DEPARTMENT OF TRANSPORTATION

Toward implementation of max-pressure control on Minnesota roads: Phase 2

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16. Abstract (Limit: 250 words)

Max-pressure (MP) traffic signal control is a new and innovative control algorithm that uses upstream and downstream vehicle counts to determine signal timing that maximizes throughput. While this method has been extensively tested in simulation, it has not yet been tested on actual traffic signals in the US. To close this gap, this report presents the results of the development of a hardware-in-the-loop traffic signal testbed where microsimulation is used to simulate realistic traffic conditions, and the MP algorithm is used to control the signal display using a traffic controller (Q-Free MaxTime controller). The hardware-in-the-loop results demonstrate that MP can be safely deployed on North American traffic signal control hardware.

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Toward implementation of max-pressure control on Minnesota roads: Phase 2

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Table of Contents

List of Figures

List of Tables

Executive Summary

Max-pressure traffic signal control is a new traffic signal control algorithm that responds to real-time traffic demand and has been shown in simulation to substantially reduce driver delay. In Phase I of this work, max-pressure signal control was implemented in simulation on 7 signals in Hennepin County and increased throughput and decreased waiting time were observed. However, before max-pressure control can be implemented in real-world traffic signals, additional testing would be needed to ensure that the control algorithm can be safely and efficiently implemented on the physical traffic signal control hardware used by Hennepin County.

This study developed a hardware-in-the-loop testbed to explore the implementation of max-pressure traffic signal control on real-world traffic signal hardware. The testbed uses the same types of traffic signal controllers used by Hennepin County and relies on a microsimulation environment to generate realistic traffic scenarios, which are provided to a software implementation of the max-pressure algorithm. The max-pressure software determines the appropriate current signal timing, and shares that with the physical traffic signal controller, which uses a virtual display to show the current phasing. Moreover, the physical controller and corresponding display is then provided back to the microsimulation environment so that vehicles in simulation are able to drive according to the signal timing being displayed by the physical controller.

The testing conducted as part of this study demonstrates that max-pressure signal control can be implemented on the traffic signal control hardware being used by Hennepin County.

Chapter 1: Introduction

In recent years, transportation engineers have increasingly favored semi and fully actuated signal controls for intersection management. Semi and particularly fully actuated signal controllers have shown significant efficiency compared to that of fixed-time algorithms. Of particular interest is max-pressure, a relatively new signal control algorithm, that has been mathematically proven to stabilize and maximize the throughput of the intersection. Moreover, one of the most important advantages of MP lies in its decentralized nature, which obviates the need for any information exchange with other intersections. Moreover, the time complexity of required computations for MP is significantly less than that of other coordinated signal control strategies. However, the implementation of MP requires significant attention, as traffic signal controllers are not yet fully compatible with this novel signal control algorithm. In this regard, we collaborate with Hennepin County to gain a comprehensive understanding of the necessary steps for implementing the max pressure algorithm on existing traffic signal hardware. To this end, this manuscript outlines our work to conduct hardware-in-the-loop (HIL) testing of the MP controller on traffic signal hardware used by our project partner, Hennepin County, Minnesota. In this article, we discuss the approaches and steps taken toward implementing the MP algorithm in currently available signal controllers and ensuring safety. We employed a traffic simulation software, namely SUMO (Simulation of Urban MObility), with random traffic flow as inputs to an intersection with 8 phases and determined the set of actuated phases using the max-pressure policy. Furthermore, we established communication between the computer running the simulation and the traffic signal controller (TSC) to transmit the corresponding set of phases that need to be actuated through the actual TSC. The actuated signal data was collected at each time step for compatibility evaluation.

In contrast to the pre-timed signal timings, where signals do not adjust timing with respect to traffic conditions, the max-pressure (MP) is a decentralized, actuated signal timing algorithm that requires only the information from the immediate adjacent links of the intersection of interest. MP's efficiency has been demonstrated and evaluated by Barman, et al. (2023), Levin, et al. (2023), Xu, et al. (2022), and Sun, et al. (2018). Particularly in Barman’s study, the authors collected data from seven intersections in Hennepin County, Minnesota, and utilized the SUMO software, which is an open-sourced traffic simulation package to test the efficiency of the MP algorithm.

The current commercially available signal controllers are designed and programmed with rigorous constraints to ensure the safety of the intersection's users, including vehicles and pedestrians. As a consequence of these safety considerations, it becomes challenging to implement new traffic control algorithms on these controllers. Hence, the necessity to conduct safety testing for any new traffic control algorithm arises and the MP algorithm is no exception. In this regard, to ensure the safety of implementing the MP control algorithm, we have designed extensive testing procedures where we closely monitor the behavior of the controller and the outcomes of the MP algorithm. In the current study, we will discuss how we manage to safely implement the MP algorithm on currently available traffic signal controllers that are used in Minnesota and across the country.

The concept of MP was initially introduced by Tassiulas and Ephremides (1990), where they were studying routing and scheduling of packet transmission in a wireless network. The term "max-pressure" or, to be exact, "maximum pressure," was first used by Dai and Lin (2005); however, MP policy was introduced for traffic control purposes simultaneously by Wongpiromsarn and Varaiya (2012). Particularly in Varaiya (2013), the author used a store and forward queuing model to find the pressure of each turning movement and assign the according phase with the maximum pressure. Furthermore, there are multiple studies that followed the research done by Wongpiromsarn and Varaiya (2012) and developed adaptable versions of MP algorithm. In particular, Barman, et al. (2023) examined how different variations of MP (namely acyclic and cyclic MP) performed using SUMO, collecting data from 7 intersections in Hennepin County, Minnesota, from two corridors.

There are a few studies that have implemented MP on actual traffic controller as well. Dixit, et al. (2020) conducted an experiment across two countries (India and Indonesia) to evaluate the effectiveness of their proposed model, which is based on MP. They used Google Maps Delay to acquire the traffic data of multiple intersections in India and Indonesia. They used an electronic chip that allows the authors to easily collect data from the intersection. This chip was used to communicate with Google Maps Delay API and change the phase according to retrieved data from the API. Nevertheless, this methodology encountered a limitation concerning data accuracy. The use of API data in this approach may not yield results as precise as those obtained directly from the traffic signal controller. The reliance on GPS and mobile phone features in Google API exhibited a potential source of imprecision, leading to inconsistencies when compared to the data directly acquired from the controller. In another study, Mercader, et al. (2020) proposed an MP policy and tested it in Jerusalem. The researchers installed Bluetooth detector devices to obtain data and change the phase according to the collected data. The constraint previously identified for Dixit, et al. (2020) was also applicable to the study by Mercader, et al. (2020), as Bluetooth detectors might not offer the same level of precision as the traffic signal controller does.

In summary, max-pressure control is a new form of signal timing that is mathematically proven to maximize network throughput. A previous Local Road Research Board (LRRB) project investigated the use of max-pressure control on 7 intersections in Hennepin County using microsimulation. Results suggested that max-pressure control could reduce delays on many intersections, but the primary benefit was how max-pressure control adapts to changes in demand. The same control algorithm was used throughout the day and compared favorably with existing actuated-coordinated optimized timings. The next step was experimental deployment on the 7 intersections. To achieve that, the project team demonstrated that max-pressure control can be safely deployed on Hennepin County systems, and this project aimed to develop such a deployment on a testbed signal.

The remainder of this report is outlined as follows. First, we discuss the hardware-in-the-loop testbed and the traffic signal control hardware used to construct it in Chapter 2. Next, we discuss technical challenges overcome to integrate detector counts from Iteris-instrumented intersections to estimate queue length at each intersection in Chapter 3. Next, we present the methodology and results for implementing max-pressure control in the hardware-in-the-loop testbed in Chapter 4, and finally, we present our conclusions including a cost-benefit analysis and discuss implementation steps in Chapter 5.

Chapter 2: Building hardware-in-the-loop signal testbed

This chapter discusses the physical hardware needed to construct the hardware-in-the-loop testbed, as well as the testbed architecture and design.

2.1 Testbed architecture

The hardware-in-the-loop testbed uses simulated traffic data, which is used as input for the max-pressure script to determine current signal timing. The current signal timing (based on simulated traffic conditions) is then communicated with the physical traffic signal controller, which changes the display (shown on a virtual display), and also interfaces with the simulated traffic intersection to allow the flow of traffic as specified by the control algorithm in simulation. Thus, the designed setup allows for the testing of the actual traffic signal control hardware that is used by Hennepin County, while interfacing with a virtual (simulated) environment to ensure safety during testing.

The overall architecture of the hardware-in-the-loop testbed is shown in Figure 1 where synthetic data generated from the microsimulation platform Simulation of Urban Mobility (SUMO) is used to compute signal timing via the max-pressure algorithm and then sent to the controller via ethernet. The controller then displays on the virtual display, which is running on the Dell Latitude laptop. Data and generally, any information related to the network management and monitoring can be stored using a management information base (MIBs), which are defined for each controller. These MIBS take the form of a text document that is computable by computer and readable by human.

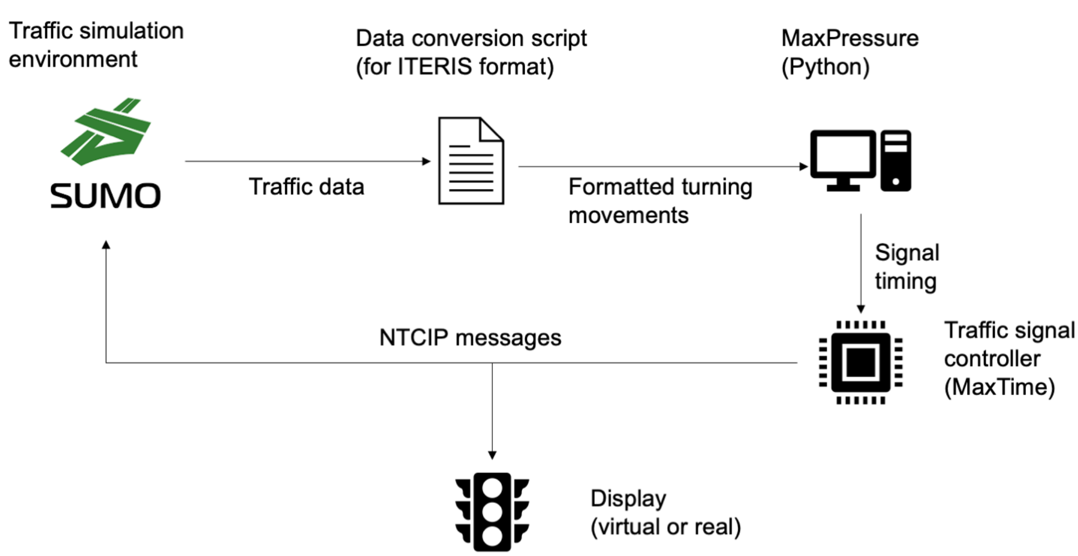

Figure 1: Hardware-in-the-loop testbed design.

2.2 Equipment

To implement the Max-Pressure traffic signal policy, two different physical controllers were purchased: the XN-2 Q-Free Controller and the Econolite Cobalt Controller. The XN-2 Q-Free Controller is specifically designed to work with both TS2-2 and TS-1 Cabinets. Since both controllers can only be connected to Windows operating systems, a Windows Dell Laptop, along with a LAN cable, is used to interface with the controllers. The laptop is equipped with an RJ-145 jack, which is commonly used for Ethernet connections, and can be used to connect to the controllers. In the testbed, the laptop is used both to run the max-pressure script written in python and communicate signal timing with the controller, as well as to run the software simulation in SUMO and display the traffic signal via the virtual display. The two different controllers purchased to construct the signal testbed are shown in Figure 2 with the Q-Free XN-2 controller on the left and the Econolite Cobalt controller on the right.

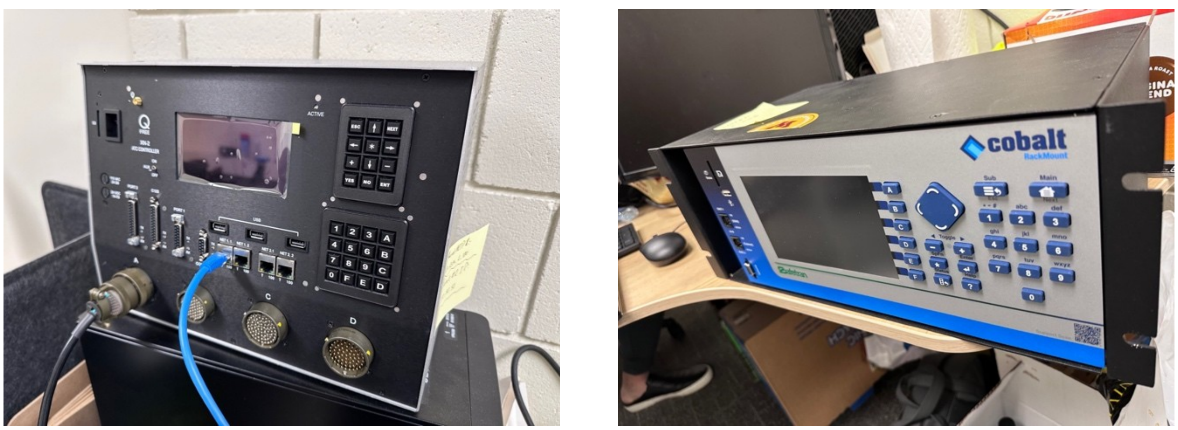

Figure 2: Traffic Signal Controllers. Q-Free XN-2 Controller (left) and Econolite Cobalt Controller (right) in the signal testbed at the University of Minnesota.

Chapter 3: Integrating detector counts

3.1 Overview

Originally, the research team proposed polling the queue length data from MaxView, which was the traffic signal management software being used by Hennepin County at the time when the proposal was submitted in 2021. However, Hennepin County Public Works has upgraded MaxView to its newer version Kinetic Signals in 2023. This cloud-based new version software created some complications for MP to directly poll the data via a API. In addition, the video detector Econolite Vision detector is not able to output queue length data. Therefore, after having discussed with the project Technical Liaison, he research team proposed to test the capability for MP to read the queue length data which could potentially be generated by Iteris video detector which has also been used by Hennepin County. However, currently, no actual queue length data is available for testing, therefore, this chapter outlines the procedure that should be followed in testing the capability for max-pressure script to read the queue data from a Iteris detector.

3.2 Data handling

As previously mentioned, synthetic data is used to evaluate the efficiency of the max-pressure control algorithm. However, the data that is generated by the microsimulation platform is not natively in the same format as the queue length data that is available from the Iteris-instrumented intersections. Therefore, the research team created a script to translate the standard SUMO simulation output to be consistent with data generated from an Iteris video detector.

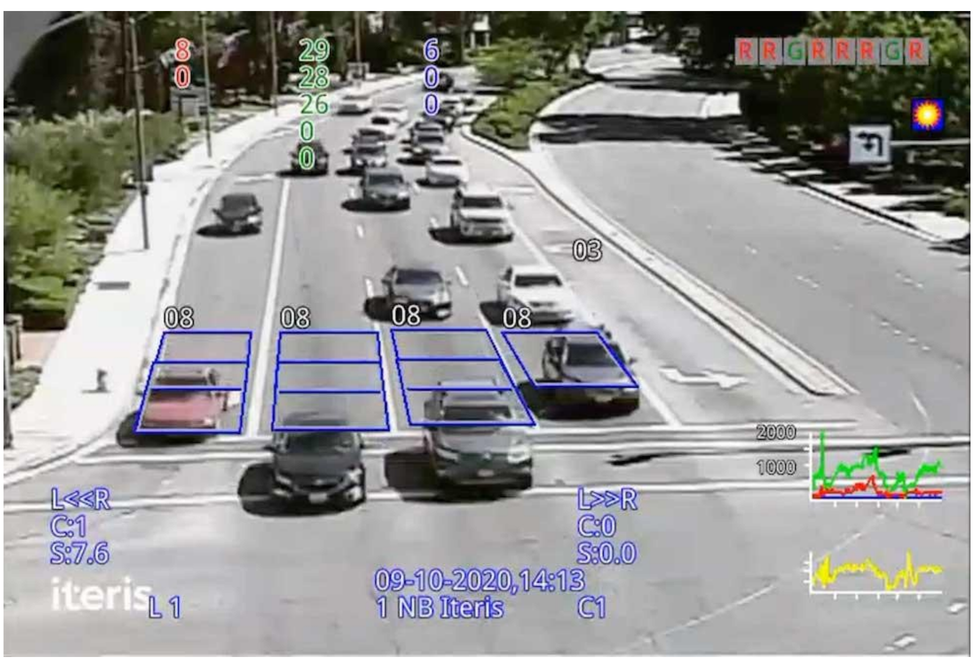

Figure 3: Iteris locating the lanes and number of vehicles on each lane.

The Iteris video detector collects traffic counts and queue length data with virtual loops using video processing technology. Figure 3 shows how Iteris detectors are instrumented and configured to detect vehicle volumes and queues in different lanes on an intersection approach. As shown in Figure 3, in this instance, the detection system identifies a queue length of one, since only one vehicle is present within each virtual loop zone on each lane. Thus, the Iteris API should provide a data output similar to what is shown below:


```
[
  {
    "time": 1,
    "lane_1": 1,
    "lane_2": 1,
    "lane_3": 1,
    "lane_4": 1
  },
  {
    "time": 2,
    "lane_1": 0,
    "lane_2": 0,
    "lane_3": 1,
    "lane_4": 1
  },
  ...
]
```


Specifically, the JSON string described above is constructed based on discussions between the research team and the software developers at Iteris, and represents how they described the data interface. Note that this JSON format is subject to change in the future when Iteris company finalizes and deploys the API, and future max-pressure implementations using Iteris-instrumented intersections should take any changes in the data structure into account.

Based on the data format provided by Iteris and presented above, the research team has developed a Python program that utilizes SUMO and TraCI (a Python library for integrating with SUMO) to generate synthetic data in the same format as Iteris data. The resulting script is able to produce synthetic data generated by the simulation that has a data structure consistent with the data collected and output from Iteris detector.

Chapter 4: Implementing max-pressure control in testbed

4.1 Implementation of max-pressure control in testbed

To test max-pressure control on a candidate intersection, we first construct a simple generic four-leg intersection with two one-way streets. Thus, there are only two allowed movements: Northbound and Eastbound. Each consists of three lanes as shown in Figure 4.

To implement max-pressure control on the hardware-in-the-loop testbed, the research team had to generate MIBs to be shared with the traffic signal controller (in this case, the Q-Free NX-2) and display the proper phase as computed by the max-pressure algorithm. This is done in a five-step procedure outlined below:

1) Configure the controllers as if they are listening to a pretimed signal timing
2) A web-application for communication to the controller was installed.
3) The computer runs a Python script which has SUMO run a simulation in background to get traffic information (such as queue length of each lane) from detectors to determine the optimized timing for each using the max-pressure algorithm.
4) The Python script then sends the actuated phase at each time step to the controller and the controller changes or keeps the current the phase per the communicated information between the computer and controller. This phase can be observed in the web-application and, if connected, on the traffic light as well.
5) Steps 2–4 are repeated until the simulation is done. Note that the simulation delay, which represents the time dilation factor applied to each real second within the simulation environment, equals to one second. In other words, one second of simulation is the same as one second of real world. This enables the simulation to replicate the field signal operations as close as possible, making it easier to study the safety of the implementation of the MP algorithm on the controller.

4.2 Testing of max-pressure control on signal testbed

We used the API provided by the controller’s manufacturer and connected the Q-Free XN-2 controller to the computer using a LAN cable. A Python script is used to enable the computer to poll the data from the simulation and compute the max-pressure cycle length and splits. Another script is used to allow the computer to communicate with the controller and send the phasing commands to the signal.

The Python script for communicating with SUMO which defines the resulting phasing time can be found in some repositories uploaded to many cloud-based services such as Github[1].

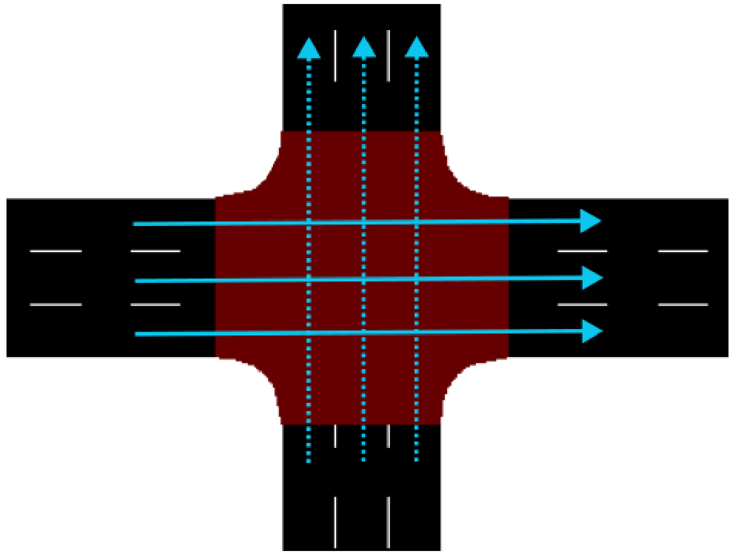

Figure 4: Traffic signal-controlled intersection with two phases (the major road is the east-west bound and the other is the minor road).

When testing the max pressure control algorithm on the signal testbed, a screen recorder is used to record and monitor the changes in controller and the simulation graphical user interface (GUI). Furthermore, during each time step, we retrieve the current phase state from the controller using Web-Sockets, enabling us to assess its alignment with the phase generated by the max-pressure algorithm. This enables us to ensure that the controller and the simulation exhibited consistent phase display and activation.

For the purpose of testing max pressure in the hardware testbed, several parameters were established before initiating the simulation. These simulation parameters were selected to generate synthetic data, and are listed in Table 1 and were selected as starting parameters to ensure the proposed system was functioning correctly.

Table 1: Simulation Parameters.

Parameter	Value	Description
Major Road Flow	600 veh/hr	The flow of the major road in the intersection
Minor Road Flow	300 veh/hr	The flow of the minor road in the intersection
Simulation delay	1000 ms	The delay between each step of the simulation.
Simulation duration	7200 s	The time span for the running simulation.

[1] E.g. Barman, et al repository for MP algorithm

As indicated in Table 1, the main road (west-east bound) has a traffic flow of $600\ veh/hr$, whereas the minor road (south-north bound) has a flow of $300\ veh/hr$. These parameters used only as an example and solely to differentiate between minor and major roads. The simulation delay, denoting the time it takes for each time step to be executed in the real world, is set to 1000 ms (1 second) to ensure a close approximation to real-world scenarios during the simulation process. This delay is crucial for accurately capturing the dynamics of the traffic flow and the behavior of the MP algorithm in a realistic environment. The testing is conducted over a two-hour period. This duration allowed us to observe the behavior of the MP algorithm and assess its impact on traffic flow, ensuring that the controller's performance remained within safe operating limits throughout the extended timeframe.

Regarding the ability of the proposed architecture to implement max-pressure control on physical traffic signal hardware, extensive testing has been conducted on the controllers to evaluate their performance under different traffic flow levels in order to ensure the safety of the controllers. To display the result on the safety of phase changing, we plot the changes in actuated phasing in the controller to make sure there is no conflict between movements, meaning there is no occurrence of two movements activated at the same time. Note that this is an added layer of safety, since potential conflict movements are also checked by the controller and prevented from happening by the malfunctioning management unit (MMU) in the field.

We use the standard Federal Highway Administration signal phasing shown in Figure 5 in the simulation, and display the resulting desired and displayed phase in Figure 6. The agreement between the desired signal display from the max-pressure algorithm, and the actual signal display observed on the virtual display, as well as the signal display relayed back to the virtual signal in SUMO indicate that the implementation was successful.

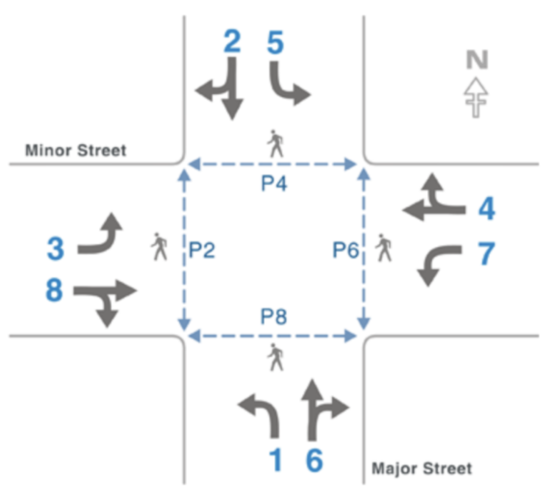

Figure 5: Signal phasing number according to Federal Highway Administration publication of Signal Timing Manual.

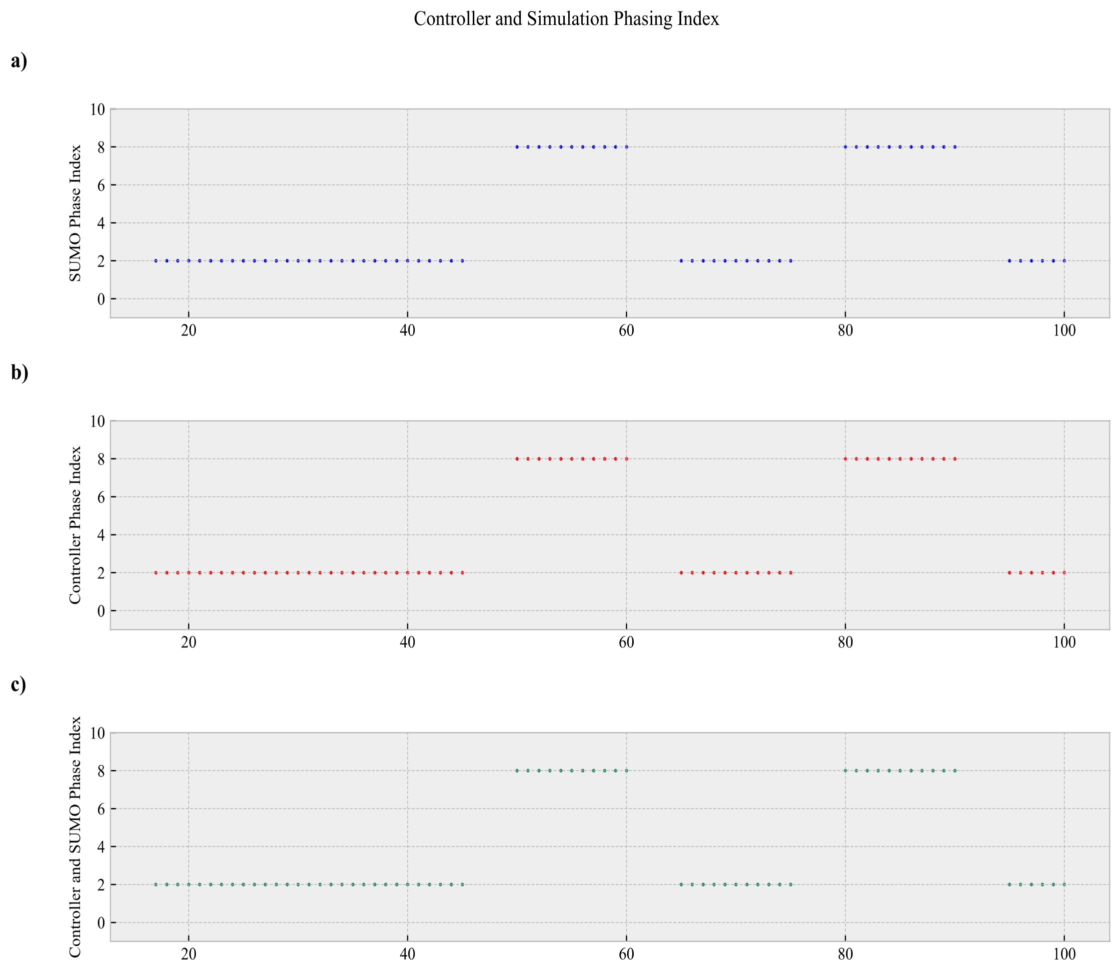

Figure 6: Phasing number captured from the simulation and the controller at each time step. TraCi, an open-source Python library to retrieve data from and communicate with SUMO and Web Sockets to communicate with the controller are used to plot (a) and (b).

4.3 Demonstrating max-pressure control on a Hennepin County signal

Finally, to demonstrate the ability of the implemented max-pressure control to handle real-world traffic conditions, the research team implemented a simulation of the intersection of Hennepin County Route 30 (97th Ave N) and Hennepin County Route 116 (Fletcher Lane) located in Rogers, Minnesota. Realistic traffic flow data was used to calibrate the SUMO model of the intersection, which is depicted in the as-built drawings in Figure 7, with the implemented SUMO intersection layout shown in Figure 8. A preliminary demonstration was conducted on April 3, 2024 at the Hennepin County Traffic Management Center (TMC) in Medina, Minnesota, as shown in Figure 9.

The video of the demonstration can be found at: https://z.umn.edu/maxpressureDemo. The first portion of the video shows the hardware-in-the-loop testbed setup. Next, a screen recording shows the traffic simulation (right) and corresponding traffic signal display (left) as the max-pressure algorithm controls the traffic signal based on real-time traffic conditions in simulation. Note that in the demonstration, due to the demand pattern and the nature of the Max-Pressure control algorithm, there are instances where approaches with high demand may not be fully cleared before moving on to the next phase.

The video demonstration shows a successful implementation of max-pressure control at a real-world traffic signal using realistic data and provides evidence that the max-pressure signal can safely be implemented on Hennepin County signal hardware.

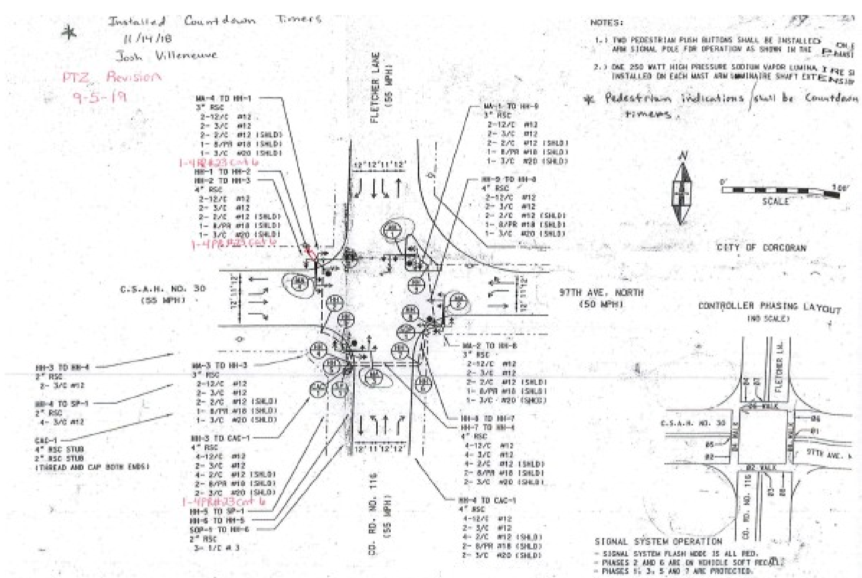

Figure 7: As-built drawing for intersection of County 30 and County 116.

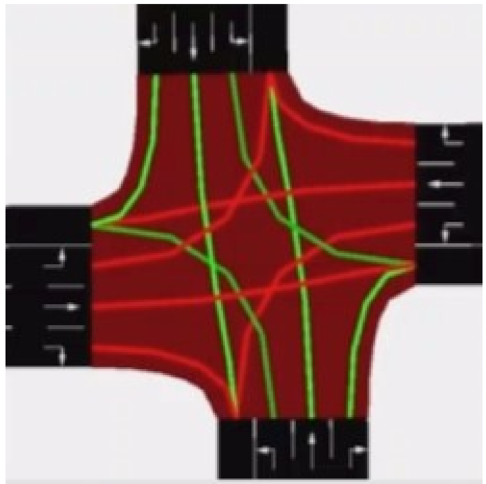

Figure 8: Intersection layout in simulation.

Figure 9: Graduate student Amir Kiani demonstrating the Max-Pressure control at the Hennepin County TMC.

Chapter 5: Conclusions

Allocating green time at intersections is a crucial aspect to safely and efficiently managing transportation infrastructure. Historically, most intersections have used fixed-time signal control, where pre-determined signal timing is implemented at each traffic signal based on historical traffic volumes. However, such pre-timed signal control algorithms are unable to respond to real-time variations in traffic demand and therefore may perform suboptimally. In contrast to pre-timed signals, actuated traffic signals use embedded sensors (e.g., video cameras or loop detectors) to identify real-time traffic demand and adjust traffic signal timing accordingly. Many different actuated signal timing algorithms have been proposed over the past several decades, and many agencies now operate a large number of actuated traffic signals. One such algorithm is the max-pressure traffic control algorithm.

Max-pressure control is a new form of signal timing that is mathematically proven to maximize network throughput. A previous LRRB project investigated the use of max-pressure control on 7 intersections in Hennepin County using microsimulation. Results suggested that max-pressure control could reduce delays on many intersections, but the primary benefit was how max-pressure control adapted to changes in demand. The same control algorithm was used throughout the day and compared favorably with existing actuated-coordinated optimized timings. This project conducted the next step to validate the methods in a hardware-in-the-loop testbed that allowed us to identify how to implement max-pressure control on the physical traffic control infrastructure used in Hennepin County. The project team was able to demonstrate that max-pressure control can be safely deployed on Hennepin County systems. To implement the research findings, the next step would be experimental deployment on an intersection in Hennepin County.

5.1 Benefits of conducted research

The benefit of the conducted work comes from the fact that intersections introduce a major but necessary bottleneck for urban road networks. Suboptimal signal timing can cause large queues and lower throughput, higher intersection delays, or higher corridor-level travel times. Consequently, signal timing is revisited periodically, and signals are timed differently for different time periods throughout the day. Max-pressure control has the potential to improve over existing signal timings due to its established mathematical properties of maximizing network throughput. In particular, when demand varies from day to day, max-pressure can respond to variations in demand while a timing plan expects historical or average levels of demand. Max-pressure can therefore achieve some benefits in intersection performance. A second benefit is that since max-pressure control uses one timing algorithm that responds to all levels of demand, separate algorithms for different time periods are not used. This would correspondingly save engineering costs for signal timing if implemented since fewer signal timings would need to be optimized by engineers.

The work conducted demonstrates that max-pressure control can be implemented on Hennepin County signal infrastructure and hardware and provides confidence for proceeding with further implementations in the field. The benefit of implementing max-pressure on roadways includes reduced wait time at traffic signals and correspondingly lower traffic emissions due to idling vehicles. This has tangible benefits in terms of improved air quality and reduced travel time.

Since the conducted research has demonstrated that max-pressure control can be implemented on standard traffic signal controllers with the addition of a small amount of dedicated hardware (roughly $100 worth of hardware for a RaspberryPi computer running the max-pressure code), the main cost associated with installing max-pressure control would be ensuring that all intersections have sufficient sensing infrastructure. For example, if loop detectors are selected, each approach would require two loops: one at the intersection threshold and one upstream of the intersection. Another option would be to use video detectors, which are becoming prevalent at many intersections and already in use at all county-owned/operated signalized intersections in Hennepin County.

Specifically, the cost of installing one loop detector per lane based on a 2013 US Department of Transportation estimate, is $2,000. Taking inflation into account, that would be roughly $2,700 in 2024. Thus, for an intersection with four approaches, each with two lanes and each requiring 2 detectors, the total cost to instrument an intersection could be estimated to be approximately $43,200. However, all signals in Hennepin County are already using video detection. Therefore, it is likely that only additional cameras would need to be installed, for a lower price. Based on the estimates identified during Phase I of this project, it is reasonable to assume this could be completed for roughly $12,500 per intersection.

According to Hennepin County, there are 450 county-owned and operated traffic signals in Hennepin County. While each of these signals is currently equipped with video detection, additional sensors (e.g., upgrades to video detection discussed above) may be needed. Therefore, we conservatively assume that each intersection would require roughly $12,500 in upgrades to install sufficient loop detectors to estimate queue lengths at each signal. Assuming each intersection in Hennepin County would be converted to using max-pressure, the total instrumentation cost for detectors would be $5,750,0000. N addition, roughly $46,000 would be required in additional hardware to install a RaspberryPi computer in each cabinet to execute the max-pressure code for a total installation price of $5,796,000.

To estimate the economic benefits, we must take into consideration the congestion mitigating effect that max-pressure control may have. During the peak hour, commuting trips are the primary contributor to congestion effects. CBS Minnesota estimated the average commute time in the Twin Cities at roughly 24 minutes per person per day in 2019. In addition, according to Minnesota Compass, there were roughly 600,000 employees in Hennepin County in 2021. Assuming roughly the same number of people commute into Hennepin County as commute out of Hennepin County, this estimate was used as the basis for the economic cost of congestion in the county. Based on the results from Phase I of the study, an average delay reduction of 47% was observed when max-pressure control was installed. Assuming the average commute time above, and the 47% reduction in travel time, a total of roughly 112,800 hours of commuter time could be saved daily in Hennepin County.

Assuming a value of travel time savings of $12.80 per hour as recommended by the US Department of Transportation, the savings in commute time represent $1,443,480 in daily savings for employees in Hennepin County. Given the substantial benefit in travel time savings obtained with max-pressure control, the cost of max pressure control would be justified in just over four days of operation. However, note that this does not take into consideration the increased cost of detector maintenance, which is difficult to assess.

A similar analysis could be conducted on a larger scale, considering a wider deployment of max-pressure control across the state.

5.2 Implementation steps

Implementation of the research results will require a Phase 3 in which first a single traffic signal and then a corridor of 3-5 traffic signals are implemented with the developed max-pressure control algorithm to demonstrate the superiority of max-pressure control over other traffic control algorithms.

A potential Phase 3 of this project would need to include (1) additional testing on the test cabinet at the Hennepin County Traffic Management Center (TMC) to ensure that the max-pressure control is able to handle all potential operating conditions, including flashing yellow arrow (FYA), pedestrian signal calls, emergency signal preemption, and red flashing, and (2) implementation first on a signal traffic signal in Hennepin County, and then, if successful, deployment on a corridor with 3-5 traffic signals. Lastly, since Hennepin County does not use the Q-Free MaxTime controller and the Iteris detector, which the testbed used in the demo of Phase 2, the Phase 3 would seek to address this to test signal operations with max-pressure hardware control at selected signals along county roadways.

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