Optimizing Intersections: An MPC Approach Incorporating Vehicle and Pedestrian Flows with Adaptive Traffic Control Systems

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***Abstract*—This project demonstrates why incorporating pedestrian flow data into adaptive traffic control systems (ATCSs) is a worthwhile project. In summation, current adaptive control systems are already designed to respond to live vehicular flow data; thus, this project seeks to design a similar adaptive control system that uses vehicle and pedestrian data. Using UXsim to simulate traffic conditions at three common intersections, we found that the pedestrian-aware MPC framework effectively alleviates congestion through queue length management. The effectiveness is influenced by the complexity of the network design, with a simpler four-link one-way intersection showing the most improvement, reducing congestion by 50%.**

I. Introduction

Adaptive traffic control systems (ATCSs) dynamically adjust traffic signals according to real-time traffic conditions. Traffic congestion can have detrimental effects to the environment and safety; thus, finding strategies to alleviate congestion are highly sought after. Starting in 2011, New York City began integrating ATCSs into intersections through the implementation of the system ”Midtown in Motion” (MIM). MIM, and similar ATCS systems, adapts in real time by processing live vehicular flow data to inform which signal timing plan (STP) will alleviate vehicular congestion [1]. However, motorized-focused ATCS systems have limitations in managing traffic flow because they do not adapt for non-motorized factors, such as bicycles and pedestrians [1]. Moreso, these systems only seek to alleviate vehicular congestion and not pedestrian congestion. When pedestrian volumes are high quality of life and safety of pedestrians are threatened. Thus, we predict incorporating live pedestrian flow data into ATCSs will have beneficial impacts on pedestrian and vehicle traffic flow while improving pedestrian safety.

A. Motivation

New York City's Vision Zero is a citywide initiative to eliminate all traffic deaths and serious injuries. Vision Zero has seen significant progress, with 2023 being considered the safest year for pedestrians, with only 101 pedestrian deaths [2]. However, this progress is not yet sustainable with a 25% surge in pedestrian deaths in 2024, the deadliest year for pedestrians since the adoption of Vision Zero [3]. The rise in pedestrian deaths highlights the urgent need to adapt to the needs of pedestrians at intersections to prioritize pedestrian safety.

B. Background

Midtown in Motion gathers live traffic data with radio Electronic Toll Collection (ETC) tag readers and microwave sensors placed at intersections [1], [4]. This data is transmitted to the traffic management center, where the Adaptive Control Decision Support System (ACDSS) processes the data to determine an applicable timing pattern that will relieve congestion [4]. MIM has two levels of control. Level 1 control considers the entire control area, and every 15 minutes, it determines optimal splits and offsets to distribute the traffic entering the core by assessing travel-time data recorded by ETC readers. Level 2 control considers a specific intersection within the core, assessing spillback detected by microwave sensors and Level 1 responses to inform split adjustments [1].

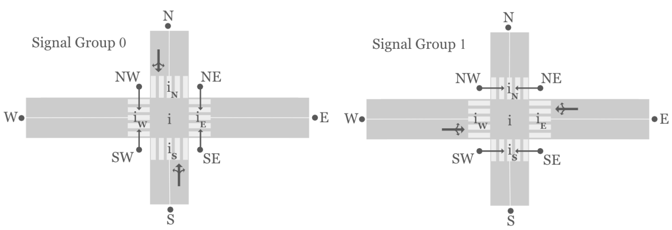
One of the many signal variables being adjusted by the ATCSs are the cycle lengths. Having adaptive cycle lengths have proven to reduce delays and gridlock [1]. Currently, adaptive cycles are controlled in level 2 based on data from microwave sensors. These sensors can be used to determine the vehicular spillback in a lane, also known as the vehicular queue length.

The integration of pedestrian data into ATCSs has been studied a few times. In Los Angeles, the AI Pedestrian Traffic Safety System was developed to detect pedestrian movement using pre-existing traffic cameras for the purpose of real-time traffic control and demonstrated more than 98% accuracy in producing live pedestrian counts [5]. Since the insights from this system can be used concurrently with traffic control systems, then exporting this data to be used with an ATCS is a realistic goal. New York also has cameras equipped with computer vision at many intersections that are capable of detecting pedestrians [6]; thus, many intersections exist that already equipped with microwave sensors and cameras that could export live vehicular and pedestrian data to inform Level 2 control.

In this project an ATCS is developed with a pedestrian-aware Model Predictive Control (MPC) framework that optimizes cycle length timing by considering real-time vehicular and pedestrian spillback. Similar studies have been conducted with vehicle-aware systems such as the Kamal et al. 2021 study [7]. We seek to design a similar study using three common intersection types found in urban areas to test the effectiveness of pedestrian-aware logic on reducing traffic congestion.

II. Approach

To evaluate a pedestrian-aware ATCS, we implement an MPC framework within a simulated urban traffic environment. We use UXsim, a traffic simulator in Python, to model vehicle and pedestrian movement through three intersection types. The MPC controller dynamically selects traffic signal phases based on predicted queue lengths, optimizing flow while accounting for both vehicle and pedestrian crossings.



(a) (b)

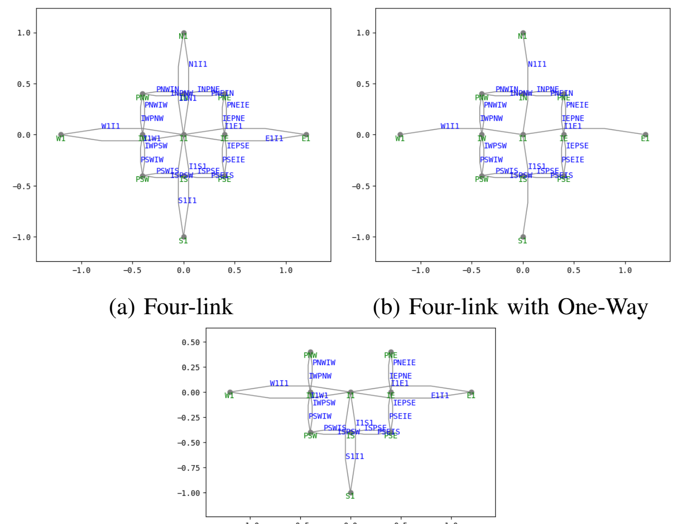
Fig. 1: Traffic flow in a standard four-link intersection

A. Traffic Simulation

The traffic simulator UXsim [8] simulates realistic traffic flows in each experiment. We simulate three different intersection types: a standard four-link intersection, a four-link intersection with one-way approaches (hereafter, '4-link one-way'), and a three-link intersection.

The standard four-link traffic network illustrated in Figure 1 consists of four vehicle nodes and four pedestrian nodes serving as points of origin and destination. Cardinal directions are used to indicate the locations of these nodes, thus vehicles flow from origins $o \in \{N, S, E, W\}$ to destination $d \in \{N, S, E, W\}$ and pedestrians flow from origins $o \in \{NW, NE, SE, SW\}$ to destinations $d \in \{NW, NE, SE, SW\}$. There is one vehicle signal node i_1 and four pedestrian signal nodes i_σ, where $\sigma \in \{N, S, E, W\}$. The signal nodes are coordinated with two signal groups, allowing vehicles and pedestrians traveling in the same direction to move simultaneously. Once a vehicle reaches the intersection, it may proceed straight, turn left, or turn right. Pedestrians may cross multiple streets as needed and always follow the shortest available path to their destination. The 4-link one-way and three-link intersection structures are variations of the standard. Figure 2 displays the intersection networks designed with UXsim in Python. While UXsim does not explicitly support pedestrian modeling, pedestrians can be approximated by treating crosswalks as links and pedestrians as vehicles with adjusted parameters.

Simulation parameters, such as link lengths, lane counts, jam densities, and free-flow speeds, were selected based on realistic estimates for an urban network similar to New York City. East–west avenues are modeled as longer, higher-capacity links than north–south streets. Traffic demand was simulated by randomly generating vehicles and pedestrians at regular intervals, with origin–destination (OD) pairs selected based on the available entry and exit nodes for each intersection type.



(a) Four-link (b) Four-link with One-Way

(c) Three-Link

Fig. 2: UXsim Network Designs

B. Model Predictive Framework

With the traffic simulation framework established, we implement an MPC strategy to optimize signal phases at each intersection.

$$x^{k+1} = Ax^k + \sum_{\gamma=1}^{2} \delta_\gamma^k B_\gamma x_\gamma^k + C \tag{1}$$

The model predictive control algorithm predicts future traffic flows and optimizes the signal cycle lengths over a finite time horizon. Traffic flows are predicted using the state equation in Equation 1. The state equation describes both the vehicle and pedestrian dynamics in the system. The key variables in the model are summarized below:

- $x^k = \left[Q_v^k \ Q_p^k\right] \in \mathbb{R}^{12\times1}$ denotes the system state at time step k, where Q_v^k is the vector of vehicle queue lengths for each entry node o, and Q_p^k is the vector of pedestrian queue lengths for each origin–destination pair $(o \to d)$.
- δ_γ^k is the input vector at time step k for signal group γ, representing the state of the traffic signals.

$$\delta^k = \begin{cases} 0, & \text{indicates green in N-S direction.} \\ 1, & \text{indicates green in E-W direction} \end{cases}$$

- v_o is the vehicle queue length (or vehicle count) on link o headed towards intersection i_1.
- p_{i-d} is the pedestrian queue length (or pedestrian count) waiting at intersection i_σ and headed towards destination d.

- $A \in \mathbb{R}^{12\times12}$ is the system matrix modeling the progression in vehicle and pedestrian queues without a signal. For all intersection types, A is the identity matrix.
- $B_\gamma \in \mathbb{R}^{12\times12}$ is the control matrix for signal group γ, modeling the outflow of vehicles and pedestrians out of the system caused by the signal activation.
- $C \in \mathbb{R}^{12\times1}$ is the demand vector, modeling the inflow of new vehicles and pedestrians into the system

$$J = \sum_{i=0}^{H-1} w_x \sum_{j=1}^{12} (x_j^i)^2 + \sum_{i=0}^{H-1} w_{\delta_j} \sum_{j=1}^{12} (\delta_j^i - \delta_j^{i-1})^2 \quad (2)$$

After allowing traffic to flow with a finite-control logic that switches signal groups every 60 seconds to simulate congestion, we add in the MPC control logic. From this point on, we perform a combinatorial optimization and evaluate all possible signal phase sequences over the prediction horizon H every T time steps. The cost equation is given by Equation 2 where w_x is the weight on queue lengths and w_{δ_j} is the weight on phase switching. The cost equation quantifies how well a phase sequence will perform, adding penalties for high traffic volumes and frequent phase switching. The sequence that best minimizes the weighted cost equation will be selected, and the first phase applied.

III. Results

To evaluate the effectiveness of the pedestrian-aware MPC framework, we analyze the simulation results for three types of intersections: four-link, 4-link one-way, and three-link. Key metrics such as average queue length, average travel time, and average delay time are examined before and after the control logic is activated.

A. Standard Four-Link

Simulating a four-link intersection, defined by Figure 2a, simulated an average of 12241 completed trips with average travel time 98 sec. and average delay 68 sec. after 3600 time steps. These metrics represent the system overall and include the first 900 time steps where the MPC control logic is not in place.

During the first phase, where the finite control was in use, the average travel time across each link was 43 sec., while the average delay was 33 sec. The delay is the difference between how long it would take a driver in free-flow to cross the link and the actual travel time. In the second phase, these averages are improved to 36 sec. travel time and 26 sec. delay, which is a 7 sec. improvement or a 20% congestion reduction.

At the link level, we assess the impact of the MPC controller by examining queue length trends at each time step, allowing for a detailed, microscopic evaluation of traffic behavior. Starting with pedestrian flow along Crosswalk Link IN_to_PNE, Figure 3 shows that the queue length increases quickly during the fixed-time phase and gradually decreases once the adaptive controller is activated. While the decline is modest, the queue length remains relatively stable around its average value, suggesting that the MPC logic effectively regulated pedestrian flow under this demand rate.

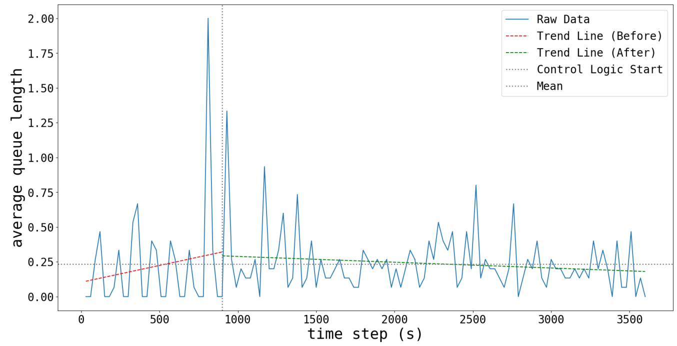


Fig. 3: Four-link: Queue (p_{IN-NE}) of Link IN_to_PNE

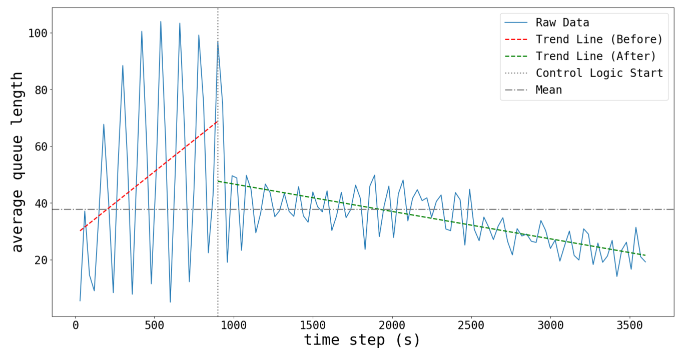


Fig. 4: Four-link: Queue (v_W) of Link $I1\_facing\_E$

The vehicle flow along Link $I1\_facing\_E$ (Figure 4) exhibits a sharp increase in queue length during the fixed-time phase, followed by a steady decline during the adaptive phase. During the fixed-time phase, the link experiences a heavy congestion, reaching a maximum queue length $v_{W max} > 100$ vehicles. After the activation of the MPC controller, the congestion is cleared in approximately 100 sec., and continues to decrease thereafter. Unlike the previous pedestrian flow, which showed regulatory fluctuations, the overall trend dips below the mean and continues its decline. The vehicular queue demonstrates a clear downward trend that dips below the mean and persists. This indicates that the MPC controller very effectively alleviated vehicular congestion under the given demand.

Further analysis of vehicular flow trends reveals that the effectiveness of the MPC controller may vary by link. As shown in Figure 15, the queue length along Link $I1\_facing\_S$ exhibits a similar rate of change before and after MPC activation. However, the mean queue length increases by approximately 10 vehicles following the transition. This suggests that some mild congestion in the north-south direction may have been necessary to alleviate the heavier congestion along the east-west links. Importantly, this localized queue growth does not indicate the controller is ineffective. When assessing system-wide vehicular flow (Figure 5), the average queue length across all links shows a clear downward trend, confirming

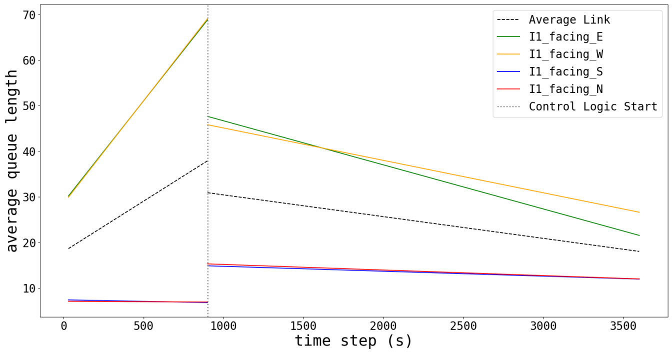


Fig. 5: Four-link: Queue (v_0) for all Vehicle Links

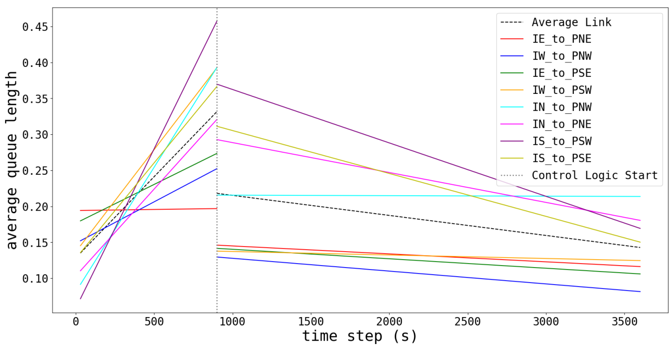


Fig. 6: Four-link: Queue (p_{i-d}) for all Pedestrian Links

that the MPC controller effectively reduces overall traffic congestion. The system-wide pedestrian flows further maintain these patterns in Figure 6.

The computation time required to run the MPC controller is also a critical evaluation metric. In this set of simulations, the average runtime for every iteration of the MPC algorithm steadily quickened as shown in Figure 16, nearing just a tenth of a second at the end of the simulation.

B. *Four-Link One-Way*

Simulating a 4-link one-way intersection, defined by Figure 2b, allowed an average of 8141 completed trips with, average travel time 47 sec., and average delay 20 sec. after 3600 time steps.

During the finite phase, the average travel time was 32 sec. and the average delay 22 sec. In the adaptive phase, the average travel time was 20 sec. and the average delay 11 sec. This is a significant improvement of over 10 seconds, or a 50% reduction, indicating this type of traffic signal is highly compatible with this intersection type.

Unlike in the four-link, at the link level, the impact of the MPC controller is not nearly as drastic on pedestrian flows in Crosswalk Link IN_to_PNE. Examining Figure 7 shows a similar trend in queue length before and after MPC activation. Under this demand rate, the results from this link indicate that the pedestrian flows are well managed by both the fixed-time and the adaptive control systems.

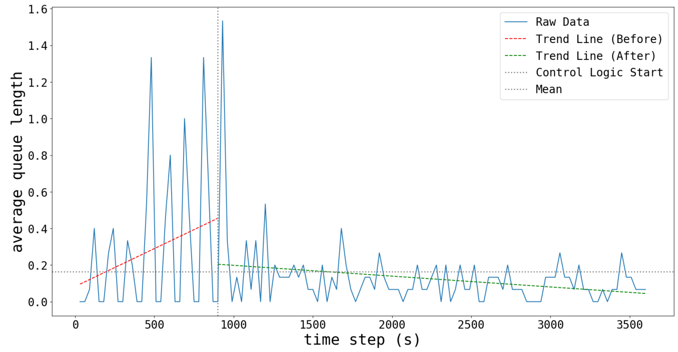


Fig. 7: 4-L One-Way: Queue (p_{I_N-NE}) of Link IN_to_PNE

Once again, the benefits of the adaptive system are more apparent in the vehicle flow analysis. Figure 8 illustrates the onset of heavy congestion on Link $I1\_facing\_E$ during the entirety of the finite state, followed by a quick regulation after adaptive logic is in place. The maximum value in the finite phase was 55.4 cars compared to a maximum value 44 cars in the adaptive phase. The rate of change in each phase is not drastic; however, the ability to efficiently move cars in and out of this link without letting queue lengths approach maximum capacity is significantly better managed by the MPC controller.

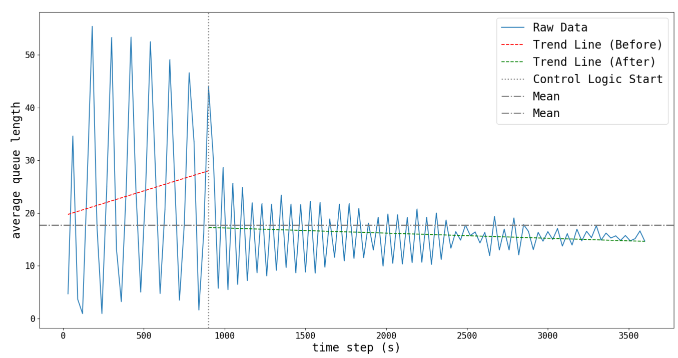


Fig. 8: 4-L One-Way: Queue (v_W) of Link $I1\_facing\_E$

The macroscopic evaluation illustrates good control over the vehicle flows in Figure 9. Despite minimal change to the average link trend before and during the adaptive phase, each link's trend direction is negative, with lower maximum values, which is more favorable than the rapid increase and decrease occurring in the finite phase. The pedestrian flow trends also constrain well during the adaptive phase. A few crosswalks are taking on longer queues to maintain lower queues in the others, but it is not to such a degree that those crosswalks become heavily congested; hence, the MPC controller regulated this system well.

The computation time for the MPC control algorithm in the 4-link one-way intersection in Figure 17 follows a trend consistent with that of the four-link. In both cases, the runtime steadily quickens and approaches one-tenth of a second after 3600 time steps. However, the one-way intersection consistently maintains a lower computation time, about 0.2 seconds

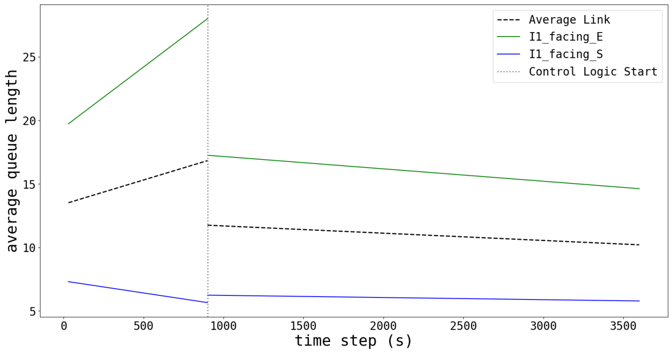


Fig. 9: 4-L One-Way: Queue (v_0) for all Vehicle Links

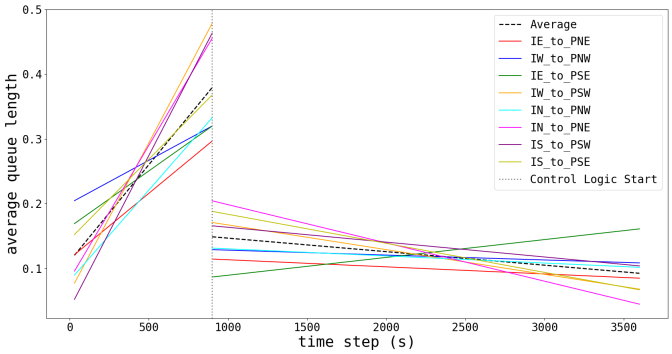


Fig. 10: 4-L One-Way: Queue (p_{i-d}) for all Pedestrian Links

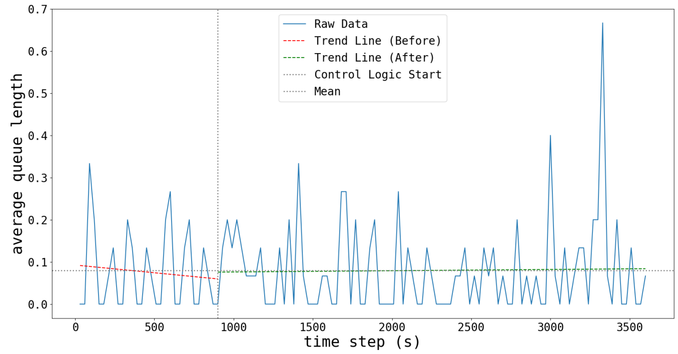


Fig. 11: Three-Link: Queue (p_{I_S-SE}) of Link $IS \rightarrow \_PSE$

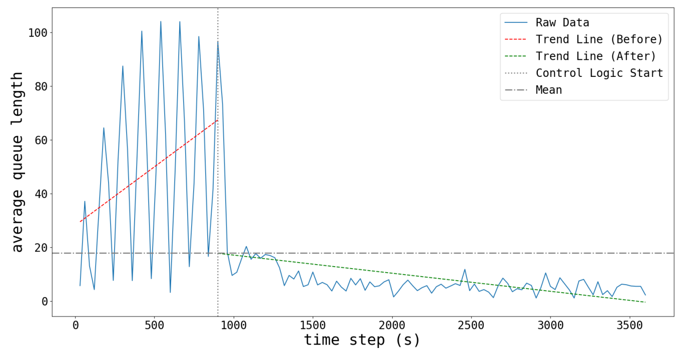


Fig. 12: Three-link: Queue (v_W) of Link $I1\_facing\_E$

faster on average per time step. This difference is expected, as the one-way configuration represents a simpler traffic network, resulting in fewer state variables and reduced computational complexity.

C. Three-Link

The final intersection to be evaluated is the three-link intersection (Figure 2c). The average simulation at the intersection completes 9860 trips with an average travel time 163 sec. and an average delay 130 sec.

The average travel time was 43 sec. and the average delay 32 sec. in the finite phase. Unlike with the other intersections, the times don't improve after the MPC logic. The average travel time was 172 sec. and the average delay 161 sec. Perhaps this could indicate an issue with the delay time calculation, or inaccuracies with the traffic demands this intersection was subject to, but it could also indicate that the MPC logic is not compatible with this form of intersection.

Similar to the 4-link one-way case, pedestrian flows in the three-link intersection show no significant change during the finite phase and the adaptive phase. As shown in Figure 11, Crosswalk Link IS_to_PSE experiences a similar low level of congestion throughout both phases. This suggests that both finite and MPC control systems are effective in managing pedestrian flow in this configuration.

Again, we observe a rapid buildup of congestion that is promptly alleviated following the activation of the adaptive control logic. For Link $I1\_facing\_E$, the queue length trend steadily declines below the average value and remains there for the rest of the simulation, as shown in Figure 12. This link experienced the most severe congestion thus far, reaching its maximum capacity. This result aligns with the restricted N-S mobility in the network, which in turn intensifies E-W traffic. Consequently, the MPC controller allows the N-S link to absorb more congestion by drastically increasing wait times.

This redistribution of vehicular flows is an effective strategy for reducing the overall system congestion, a pattern also seen in the previous intersection configurations. Figures 13 and 14 reaffirm this, showing a consistent decline in average queue lengths. On the pedestrian side, all six crosswalk links exhibit reductions in pedestrian queues under the given demand level.

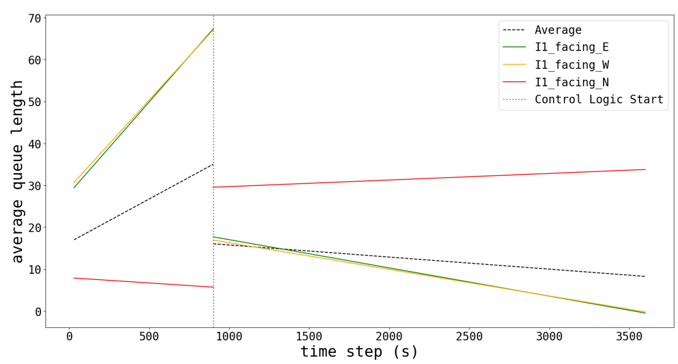


Fig. 13: Three-link: Queue (v_0) for all Vehicle Links

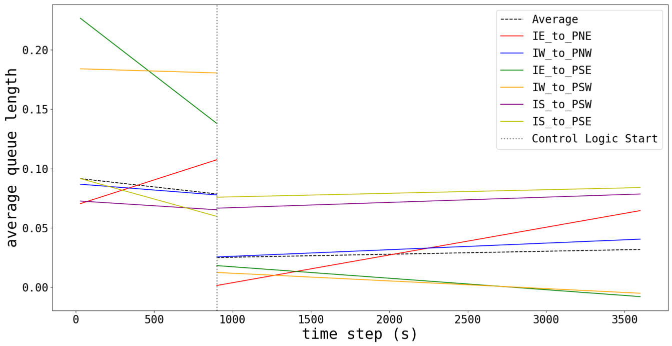


Fig. 14: Three-link: Queue (p_{i-d}) for all Pedestrian Links

Finally, the MPC control algorithm computation time for the three-link intersection in Figure 18 demonstrates the same trend as the four-link and 4-link one-way networks. Despite a reduction in the number of links, the network complexity remains high, resulting in a comparable runtime with the four-link intersection throughout the entire simulation run.

D. Dicussion

All three intersections demonstrated effectiveness by consistently reducing vehicle and pedestrian queue lengths for the average link. The E-W direction experienced the most congestion in all three intersections, as expected. This was seen at its greatest intensity in the three-link, where lanes reached maximum capacity during the finite phase. Nonetheless, the MPC logic was able to reduce congestion.

However, the three intersections displayed variable results in the control systems ability to minimize delay times. The 4-link one-way saw the most improvement with over 10 seconds. The four-link next with 7 sec. improvement. But, the three-link showed a drastic increase in travel time. Thus, if we assess the effectiveness in reducing delay times, the three-link is not effective. However, the three-link displayed more consistent management of pedestrian flows than vehicular flows, suggesting partial effectiveness.

It also appears that the network's complexity influences efficiency, as the computation time for the MPC was faster with 4-link the one-way rather than the four-link two-way.

IV. Conclusion

In modeling traffic networks inspired by NYC urban traffic flows, we tested the effectiveness of a pedestrian-aware MPC control logic on three different intersection types. The ATCS was highly effective with the 4-link one-way, effective with the four-link, and partially effective with three-link intersections. All three types demonstrated the ability to quickly reduce heavy congestion in the E-W direction during the adaptive phase. However, due to network complexity, the MPC computation time was notably faster in the simpler 4-link one-way network than in the four-link and three-link networks. Similarly, the 4-link one-way and four-link networks showed far greater improvements in N-S travel delay reduction than the three-link.

These results are significant as they demonstrate a viable alternative to existing adaptive traffic control (ATC) systems that primarily focus on vehicular flow, such as New York City's Midtown in Motion. With initiatives like Vision Zero still in effect, it is increasingly important to develop solutions that directly account for pedestrian activity. While this control system may not always outperform a state-of-the-art vehicle-aware ATCS in minimizing vehicle wait times, it has consistently and effectively reduced queue lengths across all three intersection types. Since congestion is often a key contributor to safety issues, this approach offers a promising alternative to traditional vehicle-aware systems and is worth further investigation.

While the simulations presented here are simplified, expanding this pedestrian-aware system to more complex, high-foot-traffic environments, such as Times Square, is a valuable next step. Although more intricate networks tend to increase computation time, real-world implementations benefit from hardware and software optimizations that mitigate this issue. Overall, the demonstrated effectiveness of the MPC-based pedestrian-aware controller on common urban street networks suggests strong potential for success in larger, more complex deployments.

Appendix

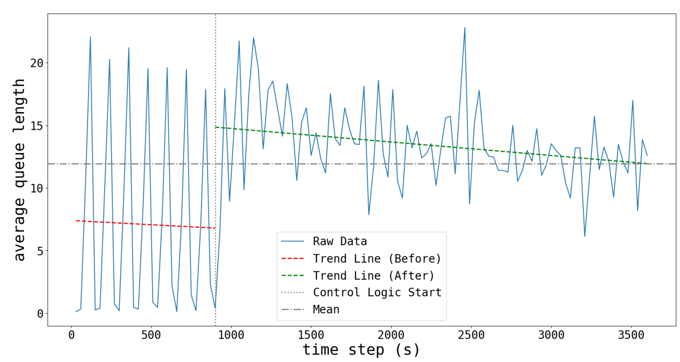


Fig. 15: Four-link: Queue v_N of Link $I1\_facing\_S$

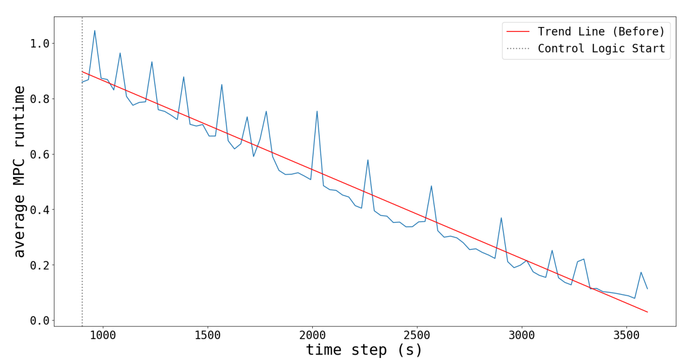


Fig. 16: Four-link: Average MPC runtime

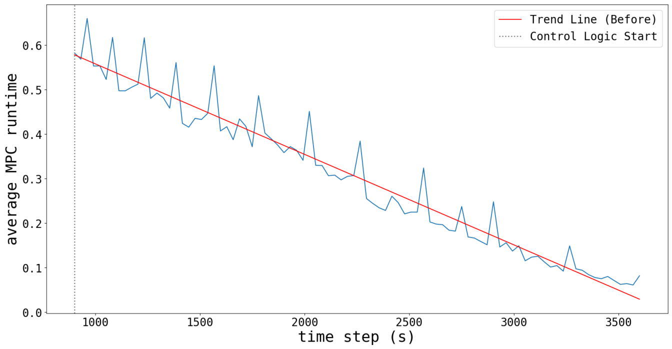


Fig. 17: 4-L One-Way: Average MPC runtime

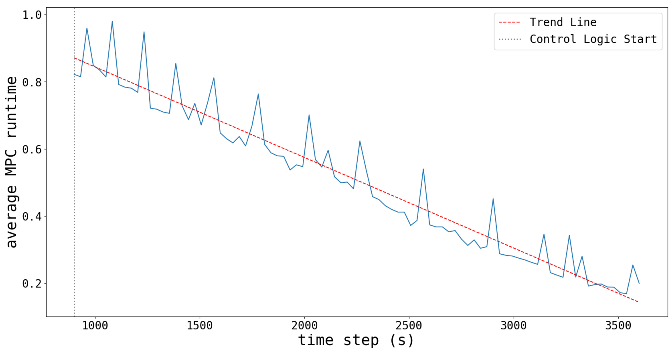


Fig. 18: Three-link: Average MPC runtime

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