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EVALUATING VARIATIONS OF ADVANCED MULTIMODAL SIGNAL CONTROL STRATEGIES FOR URBAN CORRIDORS

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Abstract

Rapid urban growth continues to increase travel demand and intensify operational challenges on metropolitan roadway networks. To improve mobility, safety, and multimodal efficiency, the City of Pittsburgh is upgrading its traffic management infrastructure through the $28.8 million Smart Pittsburgh (SmartPGH) initiative, which deploys advanced intelligent transportation technologies across the city. As one of the outcomes of the SmartPGH project, this study evaluates the performance of a specific multimodal corridor, Second Avenue in Pittsburgh, under a suite of traffic signal control strategies across four time-of-day periods reflecting distinct traffic patterns. This study analyses combinations of advanced traffic-control strategies including fixed-time control, actuated control, Transit Signal Priority (TSP), and other vehicle technology applications to determine how various signal-operation configurations perform when paired with optional treatments such as TSP and pedestrian-safety features (passive pedestrian detection, or dynamic exclusive phases). As a central treatment, TSP is modelled as a cloud-based priority-request system that identifies late-running buses and issues conditional green extensions or early red termination only when necessary to maintain schedule adherence. Overall, TSP paired with actuated control, delivers the most consistent delay reductions. Coordination works best in peak periods, while off-peak conditions often favor free (isolated) control, when platoons dissipate and side-street responsiveness matters more.

Keywords: traffic operations, intelligent transportation systems, microsimulation

1 Introduction

Transportation infrastructure is one of the most notable features supporting development and economic improvement in modern urban areas. However, one of its main challenges is serving constantly increasing travel demand. While increasing capacity by adding new roads or building additional lanes can initially help, it is often not the most sustainable solution because it requires more space for transportation infrastructure and it is affected by the phenomenon of induced travel demand [1]. Furthermore, since developed urban areas often do not have enough space for new infrastructure, transportation agencies rely on traffic control methods, to fully utilize the available infrastructure in a safe and efficient manner.

Traffic control methods span a wide range of approaches, with one of the most common being fixed-time control, which relies on pre-timed signal plans. In fixed-time control, all parameters (e.g., cycle length, green durations) are fixed, meaning they do not change with traffic demand and are set based on historical traffic patterns. This method is one of the earliest and most traditional approaches; however, it often fails to address more complex or highly variable traffic conditions. In contrast, actuated control typically outperforms fixed-time control because it can respond to changing demand.

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Using a detection system, an actuated controller can extend the green duration or, in some cases, skip a phase when there is no demand, which often leads to improved performance compared to fixed-time operation. In addition to traffic control methods, state-of-the-art traffic operations strategies increasingly rely on modern computing power and communication technologies, often referred to as intelligent transportation systems (ITS). These methods are broad and require different levels of computational support, and they can relate to vehicle technologies and connected and autonomous vehicles [2, 3], traffic management [4, 5] or integrated applications such as autonomous intersection management [6, 7]. Depending on the operational objective, ITS can be applied in different ways. For example, for general traffic operations, private vehicles equipped with onboard units can communicate with traffic signals and use green light optimal speed advisory (GLOSA) [8, 9] to recommend an appropriate speed to arrive during the next green interval. Alternatively, ITS can support transit operations: depending on schedule adherence and service conditions, buses can request transit signal priority (TSP) [10-12], improving overall transit performance.

One can note that many traffic operations solutions are designed to meet different goals, which are often in conflict [13]. Some strategies can improve vehicular performance while increasing pedestrian delay. Conversely, other strategies can improve pedestrian efficiency but reduce transit performance and overall roadway efficiency. Depending on the overall objective, a main challenge for transportation agencies is deciding which traffic control method to use, and which intelligent technologies to pair with it, to achieve a balanced outcome, especially when goals and constraints (e.g., change in traffic demand, multiple types of road users etc.) vary across different periods of the day.

As part of the Smart Pittsburgh (SmartPGH) initiative, the City of Pittsburgh has been working to enhance its transportation infrastructure by deploying ITS technologies that improve mobility and safety on urban streets [14]. The central objective of the SmartPGH initiative is to improve multimodal transportation safety and mobility through the deployment of advanced, multimodal-responsive control strategies. As a result of this effort, an analysis was conducted of advanced traffic-control strategies, including fixed-time control, actuated control, TSP, and vehicle-technology applications such as GLOSA. The goal is to determine how various signal-operation configurations (e.g., fixed-time, actuated-free) perform when paired with optional treatments such as TSP and pedestrian-safety features (e.g., passive pedestrian detection or dynamic exclusive phases).

2 Methodology

To support an overall assessment and to investigate different combinations of traffic operations, the study followed a systematic approach to determine the best balance across competing objectives:

- Based on the main characteristics of the signal control strategies, we defined combinations of traffic signal control strategies (e.g., fixed-time and actuated control) and paired them with ITS technologies (TSP and GLOSA) tailored to time-of-day demand patterns (peak and off-peak periods).
- We developed a software-in-the-loop simulation (SILS) framework that integrates PTV Vissim with Q-Free MaxTime controllers to quantify multimodal outcomes. SILS ensures that the same traffic controller logic used in simulation can be deployed in the field with minimal changes, enabling validation of ITS technologies before field deployment. In addition, this approach supports traffic control deployments that are more reliable, cost-effective, and scalable. The microsimulation platform generates traffic and produces performance outputs including general-traffic delay and travel time, and pedestrian delay by crosswalk leg.

2.1 Traffic signal control strategies

The study uses a core traffic signal control strategy as the foundation for each scenario. These strategies define the overall operating mode of the signal controller, and each mode can be configured in multiple ways.

2.1.1 Coordinated signal configuration

Coordinated signal operation establishes progression along a corridor of coordinated intersections. Coordination is achieved by introducing offsets that allow signals to turn green in a planned sequence, so that platoons of vehicles can travel through consecutive intersections with fewer stops. For each coordinated intersection, the offset is calculated based on the average travel speed along the corridor and the spacing between intersections. Under this design, a vehicle traveling at the average speed and departing from intersection i is expected to arrive at intersection i+1 at the time its signal turns green. In practice, downstream queues may be present and can reduce effective progression. To account for this, offsets are adjusted by an estimated queue clearance time (e.g., 5-6 seconds), with the goal of improving the probability that vehicles arrive during a green interval with sufficient discharge capacity. A main requirement of coordinated operation is that all coordinated intersections operate using a common cycle length. Within coordinated operation, this study distinguishes between two control principles:

- Fixed time control (FTC) uses pre-timed signal plans with fixed parameters, including cycle length and green splits. Signal timings do not change in response to real-time demand and are typically determined from historical traffic patterns.
- Actuated coordinated control (ACC) adjusts green durations based on detector actuations while maintaining progression. The controller uses specified minimum and maximum green times for each phase. When a phase is served, it initially runs to the minimum green (which provides a baseline discharge time) and can be extended in response to vehicle detections, typically in predefined extension increments (e.g., 3 s). A phase terminates when no further calls are received after the minimum green or when the maximum green is reached. Non-coordinated phases (typically side-street movements) may be skipped when no demand is present.

In actuated coordinated operation, the coordinated main-street phases are constrained to preserve progression and therefore typically “max out” as needed to maintain coordination, whereas non-coordinated phases are served on demand and only extend when required. Any unused green time from side-street phases can be reallocated to the coordinated phases, providing additional green for the mainline traffic and reducing unnecessary stopping along the corridor.

2.1.2 Free signal configuration

Free (uncoordinated) signal control uses the same general principles as actuated operation, but intersections are not coordinated with one another. Each intersection operates independently, with timing parameters (e.g., minimum and maximum green times and cycle-related settings) defined based on local traffic patterns. As a result, cycle lengths do not need to be consistent across intersections, unlike coordinated operation. This study considers two types of free-signal configurations:

- Standard actuated-free control (AF) where each intersection is controlled using actuated logic with locally defined minimum and maximum greens. Phases are served based on detector actuations at the intersection. When demand on competing approaches is ab-

sent, the controller remains in the currently served phase (i.e., continue serving the last active approach) until a call is registered on another approach or a maximum constraint is reached.
- Rest-in-red control (RIR) which uses locally defined minimum and maximum green times, but the controller “rests” in an all-red state when no demand is present. In other words, after a green interval terminates, the controller returns to red and remains red until a vehicle detection triggers service. This configuration is applied during evening periods, where the intent is to encourage lower approach speeds by presenting a red indication to approaching drivers, while still providing service once a vehicle is detected near the stop line.

2.2 ITS features

In addition to the traffic signal control strategy, each signal-operations scenario is combined with ITS features related to either general vehicular traffic or transit operations. Depending on the scenario definition, signal operation can be paired with one or both of the following strategies:
- Transit signal priority (TSP): TSP modifies signal timing when transit vehicles are detected at specified locations. In this study as shown in Figure 1, bus priority requests are transmitted to the traffic signal controller via an Ethernet connection using the National Transportation Communications for ITS Protocol (NTCIP 1211) standard. The TSP system uses real-time bus status information (e.g., speed, heading, and route) to estimate the bus’s time of arrival at the downstream traffic signal. A main feature of the implemented TSP logic is that it is conditional where priority is granted only to buses that are behind schedule. Thus, TSP is activated only when needed rather than for every bus arrival, and no priority is provided when a bus is operating on schedule.

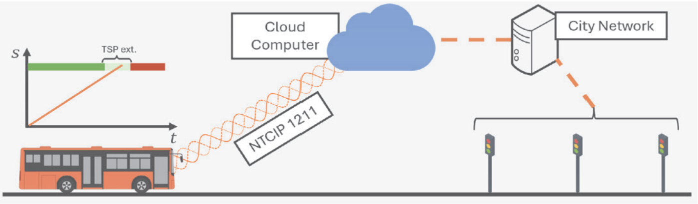


Figure 1 TSP system architecture

- Green light optimal speed advisory (GLOSA): GLOSA provides vehicles with information about upcoming signal timing to support speed adjustments that reduce unnecessary stops. Specifically, it uses signal phase and timing (SPaT) data to compute an advisory speed profile and deliver advance speed recommendations that promote smoother progression through the corridor. SPaT messages are broadcast by roadside units and received by on-board units installed in equipped vehicles. By having smoother acceleration and reducing abrupt speed changes, GLOSA can reduce fuel consumption and emissions.

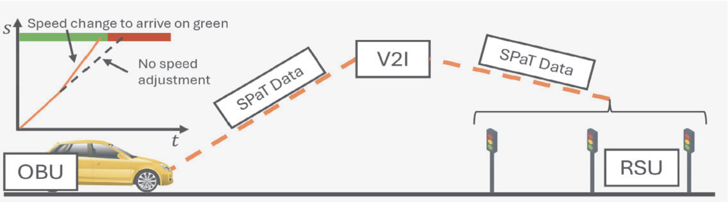


Figure 2 GLOSA system architecture

2.3 Pedestrian features

This study examines pedestrian-oriented signal timing treatments that incorporate pedestrian needs into modern traffic signal control and support multimodal operations. Two pedestrian operation features are evaluated:

- Dynamic exclusive pedestrian phase (DEPP): DEPP provides an exclusive pedestrian phase during which pedestrians are served in all directions while all vehicular movements are stopped. While a common implementation is to provide an exclusive pedestrian phase every cycle, this study evaluates a dynamic approach in which the exclusive phase is activated only when pedestrian demand exceeds a specified threshold (e.g., more than 15 pedestrians per minute). When demand is below the threshold, pedestrians are served using concurrent pedestrian phases operating with compatible vehicular movements. This approach aims to preserve the safety and operational benefits of exclusive pedestrian service while avoiding impact on vehicular traffic.
- Pedestrian protection logic (PPL): PPL is a safety feature intended to protect slow-moving pedestrians and ensure that pedestrians can complete their crossing before conflicting vehicle traffic resumes. Under PPL, if a slow pedestrian is detected near the end of the pedestrian clearance interval, the controller does not extend the pedestrian indication. Instead, it extends the red interval for conflicting vehicular movements to provide additional clearance time. During this extension, the pedestrian display shows a solid DON'T WALK to discourage new pedestrians from initiating a crossing.

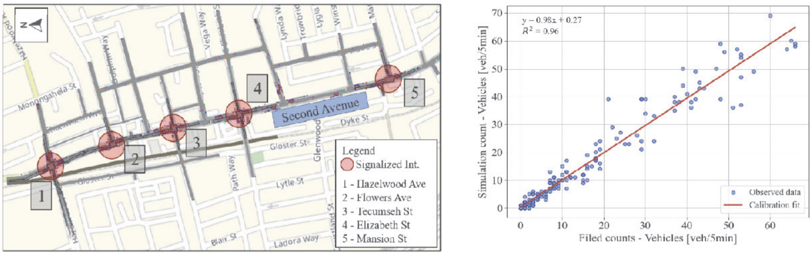
2.4 Traffic scenarios and experimental setup

The study examines combinations of traffic operations scenarios by four distinct time-of-day periods (AM, PM, Midday, and Evening), with different scenario sets defined for peak and off-peak periods. Scenario selection is based on TOD-specific demand levels and traffic patterns. The resulting scenario combinations for each TOD are summarized in Table 1.

Table 1 Scenario combinations for each TOD

Time of day	Scenario Combination
Peak period (AM and PM)	TSP + Fixed-time control
	TSP + Actuated coordinated control
	TSP + ACC (Coordinated for transit)
	TSP + ACC + Pedestrian protection logic
	TSP + ACC + PPL + Exclusive pedestrian phase
	TSP + ACC + GLOSA (30% penetration rate)
Off-peak period (Midday and Evening)	TSP + Fixed-time control
	TSP + Actuated coordinated control
	TSP + Actuated free
	TSP + Rest in Red
Midday only	TSP + AF + PPL + Exclusive ped phase
Evening only	TSP + RIR + PPL

To evaluate the various combinations of traffic strategies, we used a PTV Vissim microsimulation model of the urban corridor Second Avenue in the Hazelwood neighborhood of Pittsburgh, Pennsylvania, USA (figure 3a). The model was calibrated using field data collected in April 2024, as shown in figure 3b. The modeled corridor includes five signalized intersections and supports three transit lines operating in both directions.



(a) VISSIM microsimulation model of Second Avenue

(b) VISSIM microsimulation model calibration

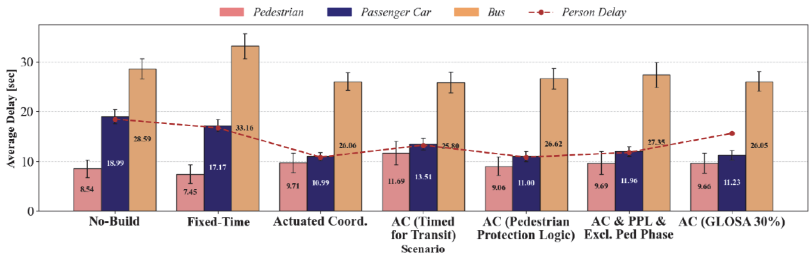
Figure 3 Second Avenue VISSIM network and calibration results

3 Results and discussion

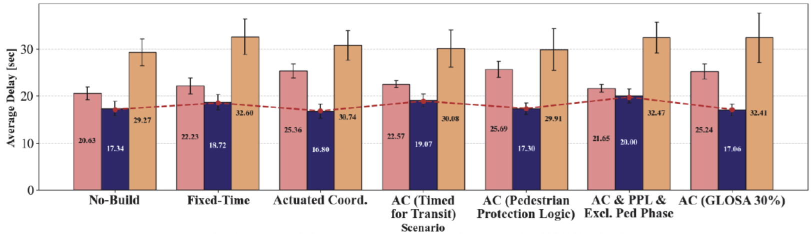
Analysis of traffic operations during peak periods (figure 4) indicates that, for both general vehicular traffic and buses, AC control consistently outperforms other control modes in terms of reducing overall delay. This advantage is largely driven by the demand imbalance between the main corridor and the side streets. Across all TODs, traffic volumes are substantially higher along the mainline than on the cross streets. Fixed-time control, by design, allocates green time to all phases at regular intervals, including side-street phases with limited demand. This leads to inefficient signal utilization and unnecessary delay on the main corridor. In addition, AC scenarios that include pedestrian features can slightly reduce vehicular performance because they prioritize pedestrian service. However, a main insight is that these treatments can provide meaningful safety benefits for pedestrians with only a modest impact on vehicle delay, suggesting that they can be deployed to improve safety while maintaining acceptable traffic performance. Also, the results indicate that fixed-time control provides the best overall performance for pedestrians. Because fixed time serves pedestrian movements whenever the associated phase runs, pedestrians receive regular and predictable walk opportunities. Under actuated control, even when a pedestrian call is present, the controller may delay or truncate pedestrian service due to competing vehicle calls or coordination constraints. This can lead to less frequent pedestrian service and, in some cases, higher pedestrian delay.

Similar insights are observed during off-peak periods (figure 5), where AC control still outperforms fixed-time control for both buses and general traffic. In addition, actuated free control provides additional benefits for buses and pedestrian performance. AF delivers the strongest performance because lower demand produces smaller, less coherent platoons, which limits the value of coordination. AF’s responsiveness serves side streets only as needed and then promptly restores green to the mainline, avoiding short, inefficient side-street greens that coordinated plans can introduce under low volumes. In the evening, rest-in-red is a reasonable safety option, balancing pedestrian service with minimal impact on corridor vehicle delays.

For the pedestrian safety features, results are also similar to those in the peak periods. Adding pedestrian protection logic or a dynamic exclusive pedestrian phase imposes only a small vehicle-delay penalty for both general traffic and buses. This suggests that, on a multimodal corridor such as Second Avenue, vulnerable road users can benefit from these safety-oriented operational features without significantly degrading vehicular performance.

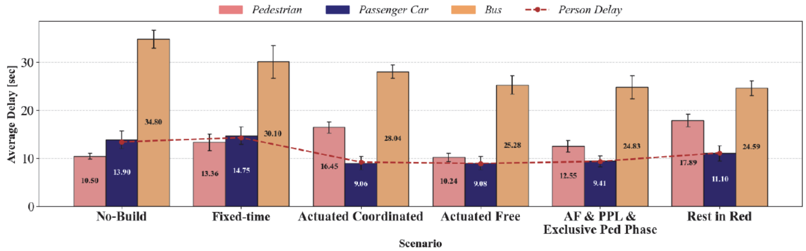


a) Average delay per mode for each scenario (AM Period)

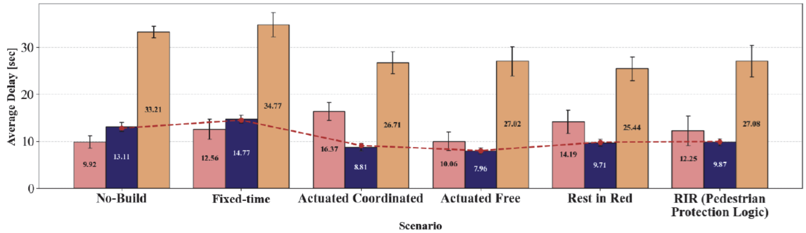


b) Average delay per mode for each scenario (PM Period)

Figure 4 Average delay per mode for peak period



a) Average delay per mode for each scenario (Midday Period)



b) Average delay per mode for each scenario (Evening Period)

Figure 5 Average delay per mode for off-peak period

4 Conclusion

This study examined the impacts of various combinations of traffic control operations and ITS technologies to evaluate how integrating different technologies affects the performance of vehicular traffic, buses, and pedestrians. The main insights indicate that the best overall performance is achieved when TSP is combined with actuated control. Coordinated operation provides the greatest benefits when demand is imbalanced between the main corridor and side streets, while free (uncoordinated) operation performs well under more balanced demand conditions. An additional finding is that, on a multimodal corridor such as Second Avenue, vulnerable road users can benefit from safety-oriented operational features without significantly degrading vehicular performance.

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