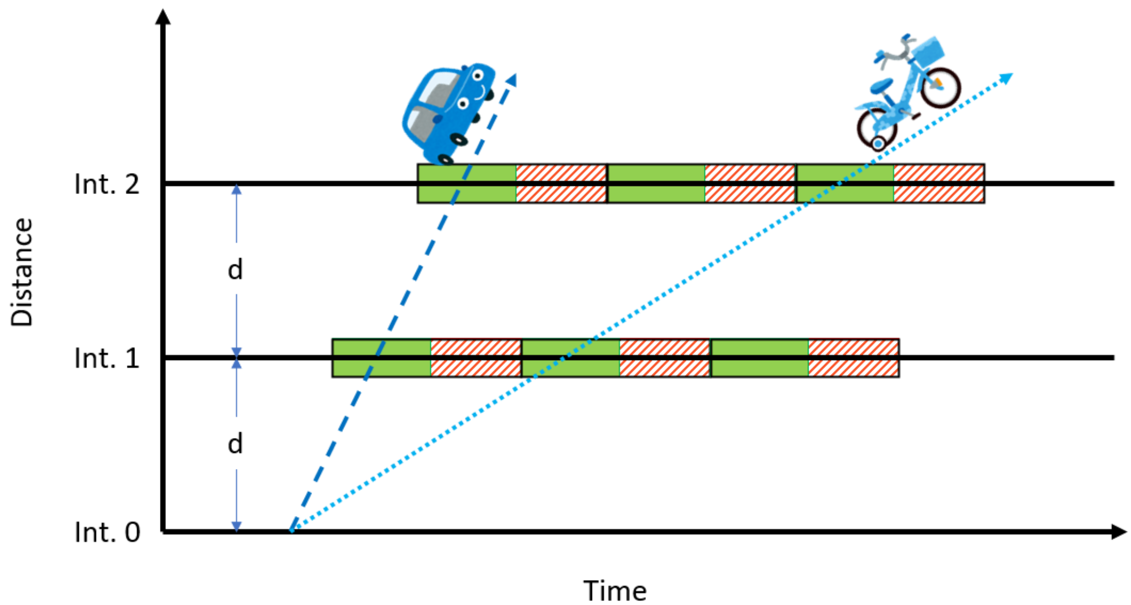
Veh Speed (MPH)	Distance (ft)	Bike Speed (MPH)					
		12			13		
		TT Veh (s)	TT Bike (s)	TT Diff (s)	TT Veh (s)	TT Bike (s)	TT Diff (s)
30	100	2.3	5.7	3.4	2.3	5.2	3.0
	200	4.5	11.4	6.8	4.5	10.5	5.9
	300	6.8	17.0	10.2	6.8	15.7	8.9
	400	9.1	22.7	13.6	9.1	21.0	11.9
	500	11.4	28.4	17.0	11.4	26.2	14.9
	750	17.0	42.6	25.6	17.0	39.3	22.3
	1000	22.7	56.8	34.1	22.7	52.4	29.7
	1250	28.4	71.0	42.6	28.4	65.6	37.2
	1500	34.1	85.2	51.1	34.1	78.7	44.6
	1750	39.8	99.4	59.7	39.8	91.8	52.0
35	100	1.9	5.7	3.7	1.9	5.2	3.3
	200	3.9	11.4	7.5	3.9	10.5	6.6
	300	5.8	17.0	11.2	5.8	15.7	9.9
	400	7.8	22.7	14.9	7.8	21.0	13.2
	500	9.7	28.4	18.7	9.7	26.2	16.5
	750	14.6	42.6	28.0	14.6	39.3	24.7
	1000	19.5	56.8	37.3	19.5	52.4	33.0
	1250	24.4	71.0	46.7	24.4	65.6	41.2
	1500	29.2	85.2	56.0	29.2	78.7	49.5
	1750	34.1	99.4	65.3	34.1	91.8	57.7

4.3 Travel Time Difference as the Cycle Length

The intended purpose of the travel time difference is to determine if there is a cycle length that can be calculated to provide progression for both vehicles and bicycles. If the gap between the two is large enough, then instead of attempting to squeeze slow moving bicycles into the same phase as vehicles, set the cycle length so that bicycles arrive at the green of the next cycle instead. There is a condition under which this is possible.

For a TTD-based cycle length to provide progression for both vehicles and bicycles, the spacing of intersections needs to be roughly equal. This allows each intersection to use the same cycle length, thus enabling coordination. With these conditions, a timing plan that has progression for vehicles can guarantee similar progression for bicycles N cycles later, with that number equal to the number of intersections from the starting point. Figure 9 below gives an example of equally spaced intersections using the TTD cycle length and with vehicle and bicycle progression.

Figure 9: Condition for TTD-based Cycle Length



***Note*. With the TTD set to one cycle length, the bicycle arrives at Int. 2 two cycles after the vehicle does.**

To test the applicability of this method, actual timing plans were created. Due to the modeling constraints in TranSync, several intersections along Sun Valley Blvd in the north part of Reno were chosen as the basis for the timing plans due to the equal spacing of the intersections. Specifically, from 1st Ave in the south to 8th Ave in the north, the spacing between signalized intersections is about 1300 ft. With the design speed of 40 mph, multiple bike speeds were checked; using a bicycle design speed of 11 mph, the TTD is 60.9 seconds which was rounded down to a 60 second cycle length.

As seen in Figure 9 above, this method guarantees similar progression for bicycles based on the vehicle progression for one-way progression; a simple two-way progression and two-way with protected left turn progression plans were also tested. Both showed that progression patterns and bandwidth for bicycles speeds closely resembled that of vehicle speeds. As an example, the parameters and TSD for the more complicated two-way protected left turn plan is given below. Table 2 gives the basic timing parameters. Figure 10 shows two versions of the same timing plan; the top plan shows progression based on vehicle speeds (40 mph) while the bottom plan shows progression based on bicycle speeds (11 mph).

Table 2: Sample Timing Parameters for TTD-based Cycle Length

	Phase Splits (s)						Offset
Intersection	1	2	4	5	6	8	
8th Ave	15	25	20	15	25	20	26
7th Ave	15	25	20	10	30	20	34
6th Ave	15	25	20	15	25	20	58
5th Ave	20	20	20	15	25	20	25
4th Ave	15	30	15	15	30	15	44
Gepford Pkwy	15	25	20	15	25	20	4
2nd Ave	15	25	20	20	20	20	34
1st Ave	10	30	20	15	25	20	56

Note. Phases 3 and 7 were ignored as they have no impact on the bandwidth. Offset is referenced to the beginning of yellow of phase 2 (northbound movement).

As seen in Figure 10 above, even with protected left turns, the timing plan offers progression at both vehicle and bicycle speeds. In fact, it is precisely because the cycle length is set to the travel time difference, that designing a functional plan for one mode guarantees a similar degree of progression for the other. By aiming for the next cycle, this method takes advantage of the cyclical design of signal timing to create bandwidth at a slower speed.

Figure 10: TSD Comparison: 40 mph (Top) vs 11 mph (Bot) Progression

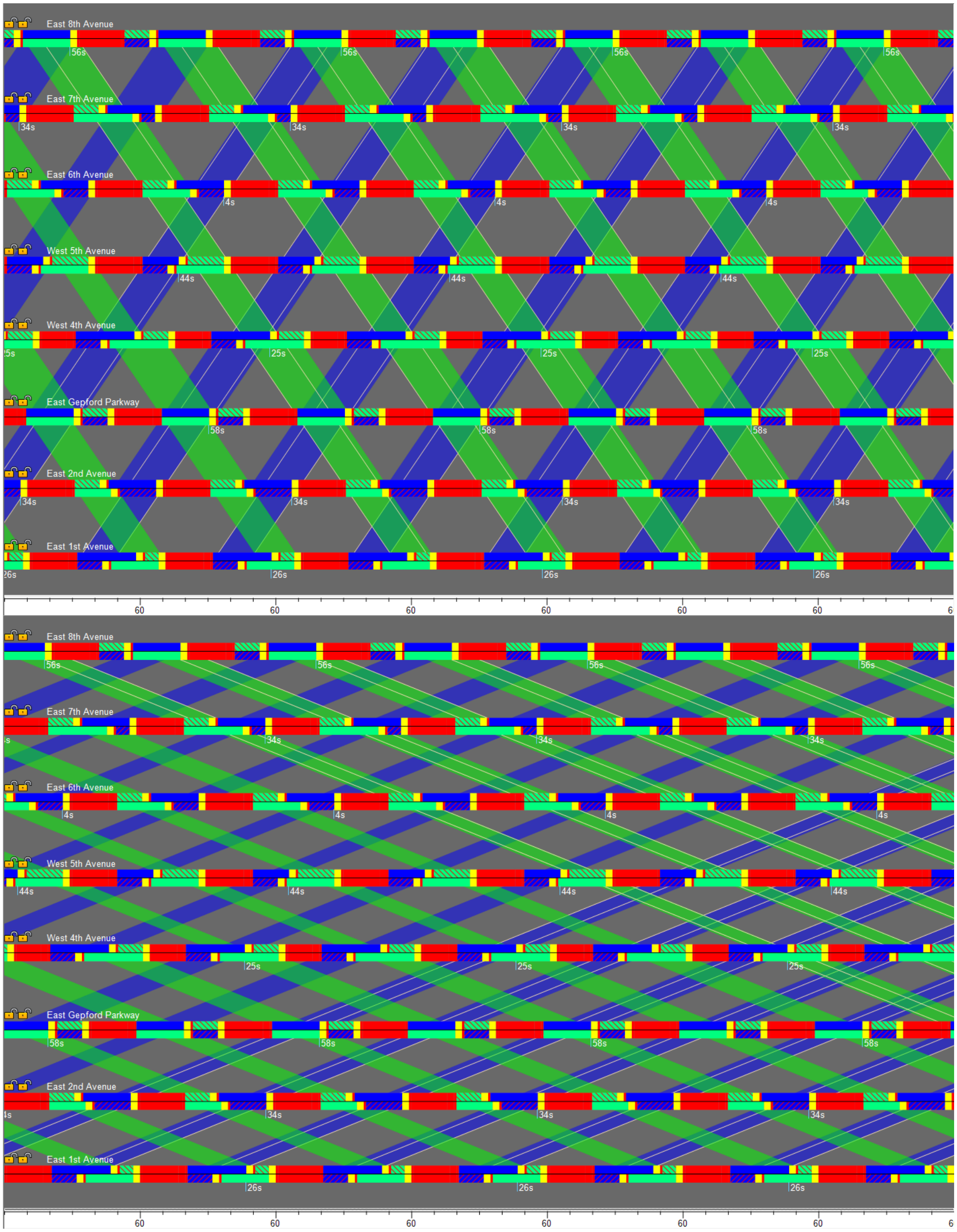


Table 3 below lists the length (seconds) of the bands between intersections for vehicle and bicycle speeds. Generally, the bicycle bands tended to be less than the vehicle bands with the exception of the segment between 1st and 2nd Ave. The reason for the difference was not heavily investigated and it is unknown if a larger range of splits would result in more drastic differences between the two bands, but from this example, the difference between vehicle band and bicycle band is minor.

Table 3: Bandwidth Differences based on Speed

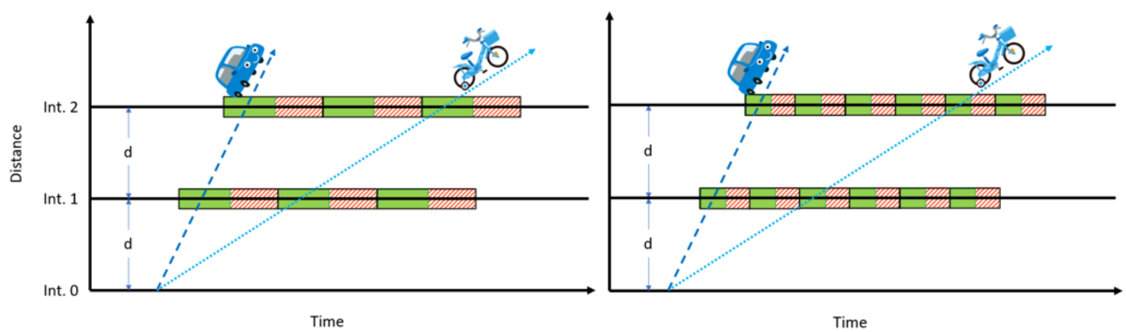
Segments		Link Bands (s)							
		Veh		Bike		Diff		% Diff	
		NB	SB	NB	SB	NB	SB	NB	SB
8th Ave	7th Ave	24.0	24.0	23.3	23.3	0.7	0.7	0.030	0.030
7th Ave	6th Ave	17.1	21.1	16.8	20.8	0.3	0.3	0.018	0.014
6th Ave	5th Ave	16.1	16.1	15.7	15.7	0.4	0.4	0.025	0.025
5th Ave	4th Ave	19.0	16.0	19.0	15.2	0.0	0.8	0.000	0.053
4th Ave	Gepford	24.0	23.9	24.0	22.9	0.0	1.0	0.000	0.044
Gepford	2nd Ave	22.0	19.0	18.6	19.0	3.4	0.0	0.183	0.000
2nd Ave	1st Ave	16.1	18.3	18.5	19.0	-2.4	-0.7	-0.130	-0.037

It should be noted that for this example, relatively simple split values were chosen to help create a longer bandwidth chain for visual purposes. Assuming that different split values were used, and a continuous chain of bandwidth was not possible for a given plan, the bicycle-based progression would still resemble the vehicle-based progression due to the relationship between the cycle length and the travel time difference; from the same cycle and starting location, the bicycle simply arrives at the Nth intersection N cycles later.

4.3.1 Modifications

There is some degree of modification that can be done to this method for increased flexibility. The first is to cut the cycle length in half or to use half the TTD as the cycle length. This effectively doubles the number of cycles. As noted by Taylor and Mahmassani (2000) and Figure 11 below, this does not negatively impact progression aside from the increase in lost time. This is because the travel time difference ensures that bicycles simply arrive 2 cycles later rather than 1; because this value is still a whole number, it guarantees the same starting position at that intersection as a vehicle so bicycles would get the same progression pattern as vehicles.

Figure 11: Regular TTD (Left) vs Half TTD (Right)



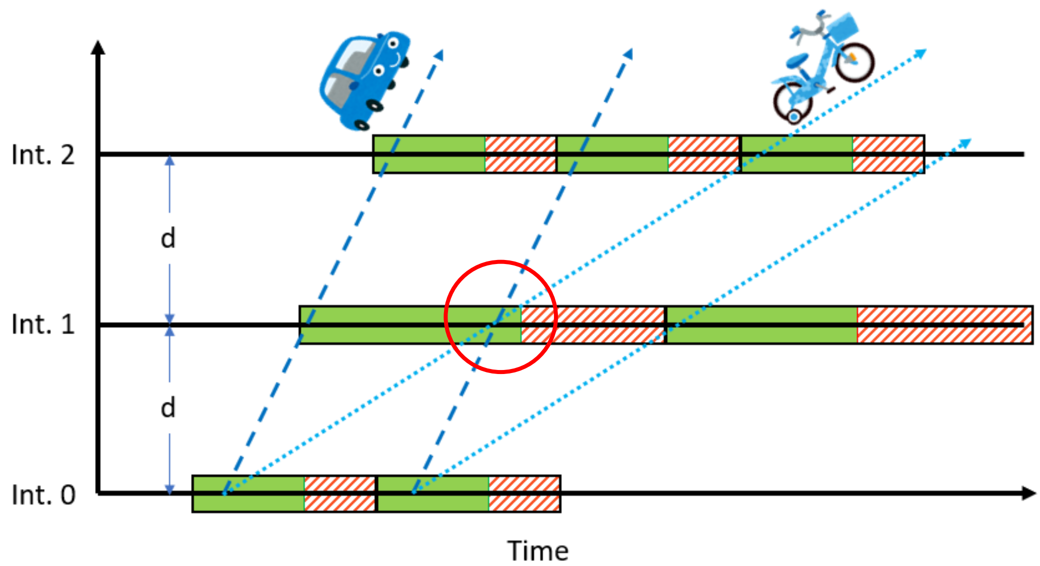
This is opposed to if a bicycle arrived half a cycle later for example. The starting point for a bicycle at that intersection then would be halfway through the cycle and potentially during the red. Even if that arrival was in the latter half of the green, not starting from the "same point" as vehicles would not guarantee similar progression.

The second modification then is to double the travel time difference for the cycle length. As noted above, this has the issue of causing bicycles to arrive halfway through the cycle, potentially during the red. The worst-case scenario as noted by Taylor and Mahmassani is that bicycles stop on red at every intersection. However, by mixing the usage of Full-TTD and Double-TTD for intersections, it is possible to run a few intersections at double the travel time difference.

Two conditions were identified where there was potential for doubling the cycle length with no or minor impacts to progression. The first condition requires that the progression split is greater than half the cycle length. With that condition in place, when doubling the cycle length, the green time then becomes greater than the TTD. With the right offset, such as shown in Figure 12 below, it is possible to utilize both the starting and ending portions for progression depending on the starting point of the vehicle or bicycle.

It should be noted that while this condition might have potential on a one-way road, on a two-way road, the increase in phases will likely make it difficult to assign more than half of the total cycle to a single phase. In that case, the progression paths circled in Figure 12 would no longer be possible.

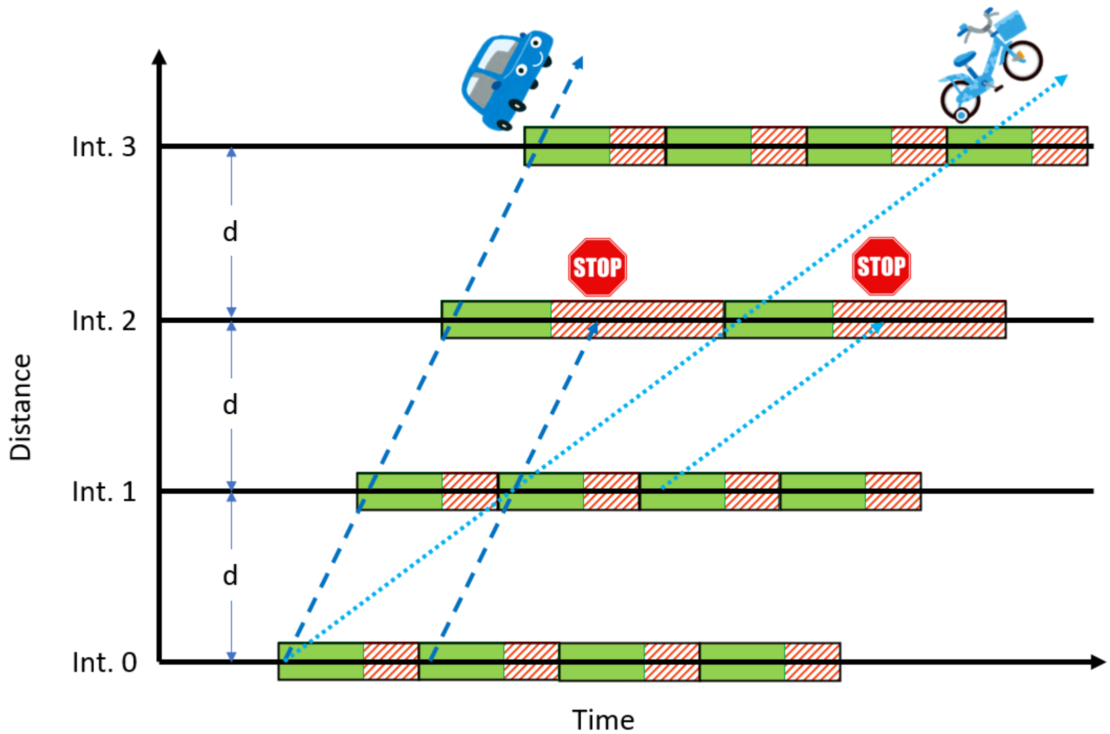
Figure 12: Double-TTD at Int. 1 with LONG Green



This brings us to the second condition – progression is still possible but is dependent on the starting intersection or cycle. Additionally, the "intended" progression band would only be available every other cycle because of the intersection running the Double-TTD based cycle. Figure 13 below shows progression with the Double-TTD cycle depending on starting location or time.

This second condition was tested with a relatively simple timing plan, again using Sun Valley Blvd as the basis. The speed limit is 40 mph, the design bicycle speed used is 11 mph, and the distance between intersections is roughly 1300 ft resulting in a TTD of 60.9 seconds, or a cycle length of 60s. The timing for the plan is given in Table 4 below and the resulting TSDs for vehicle and bicycle progression are shown in Figure 14.

Figure 13: Double-TTD at Int. 2 with SHORT Green



Note. Some of the starting times and locations are not within bands and result in stops at the double cycle length intersection.

Table 4: Timing for Double-TTD example

	Phase Splits (s)						Offset	Cycle (s)
Intersection	1	2	4	5	6	8		
8th Ave	12	30	18	17	25	18	23	60
7th Ave	25	50	45	25	50	45	18	120
6th Ave	35	45	40	30	50	40	107	120
5th Ave	15	25	20	15	25	20	14	60
4th Ave	16	22	22	14	24	22	50	60
Gepford	20	40	60	20	40	60	36	120
2nd Ave	13	27	20	17	23	20	7	60
1st Ave	17	23	20	13	27	20	45	60

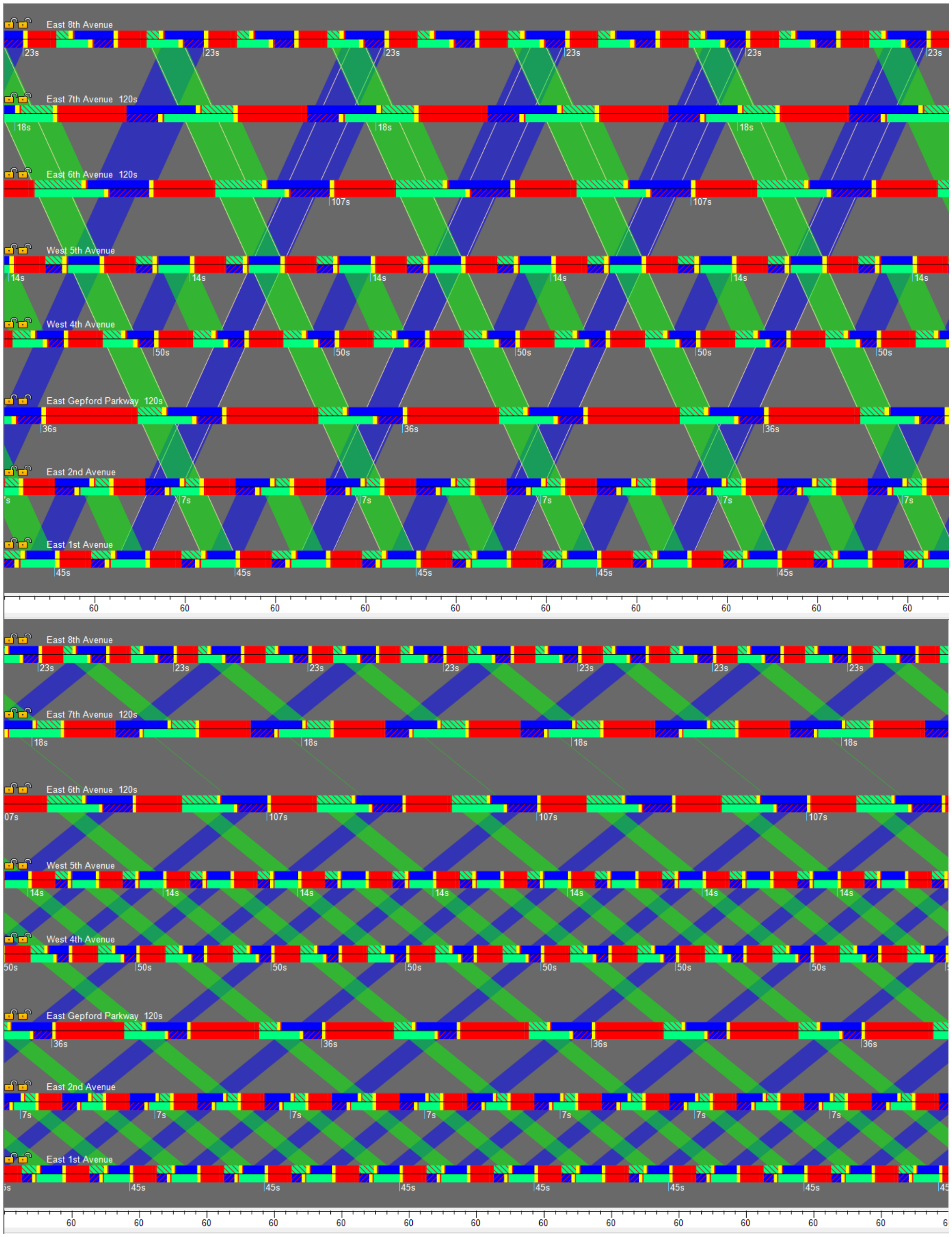
Note that Gepford Pkwy, 6th Ave, and 7th Ave are running a Double-TTD-based cycle length (120 seconds). Gepford Pkwy (3rd intersection from the bottom) is adjacent to two intersections running the regular TTD-based cycle. As a result, the progression band on either side of Gepford Pkwy is only available every other cycle for both vehicle and bicycle speeds. Additionally, 7th Ave and 6th Ave (2nd and 3rd intersections from the top) are adjacent and both running Double-TTD-based cycle lengths. In this case, uninterrupted progression through the entire corridor is possible for vehicle speeds. Also note that bands between the other adjacent intersections, 8th Ave and 5th Ave, are only available every other cycle. However, looking at the bicycle speed TSD, the consecutive Double-TTD-based cycles results in no band between 7th and 6th Ave. This is because running Double-TTD-based cycles next to each other naturally lends itself to the worst-case scenario noted by Taylor and Mahmassani where bicycles arrive at the start of red. Because the TTD is the gap between vehicle and bicycle arrivals, if the green is not more than half the cycle as needed for condition one, then doubling the cycle length results in a green less than the TTD and bicycles will arrive during the red interval.

For comparison, the bands for the TSDs shown in Figure 14 are listed in Table 5. While there is a sliver of a band between 7th and 6th in the southbound direction, it is essentially nonexistent. Optimizing the plan for bicycle progression (bottom) similarly eliminates the band between 7th and 6th for vehicle progression (top).

Table 5: Bandwidth Difference for Double-TTD

Segments		Link Bands (s)							
		Veh		Bike		Diff		% Diff	
		NB	SB	NB	SB	NB	SB	NB	SB
8th Ave	7th Ave	29.0	24.0	29.0	24.0	0.0	0.0	0.000	0.000
7th Ave	6th Ave	40.6	37.6	0.0	0.7	40.6	36.9	-	52.714
6th Ave	5th Ave	24.0	23.3	24.0	22.9	0.0	0.4	0.000	0.017
5th Ave	4th Ave	21.0	23.0	21.0	22.5	0.0	0.5	0.000	0.022
4th Ave	Gepford	21.0	23.0	21.0	23.0	0.0	0.0	0.000	0.000
Gepford	2nd Ave	26.0	22.0	26.0	22.0	0.0	0.0	0.000	0.000
2nd Ave	1st Ave	22.0	22.0	22.0	21.3	0.0	0.7	0.000	0.033

Figure 14: Double-TTD Vehicle Speeds (Top) vs Bicycle Speeds (Bottom)

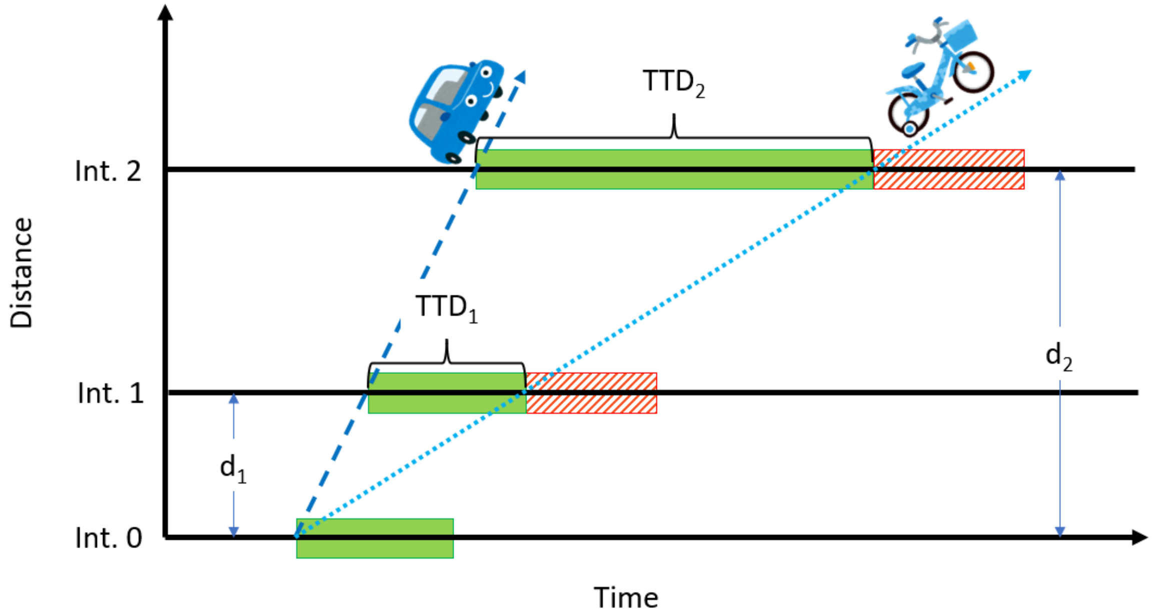


4.4 Travel Time Difference as Minimum Split Length

The second application of the travel time difference came about after calculating and noting some of the travel time difference values from Table 1. For segments where the speed limit is low or the distance between intersections is small, the TTD generated is generally too small to be used as a reasonable cycle length. Additionally, for corridors where the segment lengths are not equal, then segments do not have the same TTD and thus, setting the TTD to the cycle length does not work. Under these conditions, the goal is instead to squeeze vehicles and bicycles through with the same cycle as shown in Figure 15. In this case, the TTD serves as the minimum required split length needed to serve both modes.

In this example, vehicles primarily utilize the early portion of the split with the end being extended in order to serve the bicycle. However, over a greater distance, this tactic ends up massively increasing the split. Hypothetically speaking, even if time were added to the split to accommodate bicycle speeds, either the cycle length would need to be increased or the split would exceed the duration of the cycle. Therefore, rather than trying to keep bicycles together in the same split as vehicles they started with, it would be more reasonable to group them with vehicles from later cycles that have caught up to the bicycles. In this situation, bicycles utilize the start of the split and vehicles that have caught up from later cycles utilize the end.

Figure 15: TTD set to Split



Note. The distance used for the TTD calculation is the total distance from the origin point rather than the distance between adjacent intersections.

To determine whether to utilize the start or the end of the split for bicycle progression, we need to compare the arrival times of vehicles both before and after the bicycle arrival time. What is important is the arrival time at each intersection; over large distances, there is the chance that the gap between vehicles and bicycles starting at the same time and location will be greater than the cycle length, so instead, we may need to consider vehicles from following cycles. This process is described in the following steps:

1. Determine the target range: Calculate two values by adding and subtracting the cycle length from the bicycle arrival time. This gives a range of time where any value within this range can be in the same cycle as the bicycle arrival time.
2. Determine vehicle arrivals: First, determine the vehicle arrival. Once that value is obtained, add N number of cycle lengths to the vehicle arrival time until this new value is between the lower range limit calculated in Step 1 and the bicycle arrival time where N is some number of cycles needed to reach that point. N can be 0. Then add N+1 amounts of cycle lengths to the vehicle arrival time to get a second value that should be between the bicycle arrival time and the upper range limit. These two values serve as the benchmarks for vehicle arrivals before and after the bicycle arrival within a cycle length of time.
3. Find the minimum split: Calculate the gap between the bicycle arrival time and the two vehicle arrival times. The purpose of this step is to determine the minimum split length required for each configuration. Generally, picking the smaller gap is a good idea because it provides more time to service the other phases, but if the difference between the two is minor, it would be more beneficial to pick the vehicle leading arrival time to maximize the band for vehicles. Because this calculation only accounts for the precise time between two units, some amount of additional time will need to be added to the split in order to provide some bandwidth for the lagging mode of transport.
4. Calculate the offset: The offset for each intersection depends on whether the split at that intersection is designed for leading vehicles or bicycles. Using the start of green as the reference, the offset for a given intersection is simply the travel time

from the starting intersection with regards to the leading mode of transport. In other words, if an intersection's split is designed with vehicles leading, the vehicle travel time should be used as the offset and vice versa.

Center St from the intersections at 4th St to 8th St shall be used in an example. The speed limit along this segment is 30 mph and 12 mph will be used for the expected bicycle speed. Figure 16 below shows a map with the area of interest. Table 6 below gives the relevant information needed for the timing plan. TSDs for the timing plans at vehicle speeds and bicycles are given in Figure 17. From Table 6, the *Before* and *After Gaps* values are compared. The smaller value between the two is chosen for the split length. An additional 5 seconds is added to that value to create bandwidth. Additionally, depending on which gap is chosen, either the vehicle or bicycle travel time is used as the offset. In this case, the offset at Int. 2 is based on the vehicle travel time (22.0) and the offsets at Int. 3 and 4 are based on the bicycle travel time (92.6 and 109.7 round to 3 and 20).

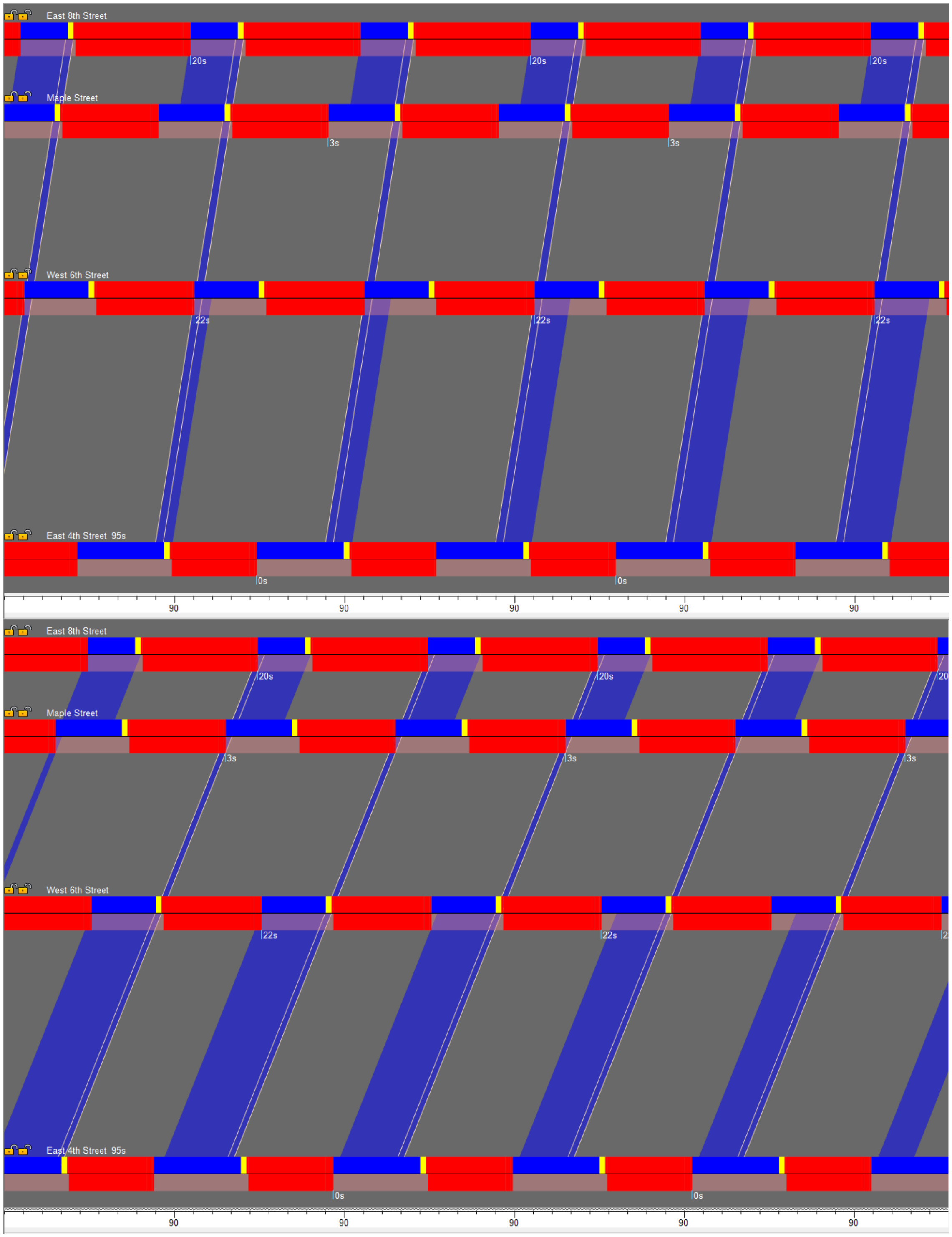
Figure 16: Center St from 4th (1) to 8th (4)

Note. Center St in Reno located in the Downtown area.

Table 6: Minimum Split Length Calculation and Timing

Cycle = 90 seconds					
Int.	Dist (ft)	Veh Ariv (s)	Bike Ariv (s)	Low Lim	Up Lim
1 -> 2	970	22.0	55.1	-34.9	145.1
1 -> 3	1630	37.0	92.6	2.6	182.6
1 -> 4	1930	43.9	109.7	19.7	199.7
	Veh Bef (s)	Veh Aft (s)	Bef Gap (s)	Aft Gap (s)	Lead
1 -> 2	22.0	112.0	**33.1**	56.9	Veh
1 -> 3	37.0	127.0	55.6	**34.4**	Bike
1 -> 4	43.9	133.9	65.8	**24.2**	Bike

Figure 17: Minimum Split Length TSD, 30 mph (Top) vs 12 mph (Bot)



4.5 Limitations

Despite the calculations simplifying the process of designing a plan for vehicle and bicycle progression by offering a mathematical solution, it is apparent that there are issues with both approaches of using the travel time difference.

Starting with the cycle length-based approach, a certain spacing between intersections is required. Generally, this is equal spacing, though there may be particular cases such as intersections where the distance from the adjacent intersections is twice the normal distance which would naturally lend itself to the Double-TTD application but essentially, intersections need to be spaced so that resulting TTDs are similar or some factor of the base TTD. On top of that, although three factors were mentioned as affecting TTD (distance, vehicle speeds, and bicycle speeds), it is difficult to control intersection distances unless building a new roadway and speed limits are generally based on the roadway type as well as the surrounding developments. The speed limit can change along a roadway which has an effect on the TTD, but these changes are generally not between each intersection which would be required to get equal TTDs with different segment lengths. That leaves expected bicycles speeds as really the only easily adjustable variable for affecting the TTD. However, bicycle speeds are restricted by human capabilities so that adjustability is limited to the range of about 11 to 15 mph for average users.

Looking at the values produced by the TTD, most are not very usable. Typically, cycle length is determined by vehicular demand or minimum pedestrian crossing times. This method ignores those concerns in favor of finding cycle lengths that produce similar progression patterns at vehicle and bicycle speeds. Many of the TTD values produced are simply too short, would be unable to handle demand, and would probably increase delay due to congestion. The conditions required to generate long TTDs are long distances between intersections and large differences between vehicle and bicycle speeds. This restricts applicable locations for the cycle length approach.

Moving onto the split-based approach, this research only tested this application on for a one-way segment. Traveling in the opposite direction produces a different TTD at the target intersection which may produce different results for the transportation mode that leads the split. The leading mode also affects which TTD is chosen as the offset. The research on this approach also ignored protected left turns, though they should have little effect on one-way progression as the minimum split for the coordinated phase and offset are independent of the presence of a protected left turn phase (ignoring demand considerations). A protected left turn phase may however benefit two-way progression as one of the directions will not be used as the offset point; a protected left turn phase could potentially push the non-reference phase closer to the required offset for progression.

Additionally, this method tends to produce very narrow bandwidths for one or both modes of transportation depending on the leading mode and if that switches between different intersections. This method was designed by calculating the exact difference between arrivals which can go into decimal values; generally, some values, such as the offset, are only accepted as whole values within controllers. Because the minimum split calculation is so exact and calculates for arrival points rather than giving a window, slight shifts to the offset disrupt the already small bandwidth so additional time needs to be added to the minimum to provide any bandwidth. Bicycle travel is still not a particularly heavily used mode of transport in the United States so even a 10 second bandwidth can effectively serve bicycle movements, but the small bandwidths will likely not be sufficient for typical vehicle volumes.

4.6 Applications and Suggestions

Having acknowledged the limitations regarding the research and methodology, here are the recommendations for applying both of the TTD-based signal timing approaches.

Provided that the necessarily conditions are in place (equal TTDs between intersections and a sufficient cycle length), setting the TTD as the cycle length guarantees that any plan designed for one speed will also produce similar progression for the other, greatly simplifying the process of designing a timing plan. Downtown areas generally have the equal spacing of intersections needed, but they also tend to be low speed areas and may benefit more from simply reducing the speed limit and coordinating everything at bicycle speeds. Therefore, the areas that would most benefit from this method are ones like Sun Valley Blvd given in the example above that have higher speed limits and happen to have equally spaced intersections.

While many of the TTD values in the table were too short to serve as cycle lengths, the Double-TTD approach could help with that. Looking at an entire corridor, there will be a mix of critical intersections, which see the heaviest volumes and set the common cycle length for coordination, and minor intersections, which do not have as much volume on their side streets and thus do not need as long a cycle length to fulfill their demand needs. Strategically applying the Double-TTD to critical intersections could grant the extra time needed to meet those specific demand requirements. As seen above, because the cycle is based on the TTD, vehicle and bicycle speeds still produce similar progression bands as long as adjacent intersections are not both running Double-TTD cycles.

Finally, this information has potential for street design, especially if the goal is to create complete streets that promote the usage of other modes of transportation aside from driving. This is most apparent with being able to design intersection spacing in new developments with this method in mind, but speed limit changes could potentially be made to already established areas for better signal timing.

Moving on, the split-based method is less of a complete process than the cycle-based method but serves more as a guideline for determining the required split length for bicycle progression on one-way streets. In terms of application, though this paper discusses how to create bandwidth for both vehicles and bicycles using this method by altering which mode utilizes the front and end portion of the split, it may be better in practice to lock the leading mode to vehicles. This will guarantee that heavy vehicle demands have access to the entire duration of the split provided the offsets are based on travel time. In exchange, bicycle bandwidth will need to be disrupted occasionally when split values based on the TTD gap are too large. As a silver lining, bicycles are still primarily muscle powered and tired cyclists may fall out of bands that extend over large distances anyways. Intersections where the gap has grown too large compared to the vehicle demand-based split should be used as reset points for bicycle progression. The next split-based TTD calculation and timing for the corridor should done from this point with the process repeating until the whole corridor is timed. This method should guarantee bicycles some progression with stops after traveling a certain distance.

CHAPTER FIVE

EMPIRICAL DESIGN: BALANCING VEHICLE AND BICYCLE PERFORMANCE

5.1 Introduction

Chapter Four attempts to solve the problem of coordinating for both vehicles and bicycles in a mathematical manner by calculating values, whether those be cycle or split lengths, that guarantee windows for progression. However, as discussed in the *Limitations* section, there are requirements for the TTD method that greatly restrict what situations and locations it can be applied to. When faced with those limitations and the current lack of guidelines or software, the remaining option is to go with the regular approach of designing the timing and coordination based on one mode (typically vehicles), testing how well that plan works for the other mode, and then making adjustments, such as slight shifts to offsets or increasing split values where possible, to attempt to provide better progression for that second mode.

This method clearly prioritizes one mode over the other and good progression for the other is not guaranteed even with adjustments. There is also the question of which mode should be prioritized for coordination. Coordination is typically targeted at vehicles in the United States as they are only reasonable mode of transportation in a lot of places and make up a large majority of traffic on roadways. On the other hand, bicycles offer numerous advantages such as their lower average price, associated health benefits, and low environmental impacts. Choosing to prioritize bicycle progression could help to promote and give people a reason to choose cycling as a viable means of transportation, but if adoption is low, then drivers are forced to deal with the increased delays from a coordination plan that benefits no one.

How do we choose between a plan that maximizes vehicle progression, one that maximizes bicycle progression, or even one that chooses to prioritize neither to ensure that neither experience significant delays when all three plans have significantly different goals? The method proposed by this research for these circumstances is to quantify relevant performance variables pulled from the timing inputs or the generated TSDs and to sum them together with weights to obtain a single, easy to comprehend grade that reflects the quality of the signal timing based on multiple factors. It is a brute force approach that aims to judge any number of timing plans based on numerical values.

5.2 Center St Corridor

The Center St corridor in Reno, Nevada, stretching from 9th St just south of the University to Virginia St in Midtown, was chosen for this research to obtain data on the performance on different timing plans. A cycle track with bicycle signals was originally planned to be built in the summer of 2021 and would have provided real-life data on the proposed timing plans. Unfortunately, the project stalled, and performance results for this research have been entirely obtained from the Vissim simulation built based on the proposed changes for the corridor.

Center St is primarily a one-way northbound road, though there is a short two-way segment between the University and the freeway that stretches two intersections. The length of the cycle track runs through the southern part of the University, the Downtown area, and a residential-heavy portion of the Midtown area. The current speed limit along much of the road is 30 mph and is unlikely to increase due to the heavy pedestrian presence in all areas. The cycle track would have run two-way along the west edge of Center St for most of the corridor with the exception of the segment between 8th and 9th where the track splits at the intersection of 8th to run along both edges of the road.

For the bicycle signal, both the north and southbound movements will be controlled by phase 6 (normally used for the southbound vehicle movement). To prevent conflicts between the cycle track and northbound left-turning vehicles, a protected left-turn phase was added.

5.3 Methodology

This research proposes that the quality of a signal timing plan can be predicted to some degree based on individual intersection timing values and their resulting time space diagram. By extracting these values, applying a weight to reflect their importance, and summing them all together, a single representative value is obtained. Some of the goals of the research with regards to this method are identifying what timing variables are indicative of the quality of timing as well as to suggest values for the weights.

The following values are thought to influence and be representative of the quality of the signal timing:

Travel Time – Time it takes to travel from the first coordinated signal to the last. The Highway Capacity Manual determines level of service for an arterial based on the average travel speeds and the roadway type. The optimal travel time for a segment is the travel time at free flow speeds (typically around the speed limit) with no stops.

Number of Stops – Total number of stops made along a coordinated segment. Generally, in signal timing, a ratio of four to five green lights for one red light is considered good. Excessive stopping, even for short durations, are especially noticeable for drivers and can add to frustration. For cyclists, multiple starts and stops can be physically challenging, especially on uphill segments.

Bandwidth – Bandwidth is the time frame or window in a cycle when a vehicle traveling from the starting intersection is able to make it past the target intersection without stopping due to the alignment of the green times. Link bandwidth specifically indicates the bandwidth between two adjacent intersections while Thru bandwidth looks at the continuous band for the whole corridor if there is one. The Thru bandwidth is more important for vehicles who are more capable of traveling the whole corridor without stopping due to the lack of human constraints. Since the Thru band looks whole corridor, the max value for this band is limited by the shortest coordinated phase at any of the coordinated intersections. This max value is used as the max or best performance for vehicles. For bicycles, there is more concern for the link bandwidth, though bicycles typically do not need a very large band due to their low volumes.

Cycle Length – The cycle length is the total time it takes to run all phases at an intersection. For coordination, typically all intersections run the same cycle length to ensure that progression between intersections is consistent each cycle. Longer cycles may be required if volumes are heavy to ensure that each phase is sufficiently serviced and can generate wider bands with their longer phases, but a shorter cycle length reduces the waiting time at an intersection and makes bands more frequent.

To provide justification for the weights of the values, simulation runs were conducted using Vissim. Data on the performance was collected, and the values and weights were adjusted based on the results from multiple timing plans to match the results of the simulations runs.

5.4 Simulation

A simulation was conducted for the corridor to provide performance values and to serve as a point of reference for calibrating the weights for the grading factors. Vissim was chosen as the simulation software for its flexibility with regards to modeling complex roadway and intersection geometry, and the ability to model bicycle traffic.

A report provided by Headway Transportation for RTC Washoe served as the basis for the simulation (Headway, 2020). The report provided expected geometry changes to Center St such as lane reductions to make room for the cycle track. The provided map with the changes was overlayed onto the simulation file to accurately model the proposed geometry. All signalized intersections as well as the unsignalized intersections located in between were modelled. However, because the two northmost signalized intersections experienced significantly higher vehicle demands and would most likely be coordinated in the east-west direction for the freeway interchange ramps, the scope of the performance results was reduced to the segment with the seven signalized south intersections.

Vehicle volumes for the peak AM and PM periods from 2019 volumes were also provided in the report. These counts were given for all 9 signalized intersections of the Center St corridor. Balancing was already done to the counts in the report, though that balancing was done with the assumption that all signalized intersections were adjacent. Some minor adjustments to these numbers were made to account for the unsignalized intersections and some major parking areas dotted between the signalized intersections.

Additionally, it was difficult to determine origin-destination (OD) patterns for the corridor. Vissim handles traffic patterns with user defined routes consisting of a starting location and any number of ending locations. Vehicles are generated at the boundaries of the simulation and upon reaching a starting location for a route, are distributed according to the weights applied to each portion of the route, allowing users to control vehicle movements very precisely in a simulation. Since there was no OD data to work from, routes were simply used to mimic turning volumes directly at intersections, letting the simulation handle vehicle movements at an intersection-by-intersection basis without much consideration for drivers' intentions. Aside from not accurately simulating overall movements patterns along the corridor, another downside to this method is that vehicle movements are calculated very late and often results in last minute lane changes and traffic jams at intersections. A counter to this is placing the starting locations further upstream away from the downstream intersection to allow vehicles to quickly decide the route and reduce erratic movements while also providing the time and space needed to potentially shift into the correct lane, but close intersections see less benefit from this tactic.

On top of the given volumes, to ensure that there was enough performance data for the length of the entire corridor, 100 additional vehicles were added to the southern boundary and directed to travel through the whole corridor. Bicycle counts were not provided by the report, but it was suggested that enough be added to simulate an average of 1 bicycle per cycle to ensure that the bicycle phase was being triggered. Bicycle volumes varied with heavier volumes being generated in the south near residential on the AM plans and in the north near the university on the PM plans. To simplify the process and because travel along the whole corridor was the primary concern, bicycles were not generated at inner intersections and no bicycles turned off Center St.

Simulation of the signal timing was done with the Vissim built-in signal controller. Multiple timing plans focusing on vehicle progression, bicycle progression, and a mix of both for the AM and PM volumes were designed. Basic universal timing parameters for the controllers (min green, yellow, red, walk, etc.) were directly pulled from the current timing from the city's signal management database. While detectors were placed into the simulation and available for use, all phases were set to max out in order to test the quality of the intended coordination.

The FHWA's *Traffic Signal Timing Manual* lists average travel speed as the indicator of level of service for an arterial. Another arterial performance indicator is the Orange County Corridor Synchronization Performance Index (CSPI) which lists speed and number of stops as indicators of performance. From the simulation, travel time and stops were chosen to calibrate the grading metric.

The summarized simulation input values and results are presented in Appendix 1.

5.5 Results and Calibration

A Bike Priority, Vehicle Priority, and Balanced plan were created for both AM and PM periods for a total of 6 plans and each plan was simulated 5 times for 30 runs worth of data.

5.5.1 Simulation Results

Starting with the travel time, the FHWA's arterial LOS grading is given below in Table 7.

Table 7: Traffic Signal Timing Manual Arterial LOS Grades

Urban Street Class	**I**	**II**	**III**	**IV**
Range of free-flow speeds (FFS)	**55 to 45 mph**	**45 to 35 mph**	**35 to 30 mph**	**35 to 25 mph**
Typical FFS	**50 mph**	**40 mph**	**35 mph**	**30 mph**
LOS	**Average Travel Speed (mph)**			
A	> 42	> 35	> 30	> 25
B	> 34-42	> 28-35	> 24-30	> 19-25
C	> 27-34	> 22-28	> 18-24	> 13-19
D	> 21-27	> 17-22	> 14-18	> 9-13
E	> 16-21	> 13-17	> 10-14	> 7-9
F	≤ 16	≤ 13	≤ 10	≤ 7

Source: FHWA *Traffic Signal Timing Manual* Chapter 3, 2008

Speed values were measured in the simulation, primarily to ensure the simulation was running properly. As a general trend, the spot speed measurements located further away from intersections tended to read about 30 mph while the average speed measurements leading up to intersections tended to drop down to the 10's, implying slowdown was occurring from queueing. Again, the speed limit along Center St is 30 mph. Bicycles were set to run from 13 to 15 mph, but tended to range from 12 to 14 mph. However, the travel time between two points was easier to collect, can be related to speed, and also gave an indication of delay. Table 8 below converts Table 7 into unitless ratios by dividing the typical free flow speed by the limits given for each LOS grade.

Table 8: Traffic Signal Timing Manual Arterial LOS Given as Ratios

Urban Street Class	**I**		**II**		**III**		**IV**	
Range of free-flow speeds (FFS)	**55 to 45 mph**		**45 to 35 mph**		**35 to 30 mph**		**35 to 25 mph**	
Typical FFS	**50**		**40**		**35**		**30**	
LOS	**Average Travel Time (Ratio)**							
A	1	1.190	1	1.143	1	1.167	1.000	1.200
B	1.190	1.471	1.143	1.429	1.167	1.458	1.200	1.579
C	1.471	1.852	1.429	1.818	1.458	1.944	1.579	2.308
D	1.852	2.381	1.818	2.353	1.944	2.500	2.308	3.333
E	2.381	3.125	2.353	3.077	2.500	3.500	3.333	4.286
F	3.125	-	3.077	-	3.500	-	4.286	-

The values presented in Table 8 do not form a linear relationship. In order to get exact number values to use as scores, the limits were plotted onto a graph given in Figure 18 below. Equations for each class were defined using a logarithmic fit. Those equations are given below in Table 9.

Figure 18: Graphical Representation of Arterial LOS Scores

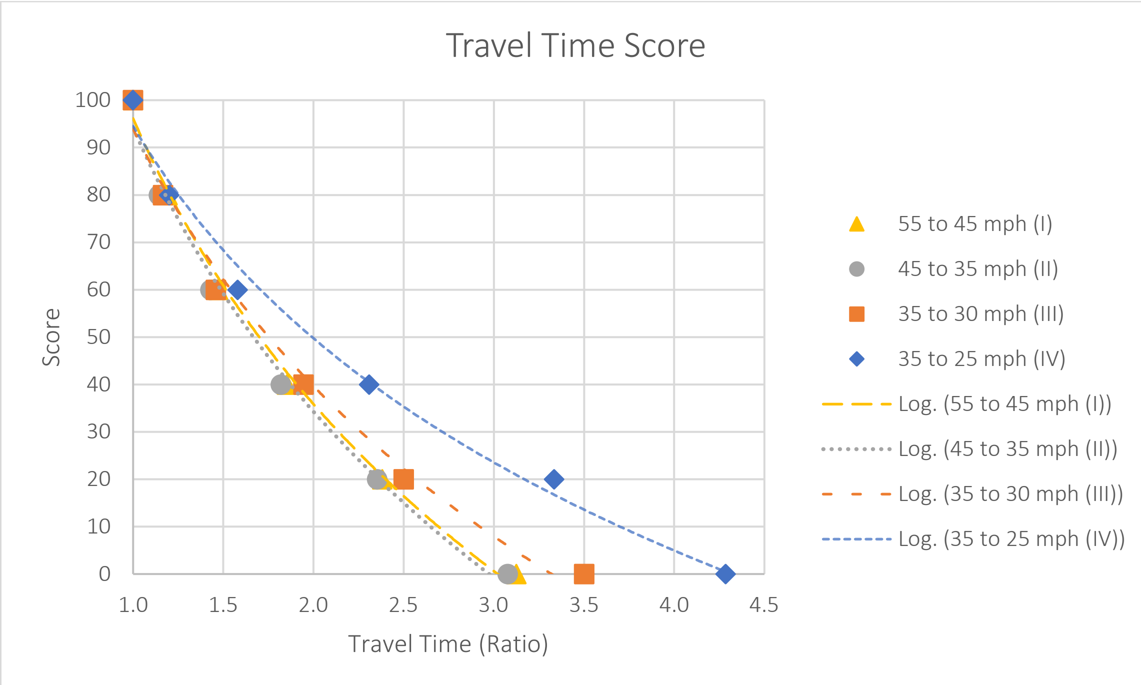


Table 9: Functions of LOS Trendlines for Given Arterial Classes

Class	f(x)	R^2
I	y = -86.37ln(x) + 94.157	0.9904
II	y = -86.94ln(x) + 96.125	0.9945
III	y = -78.24ln(x) + 93.886	0.9878
IV	y = -64.6ln(x) + 94.519	0.9895

It should be noted that the relationship between different urban classes is not linear either. The ratios for Class II are lower than Class I, implying that range of travel times is tighter and that higher speeds are needed to stay within grades. However, Classes III and IV swing the opposite direction with wider ranges despite their lower speeds. For this reason, Class IV was used for the bicycle scores rather than trying to interpolate to the lower bike speeds. After choosing the appropriate function (Class IV), scores for the simulation travel times were calculated.

Moving onto stops, Vissim outputs stops at intersections as a percentage of the total volume of vehicles. For example, 0.6 would indicate that 60% of vehicles stopped for a given movement. Vehicles will be in one of two states at the intersections–they are either stopped or they're not. Since they are only two states, it was decided that values over 0.5 are considered a stop while those under are not. Using this broad definition, total likely stops along the arterial were counted for vehicles and bicycles.

Using total stops, the ratio of greens to reds can be calculated with stops presumably being due to red lights. The number of green lights then is the remaining number of signals minus one to account for the unpredictable arrival time at the first intersection. Based off personal judgement, it was decided that a ratio of 4:1 for vehicles and 3:1 for bicycles would be considered the result of good coordination and get a max score (100) for stops. On the other hand, a ratio of 0 for either mode would indicate hitting a red at every intersection and get the worst score (0). Linear interpolation was used to calculate any scores in between these ranges.

By combining these two scores, a grounded idea of the performance of a signal timing plan is obtained. A weight of 0.65 was used for travel time while 0.35 was used for the stop ratio. It was decided to favor travel time more heavily in the scoring because stops do not necessarily give an idea of the delay they cause, while travel time can give an idea of delay caused due to stops. This goes against established grading methods which weight stops more heavily on the assumption that drivers are more likely to notice stops.

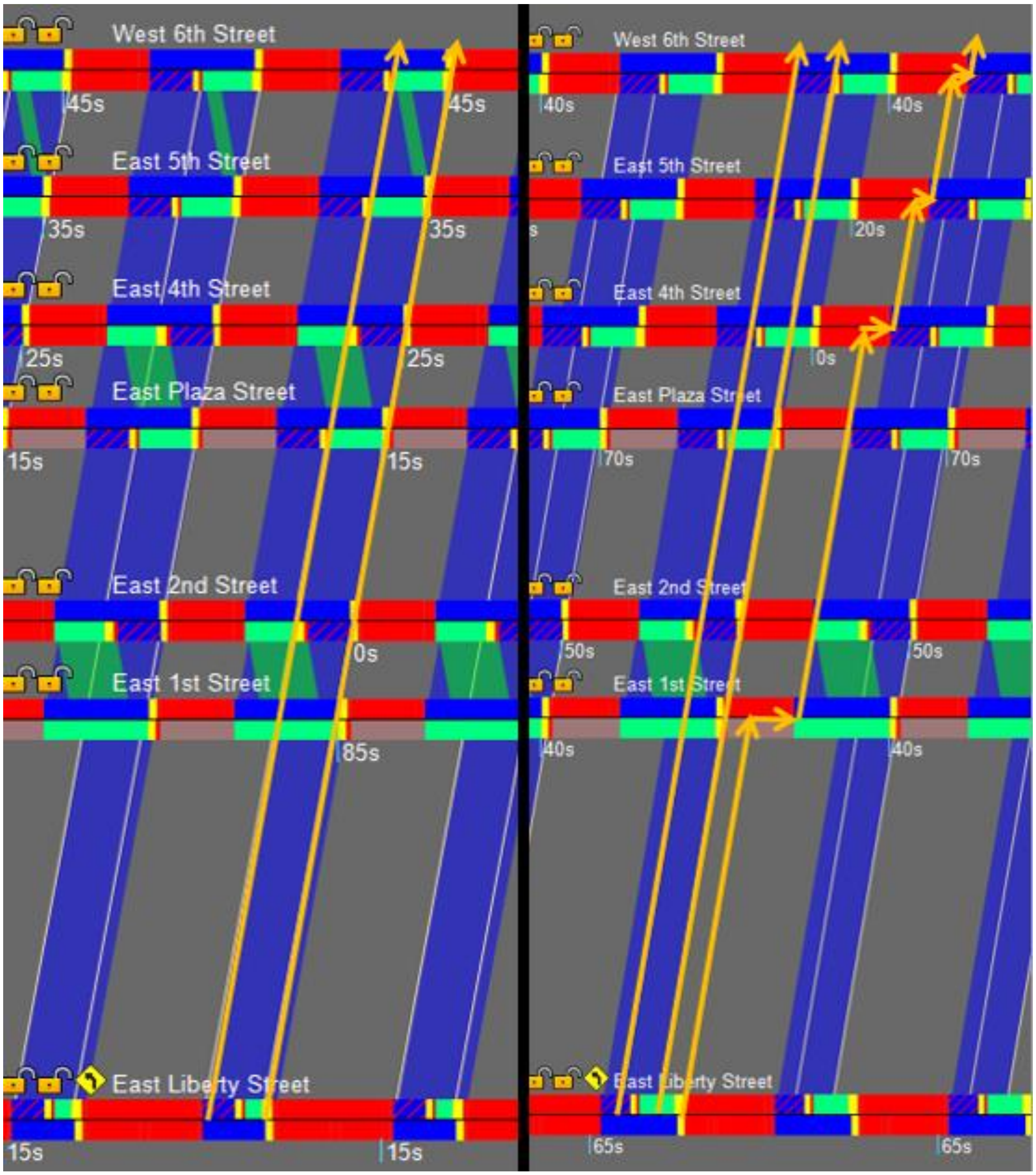
5.5.2 TSD Prediction

With the simulation runs serving as a benchmark, values can be pulled from the time space diagram and timing plan with the goal of emulating the score. Expected Travel Time, Expected Stops, and Band Availability are the three variables chosen to predict timing plan performance.

Expected Travel Time – The Expected Travel Time is the expected travel time based on the TSD. Transync has a built-in tool to project virtual trajectories using the given speed limit which can be used to determine both the expected travel time and number of stops depending on the starting time/location. Without Transync, an engineer familiar with TSDs should be capable of estimating the expected travel time manually given the optimal travel time and the cycle/split lengths. Any delay caused at the outer intersection (Liberty) before the vehicle or bicycle enters the system should not be counted.

The expected travel time is not always clear. Figure 19 shows two different plans. The TSD on the left has a solid thru band that occupies most of the split for the southernmost intersection. This means that regardless of the starting point within that split, the expected travel time is about the same. On the other hand, the TSD on the right has a link band that only uses about half of the split at Liberty and an even smaller thru band. The orange arrows highlight the possibility that late arrivals will have a very different experience travelling the corridor than those arriving within the thru band. In cases like this, engineering judgement should be used to pick an appropriate travel time.

Figure 19: Travel Trajectory Comparison



Another consideration is the dispersal rate of vehicles. Because a queue builds up during the red, the start of the split will see a higher density of vehicles and thus, travel times taken from the start of the split may be more representative of an expected travel time.

Once the expected travel time is chosen, divide by the optimal travel time. For bicycles, this optimal time is simply the total distance of the corridor divided by the free flow speed, uninterrupted by stops. For vehicles, an additional 10% was added to adjust for slowdown due to congestion. Once the ratio between the expected and optimal travel time is obtained, pick the appropriate function from Table 9 to calculate the score for travel time. Again, the function for Class IV was used for bicycles rather than trying to interpolate for lower speeds.

A weight of 0.55 was chosen for travel time.

Expected Stops – The Expected Stops is the ratio of green lights to red lights. The expected stops can be obtained from the TSD. Similar to the travel time, the expected number of stops is not always clear. Looking back at the right TSD on Figure 19, vehicles arriving in the early portion of the split make no stops, but late arrivals potentially face 4 stops. Once again, engineering judgement should be used to determine an appropriate estimate.

After determining the estimated stops, the score is calculated in the same way as with the simulation runs. A ratio of 4:1 for vehicles and 3:1 for bicycles is considered good coordination and gets a full 100; 0 or all reds gets a score of 0. Linear interpolation should be used to determine any scores between these two points.

A weight of 0.25 was chosen for the expected stops. The number of stops has a significant influence over drivers' and cyclists' perceptions of the quality of a timing plan and it was decided that it was the second most indicative measure of a corridor being well timed.

Band Availability – Band Availability is how much bandwidth is available. Unlike the previous two variables, the calculation for scoring band availability is different between bicycle and vehicles.

Starting with bicycles, the band availability score is decided by the average link bandwidth and the number of bandwidths. The average is calculated by summing the available bandwidths and dividing by the total number of segments (including segments without bandwidth). A flat score is assigned depending on the value. Averages above 15 seconds received a score of 100 and those above 10 seconds received a score of 50. In the United States, bicycle traffic is generally not heavy and in need of significant bandwidth. For the simulation, no bicycle volumes were given but it was suggested that enough were simulated to get a cyclist every cycle on average. With 90 second cycles, that gives a minimum of 40 cyclists per hour. Liberty, the largest intersection in the corridor, has a crossing distance of about 100 ft. Dividing that by 13 mph results in a crossing time of about 5.2 seconds. Due to the low demand, these static values are used for scoring.

The other half of the bicycle band availability is the ratio of bands to segments. Counted bands should be long enough to be usable. The ratio is given by the number of link bands divided by the number of road segments. This ratio is multiplied directly by 100 to get the ratio portion of the score. The two scores are then averaged to get the bicycle band availability score.

This score has a weight of 0.2. The band availability represents the potential or ease of being able to cycle through multiple intersections without stopping.

Moving onto vehicles, both the link bands and the thru band are considered. Starting with the link bands, the average band is calculated in the same manner with the sum of the link bands being divided by the total number of segments. The next calculation is for the average split length of the coordinated phases. The inner intersections should be counted twice. Divide the average band by the average split. This ratio essentially gives the percentage of the splits that the bands occupy or utilize. With the thru band, divide it by the smallest split of the coordinated phases, or the min split, to get the percentage of the maximum possible bandwidth. For both values, it was decided that 0.9 or 90% utilization is good (100) and 0 is poor (0). The ratios are adjusted with linear interpolation using this scale to give the link band and thru band scores. These numbers are meant to indicate how effectively coordination is able to produce bands or progression opportunity.

The weight of the link bands is 0.15 and the weight of the thru bands is 0.05. The thru band was given significantly less weight. Even through a large thru band can guarantee good progression, it can be difficult to attain is not required for good progression. A single stop might be all it takes to disrupt the thru band between two otherwise heavily connected segments.

Cycle Length – Ultimately, the cycle length was not used as an indicator of performance, primarily because the length does not change with adjustments to the TSD, and all the plans share the same cycle length. A shorter cycle length does result in shorter delays provided the intersection is still under capacity. Potentially a bonus score of up to 10 could be added to the total score depending on the how short the cycle is.

By summing the products of the individual scores and their weights, the respective total score can be calculated for each movement.

The scores should range from 0 to 100 for both the individual variables and the total score. If any of the calculations result in a score outside this range, the calculation should be checked to ensure that it makes sense and then truncated to 0 or 100 depending on which side it exceeds. The individual variables should not give bonus points or take away from the total. Table 10 below shows the comparison of the scores obtained from the simulation results and the scores calculated using the TSD Performance Estimate.

A sample of the TSD Prediction Estimate sheet is presented in Appendix 2.

5.5.3 Comprehensive Score

Much like the individual scores before, the scores for each movement can be summed together with weights into a single score representative of all aspects of the coordination plan. However, while the weights for the individual variables were adjusted with simulation runs, the movement weights are more flexible. Since there are no simulation results to try and match up to, there are a few options when selecting movement weights.

Table 10:Comparison of Simulation Scores and TSD Estimation Scores

AM Bike Priority Simulation				
	NB	*SB*	*Veh*	*Weight*
TT	89	68	82	0.65
Stops	100	17	50	0.35
Total	**93**	**50**	**71**	
AM Bike Priority TSD Estimation				
TT	90	68	81	0.55
Stops	67	17	35	0.35
	100	58	-	0.2
Band	-	-	82.9	0.15
	-	-	0	0.05
Total	**93**	**55**	**69**	
% Diff	**0.1%**	**9.6%**	**-2.2%**	

PM Bike Priority Simulation				
	NB	*SB*	*Veh*	*Weight*
TT	64	100	79	0.65
Stops	33	100	25	0.35
Total	**53**	**100**	**60**	
PM Bike Priority TSD Estimation				
TT	66	91	94	0.55
Stops	33	100	50	0.25
	25	100	-	0.2
Band	-	-	80	0.15
	-	-	48	0.05
Total	**53**	**105**	**84**	
% Diff	**-0.6%**	**5.1%**	**39.1%**	

AM Mix Priority Simulation				
	NB	*SB*	*Veh*	*Weight*
TT	100	62	87	0.65
Stops	100	17	25	0.35
Total	**100**	**46**	**65**	
AM Mix Priority TSD Estimation				
TT	100	63	88	0.55
Stops	100	17	50	0.25
	100	50	-	0.2
Band	-	-	90	0.15
	-	-	48	0.05
Total	**110**	**51**	**82**	
% Diff	**10.0%**	**9.4%**	**25.3%**	

PM Mix Priority Simulation				
	NB	*SB*	*Veh*	*Weight*
TT	82	68	86	0.65
Stops	100	17	100	0.35
Total	**88**	**50**	**91**	
PM Mix Priority TSD Estimation				
TT	86	73	94	0.55
Stops	100	33	100	0.25
	92	58	-	0.2
Band	-	-	89	0.15
	-	-	60	0.05
Total	**101**	**63**	**103**	
% Diff	**14.0%**	**26.2%**	**13.4%**	

AM Veh Priority Simulation				
	NB	*SB*	*Veh*	*Weight*
TT	68	73	100	0.65
Stops	33	33	100	0.35
Total	**56**	**59**	**100**	
AM Veh Priority TSD Estimation				
TT	71	71	94	0.55
Stops	17	33	100	0.25
	58	92	-	0.2
Band	-	-	99	0.15
	-	-	69	0.05
Total	**57**	**69**	**105**	
% Diff	**1.5%**	**16.9%**	**5.0%**	

PM Veh Priority Simulation				
	NB	*SB*	*Veh*	*Weight*
TT	82	59	82	0.65
Stops	67	7	100	0.35
Total	**77**	**41**	**88**	
PM Veh Priority TSD Estimation				
TT	81	74	100	0.55
Stops	47	33	100	0.25
	67	58	-	0.2
Band	-	-	100	0.15
	-	-	89	0.05
Total	**74**	**64**	**109**	
% Diff	**-3.1%**	**56.5%**	**24.0%**	

Note. NB and SB are the bicycle movements.

The first group of options involve some ratio of cars to bicycles being used as the weights. The first thing that comes mind is to directly compare the ratio of the vehicle and bicycle thru movements. The problem with this option is that vehicles vastly outnumber bicycles so a direct ratio between the two would end up with the bicycle movements having almost no weight in influencing the total score. The natural line of thinking then is to modify the volumes with some variable to make them more equal. A possible variable to balance things out is the space efficiency ratio of bicycles to vehicles.

One argument that can be made in favor of promoting cycling as a form of transportation is that bicycles take up much less space than vehicles and can help reduce space problems like congestion and parking. By multiplying the number of bicycles by some factor of car equivalency, the number of bicycles can be inflated. For example, if 4 bicycles can fit within the same space as 1 car, then bicycles are four times as space efficient. Assuming 1 person per bike and 1.5 people per car, that results in a ratio of 4:1.5 or 2.67 people on bikes compared to vehicles. Bicycle numbers could then be inflated by a factor of 2.67 and would be much closer to vehicle volumes and less likely to be completely dominated in the total score.

There are a lot of images floating around the internet showing the space utilization of different modes of transportation, and while those images really show off the space inefficiency of single occupancy vehicles, they do not necessarily provide usable ratios. The primary issue is that as vehicles or any mode transportation moves, headway is needed between vehicles for safety and as speeds get higher, this distance becomes greater. Most of these images usually show parked vehicles. Luckily, a study done by

Cao and Sano (2012) proposed a relationship between speed and what they termed as effective space, or the space needed for some mode to travel at a given speed safely. Table 11 shows the effective space as a function of speed for vehicles and bicycles as defined by Cao and Sano.

Table 11: Space Utilization by Modes While Moving

Transport Mode	Mean Speed (mph)	Mean Speed (m/s)	Effective Space (m^2)
Car	30	13.4	47.03
Bicycle	13	5.8	8.49

Note. Adapted from "Estimating Capacity and Motorcycle Equivalent Units on Urban Roads in Hanoi, Vietnam," by N. Cao and K. Sano, 2012, Journal of Transportation Engineering, 138(6), (https://ascelibrary.org/doi/full/10.1061/%28ASCE%29TE.1943-5436.0000382).

According to Cao and Sano, moving at the given speeds, vehicles occupy 47.03 m^2 and bicycles occupy 8.49 m^2 of space. Assuming cars have an average occupancy of 1.5 people and bicycles have an average occupancy of 1 person, then the ratio of space per person for bicycles and vehicles is about 5.5:1.5 or simplifying it, bikes (13 mph) are about 3.7 times as space efficient as vehicles (30 mph). Therefore, one could justify multiplying the volume of bicycles by 3.7 to balance out the weight of the volume of vehicles.

The other group of options for choosing weights is to just pick static values. Choosing a weight of 0.33 (0.25 with 2 vehicle and bicycle movements) would give each movement equal weight. An engineer might also choose to apply a heavier weight at their own judgement to promote a certain movement. Ultimately, the weights of the movements are flexible and can be adjusted depending on the desired outcome.

5.6 Conclusion

It should be noted that the weights used do not result in identical or even similar scores at times. For example, both the PM Mix and Veh SB Bike movements have large differences between the scores based on the simulation results and those produced by the TSD Performance Estimate. Additionally, because of the heavy weight used for the travel time and the stops, accurate estimates from the engineer are required in order to obtain a score that resembles real performance.

Ultimately, the point of the scores is to provide a tangible means of comparison between different plans. Provided they are all graded using the same values, at least some comparison can be drawn for the expected performance. The weights chosen were calibrated with simulation, but a more varied set of timing plans could help to better define them. Additionally, only three variables were chosen for the TSD Performance Estimate. Travel time and number of stops are common measures for arterial performance and bandwidth was chosen to represent the likelihood or potential for progression. These three values are relatively easy to obtain so they can be used to quickly estimate performance, but there may be other variables indicative of performance that were missed.

For a similar reason, no letter grades were assigned to the scores. Typical grading systems rank a 50 as an F, but that is not necessarily true for these scores. Giving letter grades also obfuscates previously clear quantitative information and makes it difficult to compare timing plans that receive the same grade. Essentially, these scores were not designed to be used as a performance rating outside the context of this method.

Finally, the adjustment of weights should be done before calculating scores. The weights should be decided with some goal in mind whether that be promoting a certain mode of transportation or trying to get equal balance. Adjusting the weights afterwards will change the scores to reflect the engineer's desires rather than being indicative of performance given the set of conditions (weights).

CHAPTER SIX

SUMMARY OF MAJOR FINDINGS, RECOMMENDATIONS, AND CONCLUSION

6.1 Introduction

The primary aim of this study was to devise a method for developing signal timing plans that can best accommodate both vehicles and bicycles which move at significantly different speeds. Two approaches were taken. A conceptual approach provided conditions for allowing progression for both modes without needing to take into account any excessive considerations. However, in the event that the rigid conditions of the conceptual approach are not met, a more rudimentary scoring system was devised that grades timings plans and accounts for progression from both modes of transportation.

This chapter summarizes the results of this research, gives recommendations for use and implementation, and discusses the future of work regarding this topic.

6.2 Summary of Major Findings

❖ ***Travel Time Difference as the Cycle Length***

It was thought fairly early on into this research that there was some cycle length that would somehow provide progression for both vehicles and bicycles. There is, but certain conditions need to be met. The idea behind this method is that rather than trying to squeeze slower bicycles into the same cycle as vehicles, it would be easier to simply have them arrive during the next cycle. Setting the cycle length to this difference in arrival times ensures that slower cyclists arrive during the new cycle. Building on that idea, if the coordinated intersections are spaced at an equal distance, then the travel time difference is the same for each intersection and a common cycle length can be set allowing coordination. Because of the deliberate design of the cycle length, progression for one mode is the same for the other, thus greatly simplifying the design process for signal timing plans.

❖ *Travel Time Difference as the Split Length*

The other application of the travel time difference is to use it as a minimum value for determining the split lengths required to get both modes of transport past some number of intersections. This method is helpful for determining the minimum split lengths but is not particularly useful for designing functional timing plans. On the other hand, it is much more flexible than the TTD Cycle Length Method which requires equal intersection spacing and a large enough TTD to serve as a suitable cycle length.

❖ *Time Space Diagram Performance Estimation*

The last approach for tackling the challenge of creating a timing plan to serve multiple modes of transport was simply to create multiple timing plans and then see which was the best. The Time Space Diagram Performance Estimate (TSDPE) method was designed as a way to combine performance for a timing plan at two different speeds into an easy-to-understand score. The TSDPE is meant to circumvent the lengthy process of developing a simulation or implementing into the field by providing a rudimentary score based on values from the TSD or timing parameters. Weights for the performance measures were calibrated using simulation. Weights for the individual movements can be adjusted depending on the desired outcome for the corridor and coordination. The TSDPE is not guaranteed to provide a score that accurately predicts real performance, but it is useful for quickly comparing different timing plans.

6.3 Recommendations for Designing Around Vehicles and Bicycles

Without a doubt, the TTD Cycle Length method produces the best circumstances for easily creating timing plans that work for multiple modes of transport moving at different speeds. If designing for multiple modes of transport, the conditions for whether this method can be applied should immediately be checked. These conditions were defined as equal intersection spacing with a large TTD value to serve as the cycle length, but there is a small exception. The only condition technically required is that the cycle length is equal to the TTD. The TTD is a function of distance, vehicle speed, and bicycle speed; the speeds are assumed to be constant, so distance also needs to remain constant to obtain a common TTD, but if speeds change, the distances also need to change to keep the same TTD.

Equally spaced intersections are not uncommon, though they are usually more common in older, downtown or CBD areas where speed limits are lower. It may be difficult to get a large enough TTD to serve as the cycle length. In the case of short cycle lengths, one of the modifications is to double the cycle length of the critical intersection. Provided the intersections are not adjacent, doubling the cycle length can help accommodate higher demand intersections without significantly disrupting progression along the corridor.

Finally, future developments can take advantage of this information. While equally spaced intersections are not technically required, they greatly help with the TTD Cycle Length method. While this research looked only at vehicles and bicycles, street level public transportation typically travels slower than the surrounding traffic and could benefit from the TTD Cycle Length method. Building new developments with equal spacing makes the signal timing more convenient.

Moving onto the TTD as Split Length Method, the recommended application is to compare the minimum values with the normal split values determined using vehicle demand. Not all intersections need the full cycle, so some phases have a bit of flexibility. The minimum values serve as a clear requirement for what is needed for bicycle progression; if there is not enough flexibility to reach the minimum value, then adding that time onto the coordinated phase for bicycle progression is pointless. Instead, that intersection should be used to segment bicycle progression and let the platoon build up again for the next group of signals with splits adjusted to accommodate bicycles.

While the application of this method in Section 4.4 proved intersecting, it does not produce a timing plan with significant bandwidth for either vehicles or bicycles and should probably be avoided.

The final method is the TSD Performance Estimate method. While the first two methods have some restrictions that limit their usability, that does not make this method the default for designing a timing plan for two modes. It might be possible to come up with a good timing plan that serves two modes without relying on any of these methods simply with bit of tinkering. However, one of the original problems encountered when trying to design a timing plan for the proposed Center St cycle track was that none of the timing plans had good progression for all modes, no doubt due to both bike directions being tied to a single phase. This method was designed with this situation in mind where at a glance, none of the timing plans stood out as the best.

6.4 Future Research

The two methods suggested to be pursued for further research are the TTD Cycle Length and the TSD Performance Estimate methods.

For the TTD Cycle Length, conditions for its applicability are of interest. For this research, equal distances were used, but as mentioned, changing speeds can be used to obtain the same TTD for different length segments. While speed limits generally remain consistent depending on the geography, it may be an interesting angle to approach the problem from.

Another area of interest is making modifications to the cycle length. One of the biggest weaknesses of the TTD Cycle Length method is that a lot of the TTD values are too short to be feasibility used as cycles lengths. Double-Length cycles were briefly investigated with this research, but not fully explored. Areas of interest include how many double-length cycles can be implemented into corridor without impacting progression or whether the cycle length can be increased by even larger factors than two.

As for the TSD Performance Estimate, the weights for the TSD values would surely benefit from a larger sample of simulations or real data for fine tuning.

At the moment, none of the large traffic simulation software can generate TSDs with bandwidths for two different speeds. The addition of such a feature would made signal timing for two modes significantly easier and would most likely render the TSD

Performance Estimate method lengthy and obsolete. However, such a function should be met with joy; the improvement it would bring to the signal timing design process would be tremendous.

6.5 Conclusion

Cycling offers numerous advantages over driving. It is healthy, good for the environment, creates less congestion, and is typically less expensive than driving. Though the United States has in the past century typically designed its cities around cars, neighborhoods where people can get around without driving are becoming increasingly desired (Cortright, 2009).

Efforts to improve cycling in the United States have typically been done from the infrastructure point of view. Lanes are reduced to make room for bike lanes and cycle tracks, and bike signals and turning boxes are added to intersections to give cyclists an equal presence on streets. However, the most notable efforts from the operations perspective are usually speed limit reductions so everyone travels at bike speeds. While this works well in downtown and slow commercial areas, it is not reasonable everywhere. However, research and practice on signal timing for two different speeds is very limited.

This research tackles this problem and proposes three methods for designing signal timing when considering different modes of transport. The first two methods are based in concept and offer a definite way of designing a timing plan. However, if these two methods are not applicable, the last method offers a brute force approach for deciding amongst multiple timing plans.

By attempting to solve the other half of this issue, progress is made towards a future less reliant on cars and more on other forms of transportation.

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APPENDICES

Appendix 1: Timing Plans and Simulation Results

AM Bike Prio					
Intersection	Offset'	Phases & Sequence			
6th	60	Φ2' (55)		Φ4 (35)	
		Φ5 (25)	Φ6 (30)	Φ8 (35)	
5th	45	Φ2' (55)		Φ4 (35)	
		Φ5 (25)	Φ6 (30)	Φ8 (35)	
4th	40	Φ2' (55)		Φ4 (35)	
		Φ6 (30)	Φ5 (25)	Φ8 (35)	
Plaza	60	Φ2' (55)		Φ4 (35)	
		Φ5 (25)	Φ6 (30)		
2nd	40	Φ2' (55)		Φ4 (35)	
		Φ6 (30)	Φ5 (25)	Φ8 (35)	
1st	25	Φ2' (55)		Φ4 (35)	
		Φ6 (55)			
Liberty	55	Φ2 (55)		Φ4' (45)	
		Φ5 (20)	Φ6 (25)	Φ7 (15)	Φ8 (30)

AM Bike Prio		
Movement	Avg Vol Bike/Veh	Travel Time
NB Bike	59	227.05
SB Bike	19	313.41
Veh	114	120.41

AM Bike Prio				
Intersection	Movement	Avg Vol	Stop Ratio	Stop
6th	Veh	450	0.33	0
	Bike SB	19	0.78	-
	Bike NB	59	0	0
5th	Veh	435	0.19	0
	Bike SB	19	1.03	1
	Bike NB	59	0	0
4th	Veh	392	0.26	0
	Bike SB	19	1.02	1
	Bike NB	59	1.11	1
Plaza	Veh	441	0.16	0
	Bike SB	19	1.09	1
	Bike NB	59	0.13	0
2nd	Veh	378	0.53	1

	Bike SB	20	1.11	1
	Bike NB	59	0.01	0
1st	Veh	406	0.6	1
	Bike SB	20	0	0
	Bike NB	59	0.01	0
Liberty	Veh	132	0.55	-
	Bike SB	19	0	0
	Bike NB	59	0.91	-
Total	Veh			2
	Bike SB			4
	Bike NB			1

AM Mix Prio					
Intersection	Offset'	Phases & Sequence			
6th	40	Φ2' (55)		Φ4 (35)	
		Φ5 (25)	Φ6 (30)	Φ8 (35)	
5th	20	Φ2' (55)		Φ4 (35)	
		Φ5 (25)	Φ6 (30)	Φ8 (35)	
4th	0	Φ2' (55)		Φ4 (35)	
		Φ5 (25)	Φ6 (30)	Φ8 (35)	
Plaza	70	Φ2' (55)		Φ4 (35)	
		Φ5 (25)	Φ6 (30)		
2nd	50	Φ2' (55)		Φ4 (35)	
		Φ6 (30)	Φ5 (25)	Φ8 (35)	
1st	40	Φ2' (55)		Φ4 (35)	
		Φ6 (55)			
Liberty	65	Φ2 (55)		Φ4' (45)	
		Φ5 (20)	Φ6 (25)	Φ7 (15)	Φ8 (30)

AM Mix Prio		
Movement	Avg Vol Bike/Veh	Travel Time
NB Bike	62	201.48
SB Bike	18	345.47
Veh	117	110.95

AM Mix Prio				
Intersection	Movement	Avg Vol	Stop Ratio	Stop
6th	Veh	449	1	1
	Bike SB	19	0.77	
	Bike NB	62	0	0
5th	Veh	437	0.14	0

	Bike SB	19	1.02	1
	Bike NB	62	0.01	0
4th	Veh	406	0.69	1
	Bike SB	19	1.09	1
	Bike NB	61	0.56	1
Plaza	Veh	448	0.16	0
	Bike SB	19	1.05	1
	Bike NB	61	0	0
2nd	Veh	386	0.44	0
	Bike SB	18	1.08	1
	Bike NB	61	0.01	0
1st	Veh	409	0.63	1
	Bike SB	18	0	0
	Bike NB	61	0.04	0
Liberty	Veh	136	0.58	
	Bike SB	18	0	0
	Bike NB	61	0.91	
Total	Veh			3
	Bike SB			4
	Bike NB			1

AM Veh Prio					
Intersection	Offset'	Phases & Sequence			
6th	40	Φ2' (55)		Φ4 (35)	
		Φ6 (30)	Φ5 (25)	Φ8 (35)	
5th	35	Φ2' (55)		Φ4 (35)	
		Φ5 (25)	Φ6 (30)	Φ8 (35)	
4th	30	Φ2' (55)		Φ4 (35)	
		Φ6 (30)	Φ5 (25)	Φ8 (35)	
Plaza	25	Φ2' (55)		Φ4 (35)	
		Φ5 (25)	Φ6 (30)		
2nd	10	Φ2' (55)		Φ4 (35)	
		Φ6 (30)	Φ5 (25)	Φ8 (35)	
1st	5	Φ2' (55)		Φ4 (35)	
		Φ6 (55)			
Liberty	10	Φ2 (55)		Φ4' (45)	
		Φ6 (25)	Φ5 (25)	Φ7 (15)	Φ8 (30)

AM Veh Prio		
Movement	Avg Vol Bike/Veh	Travel Time
NB Bike	60	315
SB Bike	20	291
Veh	111	89

AM Veh Prio				
Intersection	Movement	Avg Vol	Stop Ratio	Stop
6th	Veh	435	0.15	0
	Bike SB	20	0.85	-
	Bike NB	60	1.03	1
5th	Veh	441	0.14	0
	Bike SB	20	0	0
	Bike NB	60	0	0
4th	Veh	406	0.08	0
	Bike SB	20	1.03	1
	Bike NB	59	1.05	1
Plaza	Veh	442	0.19	0
	Bike SB	20	0	0
	Bike NB	59	0	0
2nd	Veh	370	0.31	0
	Bike SB	20	1.14	1
	Bike NB	61	0	0
1st	Veh	40	0.28	0
	Bike SB	20	0	0
	Bike NB	61	1.15	1
Liberty	Veh	128	0.6	-
	Bike SB	20	0.72	1
	Bike NB	61	0.99	-
Total	Veh			0
	Bike SB			3
	Bike NB			3

PM Bike Prio					
Intersection	Offset'	Phases & Sequence			
6th	50	Φ2' (55)		Φ4 (35)	
		Φ6 (30)	Φ5 (25)	Φ8 (35)	
5th	50	Φ2' (55)		Φ4 (35)	
		Φ5 (25)	Φ6 (30)	Φ8 (35)	
4th	10	Φ2' (55)		Φ4 (35)	
		Φ6 (30)	Φ5 (25)	Φ8 (35)	
Plaza	5	Φ2' (55)		Φ4 (35)	
		Φ5 (25)	Φ6 (30)		
2nd	65	Φ2' (55)		Φ4 (35)	
		Φ6 (30)	Φ5 (25)	Φ8 (35)	
1st	60	Φ2' (55)		Φ4 (35)	
		Φ6 (55)			
Liberty	0	Φ2 (55)		Φ4' (55)	

		Φ5 (20)	Φ6 125)	Φ7 (30)	Φ8 (25)

PM Bike Prio		
Movement	Avg Vol Bike/Veh	Travel Time
NB Bike	39	336
SB Bike	77	207
Veh	187	126

PM Bike Prio				
Intersection	Movement	Avg Vol	Stop Ratio	Stop
6th	Veh	860	0.59	1
	Bike SB	79	0.97	-
	Bike NB	39	1.04	1
5th	Veh	813	0.9	1
	Bike SB	79	0	0
	Bike NB	39	1.23	1
4th	Veh	769	0.08	0
	Bike SB	79	0.08	0
	Bike NB	41	1.02	1
Plaza	Veh	905	0.17	0
	Bike SB	79	0	0
	Bike NB	40	0.25	0
2nd	Veh	913	0.43	0
	Bike SB	79	0.03	0
	Bike NB	40	0.01	0
1st	Veh	859	0.53	1
	Bike SB	79	0	0
	Bike NB	40	0	0
Liberty	Veh	328	0.08	-
	Bike SB	77	0.65	1
	Bike NB	40	1.04	-
Total	Veh			3
	Bike SB			1
	Bike NB			3

PM Bike Prio					
Intersection	Offset'	Phases & Sequence			
6th	50	Φ2' (55)		Φ4 (35)	
		Φ6 (30)	Φ5 (25)	Φ8 (35)	
5th	50	Φ2' (55)		Φ4 (35)	
		Φ5 (25)	Φ6 (30)	Φ8 (35)	

4th	10	Φ2' (55)		Φ4 (35)	
		Φ6 (30)	Φ5 (25)	Φ8 (35)	
Plaza	5	Φ2' (55)		Φ4 (35)	
		Φ5 (25)	Φ6 (30)		
2nd	65	Φ2' (55)		Φ4 (35)	
		Φ6 (30)	Φ5 (25)	Φ8 (35)	
1st	60	Φ2' (55)		Φ4 (35)	
		Φ6 (55)			
Liberty	0	Φ2 (55)		Φ4' (55)	
		Φ5 (20)	Φ6 125)	Φ7 (30)	Φ8 (25)

PM Bike Prio		
Movement	Avg Vol Bike/Veh	Travel Time
NB Bike	39	336
SB Bike	77	207
Veh	187	126

PM Bike Prio				
Intersection	Movement	Avg Vol	Stop Ratio	Stop
6th	Veh	860	0.59	1
	Bike SB	79	0.97	-
	Bike NB	39	1.04	1
5th	Veh	813	0.9	1
	Bike SB	79	0	0
	Bike NB	39	1.23	1
4th	Veh	769	0.08	0
	Bike SB	79	0.08	0
	Bike NB	41	1.02	1
Plaza	Veh	905	0.17	0
	Bike SB	79	0	0
	Bike NB	40	0.25	0
2nd	Veh	913	0.43	0
	Bike SB	79	0.03	0
	Bike NB	40	0.01	0
1st	Veh	859	0.53	1
	Bike SB	79	0	0
	Bike NB	40	0	0
Liberty	Veh	328	0.08	-
	Bike SB	77	0.65	1
	Bike NB	40	1.04	-
Total	Veh			3
	Bike SB			1
	Bike NB			3

PM Mix Prio						
Intersection	Offset'	Phases & Sequence				
6th	45	Φ2' (55)		Φ4 (35)		
		Φ5 (25)	Φ6 (30)	Φ8 (35)		
5th	45	Φ2' (55)		Φ4 (35)		
		Φ6 (30)	Φ5 (25)	Φ8 (35)		
4th	25	Φ2' (55)		Φ4 (35)		
		Φ6 (30)	Φ5 (25)	Φ8 (35)		
Plaza	15	Φ2' (55)		Φ4 (35)		
		Φ5 (25)	Φ6 (30)			
2nd	0	Φ2' (55)		Φ4 (35)		
		Φ6 (30)	Φ5 (25)	Φ8 (35)		
1st	75	Φ2' (55)		Φ4 (35)		
		Φ6 (55)				
Liberty	20	Φ2 (55)		Φ4' (55)		
		Φ5 (20)	Φ6 125)	Φ7 (30)	Φ8 (25)	

PM Mix Prio		
Movement	Avg Vol Bike/Veh	Travel Time
NB Bike	37	255
SB Bike	77	315
Veh	190	114

PM Mix Prio				
Intersection	Movement	Avg Vol	Stop Ratio	Stop
6th	Veh	863	0.41	0
	Bike SB	79	0.87	-
	Bike NB	37	0.03	0
5th	Veh	816	0.23	0
	Bike SB	79	1.12	1
	Bike NB	37	0.03	0
4th	Veh	767	0.06	0
	Bike SB	79	1.28	1
	Bike NB	37	0.99	1
Plaza	Veh	923	0.19	0
	Bike SB	80	0	0
	Bike NB	37	0.04	0
2nd	Veh	921	0.77	1
	Bike SB	80	0.88	1
	Bike NB	38	0.04	0
1st	Veh	888	0.01	0

	Bike SB	80	0	0
	Bike NB	38	0	0
Liberty	Veh	348	0.74	-
	Bike SB	77	0.51	1
	Bike NB	38	0.95	-
Total	Veh			1
	Bike SB			4
	Bike NB			1

PM Veh Prio					
Intersection	Offset'	Phases & Sequence			
6th	45	Φ2' (55)		Φ4 (35)	
		Φ5 (25)	Φ6 (30)	Φ8 (35)	
5th	35	Φ2' (55)		Φ4 (35)	
		Φ5 (25)	Φ6 (30)	Φ8 (35)	
4th	25	Φ2' (55)		Φ4 (35)	
		Φ6 (30)	Φ5 (25)	Φ8 (35)	
Plaza	15	Φ2' (55)		Φ4 (35)	
		Φ5 (25)	Φ6 (30)		
2nd	0	Φ2' (55)		Φ4 (35)	
		Φ6 (30)	Φ5 (25)	Φ8 (35)	
1st	85	Φ2' (55)		Φ4 (35)	
		Φ6 (55)			
Liberty	15	Φ2 (55)		Φ4' (55)	
		Φ5 (20)	Φ6 125)	Φ7 (30)	Φ8 (25)

PM Veh Prio		
Movement	Avg Vol Bike/Veh	Travel Time
NB Bike	39	255
SB Bike	75	359
Veh	181	120

PM Veh Prio				
Intersection	Movement	Avg Vol	Stop Ratio	Stop
6th	Veh	858	0.36	0
	Bike SB	79	1.2	-
	Bike NB	39	0	0
5th	Veh	814	0.07	0
	Bike SB	79	1.12	1
	Bike NB	39	0.69	1
4th	Veh	768	0.06	0

	Bike SB	79	1.21	1
	Bike NB	41	0.98	1
Plaza	Veh	913	0.19	0
	Bike SB	78	0	0
	Bike NB	41	0	0
2nd	Veh	912	0.79	1
	Bike SB	78	1.16	1
	Bike NB	40	0.02	0
1st	Veh	857	0.5	0
	Bike SB	78	1.22	1
	Bike NB	40	0.02	0
Liberty	Veh	328	0.78	-
	Bike SB	75	0.82	1
	Bike NB	40	1.04	-
Total	Veh			1
	Bike SB			5
	Bike NB			2

Appendix 2A: TSD Performance Estimate

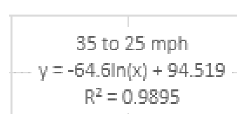
Street		Units	-Basic Information About Corridor
Distance		ft	-Distance from first intersection to last
Veh Speed		mph	-Speed limit/Free Flow Speed
Bike Speed		mph	-Design Bike Speed
No. of Intersections			-Number of Coordinated Intersections
Cycle Length		s	-Common cycle length
Veh Optimal Travel Time +10%		s	-Optimal Travel Time
Bike Optimal Travel Time		s	-Optimal Bike Travel Time

Performance Prediction

Travel Time	Expected	Ratio	Score	Weight
NB Bike				
SB Bike				
Veh				0.55

-*Expected Travel Time* can be obtained from TSD. Use engineering judgement when choosing the travel time.

-Divide by *Optimal Travel Time* to obtain ratio. Plug ratio into appropriate speed function to obtain score.



ex. score function

Stop Ratio	Veh	Bike	Score
Good	4	3	100
Worst	0	0	0

Stops	Expected	Ratio	Score	Weight
NB Bike		No Stops	100	0.25
SB Bike		No Stops	100	
Veh		No Stops	100	

-*Stop Ratio* is number of greens to reds considered good progression. For vehicles 4 green lights for every 1 red and for bicycles, 3 for 1, were considered good coordination (100).

-0 greens or all reds was considered the worst (0).

-Use 1 less than total intersections when calculating ratio to ignore first intersection.

-"No red lights = no stops" and "Ratio > Good" gives score of 100.

Bike Band Scores		Weight
15	100	0.2
10	50	

Band Availability	Average	Score	No.	Ratio	Total Score
NB Bike		0		0.00	0
SB Bike		0		0.00	0

-Bike and Veh bandwidth scores are calculated differently.

-Calculate average bandwidth by summing link bands and dividing by number of segments

-For the Bike Bandwidth, the score portion based on the average band is either 50 or 100 based on if it's > 10s or >15s. Band for bikes does not need to be large.

-"*No.*" is number of segments with "useable" bandwidth. Divide by total number of

Veh Band Ratio	Veh	Score
Good	0.9	100
Worst	0	0

Band Availability			Ratio	Score	Weight
Link Band	Avg Band	Avg Split		0	0.15
Thru Band	Thru Band	Min Split		0	0.05

-Veh Band Score is based on Link Bandwidth and Thru Bandwidth

-Calculate average bandwidth by summing link bands and dividing by number of segments.

-Calculate average split of coordinated phase. Make sure to count the inner intersections twice.

-Calculate the ratio of the average link band to the average split length to get utilization ratio.

-Divide Thru bandwidth by shortest split to find thru ratio.

-0.9 or 90% for link and thru considered good utilization of split for band.

Individual Scores

NB Bike

SB Bike =(*TT***Weight*)+(*Stop***Weight*)+(*BikeBand***Weight*)

Veh =(*TT***Weight*)+(*Stop***Weight*)+(*VehBand***Weight*)

-Individual Scores based on *Travel Time*, *Stops*, and *Band Availability*. Sum together with recommended weights to obtain an overall score for each movement.

-Make sure to use different band calculations for bike and veh.

- Highlighted cells should be filled by user. Those already filled are suggestions and can be adjusted.

-Suggested weights were calibrated with simulation run results.

Appendix 2B: TSD Performance Estimate Example AM Veh Priority

Center St - 6th to Liberty AM Veh Prio

Distance	3980	ft
Veh Speed	30	mph
Bike Speed	13	mph
No. of Intersections	7	
Cycle Length	90	s
Veh Optimal Travel Time +10%	99.5	s
Bike Optimal Travel Time	208.7	s

Performance Prediction

Travel Time	Expected	Ratio	Score		
NB Bike	300.0	1.437	71		
SB Bike	300.0	1.437	71		Weight
Veh	100.0	1.005	94		0.55

Stop Ratio	Veh	Bike	Score
Good	4	3	100
Worst	0	0	0

Stops	Expected	Ratio	Score		Weight
NB Bike	4	0.5	17		0.25
SB Bike	3	1	33		
Veh	0	No Stops	100		

Bike Band Scores		
15	100	Weight
10	50	0.2

Band Availability	Average	Score	No.	Ratio	Total Score
NB Bike	11.3	50	4	0.67	58
SB Bike	19.5	100	5	0.83	92

Veh Band Ratio	Veh	Score
Good	0.9	100
Worst	0	0

Band Availability			Ratio	Score	Weight
Link Band	48.3	54.2	0.89	99	0.15
Thru Band	27.9	45	0.62	69	0.05

Individual Scores	
NB Bike	**54.9**
SB Bike	**65.8**
Veh	**95.1**