Green Net Coordination for Pedestrian Corridors with Bounded Waiting

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Short summary

We consider pedestrians who move along a corridor and cross the road at one of several signalised crossings. Such movement is often hindered by waiting at crossings, reducing walkability. Unlike vehicular green waves, which require coordinated progression through sequential intersections, pedestrians need to cross only once and may do so at any encountered crossing along their path. We study signal coordination that maximises vehicular throughput while guaranteeing that pedestrians can cross within a bounded waiting time. Signal timings are optimised using a genetic algorithm, and vehicular performance is evaluated using a Link Transmission Model. Results for two- and three-crossing corridors show that small waiting allowances substantially increase throughput, with the largest marginal gains at low waiting values. Increasing waiting also changes how pedestrian service is coordinated, shifting from distributed coverage across crossings towards concentrated service at fewer locations and shorter cycle times, as temporal waiting increasingly substitutes for spatial coverage.

Keywords: pedestrian signal coordination; multimodal traffic control; optimisation; walkability

1 Introduction

Walkability is increasingly prioritised in urban transport systems due to its contributions to accessibility, sustainability, and public health (Baobeid & Koç, 2021). However, along signalised corridors, a key barrier to walkability is the repeated stopping experienced by pedestrians at crossings. Frequent red indications increase journey travel time and make pedestrian movement fragmented. While signal control strategies often consider pedestrian service at individual crossings, corridor-level coordination remains largely underexplored.
Signal coordination has traditionally focused on vehicular progression, where green waves are designed to allow uninterrupted movement along an arterial (Little et al., 1981; Zhang et al., 2020). These approaches require alignment of signals along a single trajectory and are sensitive to travel speed.
In contrast, pedestrians walking along a corridor need to cross only once and may do so at any available crossing encountered along their path, as illustrated in Fig. 1. This flexibility changes the coordination problem fundamentally: instead of ensuring that downstream signals turn green in alignment with vehicle arrivals along a progression path, it is sufficient that at least one crossing is serviceable for each pedestrian. Analytical work has shown that, under certain conditions, increasing pedestrian crossing opportunities can improve both pedestrian accessibility and vehicular flow efficiency (Daganzo & Knoop, 2016).
This observation motivates a coverage-based coordination approach, referred to here as a *Green Net*. Under this concept, pedestrian trajectories through the corridor are mapped to arrival times at successive crossings, and signal timings are arranged so that each trajectory can be served at at least one of these crossings. The resulting coordination distributes service opportunities across crossings and departure times, forming a temporal "net" that captures bidirectional pedestrian movements.

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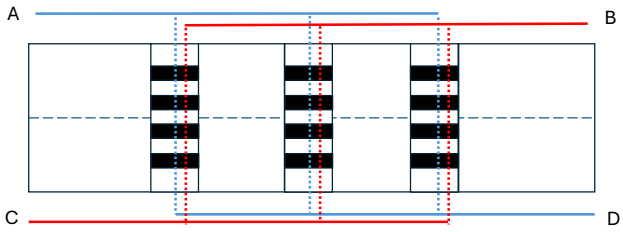


Figure 1: Signalised corridor with multiple pedestrian crossings and bidirectional flows (e.g., A–D, B–C). Pedestrians may cross at any encountered crossing along the corridor. Solid red/blue lines indicate pedestrian path travel; dotted lines indicate crossings.

While immediate service upon arrival is an appealing objective, practical operation may benefit from allowing limited waiting at crossings. In this paper, pedestrian service is therefore formulated in terms of a maximum allowed waiting time, which guarantees that pedestrians can be served within a bounded delay after reaching a crossing. As shown later, varying this waiting allowance affects not only the throughput trade-off, but also the structure of the optimal coordination, including service distribution across crossings and the associated cycle length.

The design problem is to determine signal timings that satisfy this pedestrian service requirement for all departure times and both walking directions, while maximising vehicular throughput. Vehicular performance is evaluated using the Link Transmission Model (Yperman, 2007), and signal timings are optimised using a tailored genetic algorithm (Goldberg, 1989). The analysis focuses on corridors with two and three crossings, allowing systematic exploration of feasible timing structures and performance trade-offs.

This paper makes three contributions. First, it formulates Green Net coordination with bounded waiting as a corridor-level pedestrian service problem. Second, it formalises pedestrian service as an at-least-one-service coverage constraint over all departure times and both walking directions. Third, numerical optimisation of two- and three-crossing corridor configurations shows that bounded waiting both improves vehicular throughput and changes the structure of optimal coordination. These cases are sufficient to understand the key mechanisms, and they reflect typical urban corridors with limited numbers of crossings between intersections.

2 Methodology

We consider a corridor with Z signalised crossings indexed by $i \in \{1, \ldots, Z\}$, operated with a common cycle length $C > 0$. Vehicles flow bidirectionally along the corridor, while pedestrians walk along both sides and may travel in either direction. Pedestrians are assumed to walk at a constant speed, independent of congestion.

The Green Net concept

The Green Net concept is illustrated in Fig. 2. With constant walking speed, pedestrian movements appear as slanted space–time trajectories. Each crossing provides periodic green intervals, and a pedestrian is served if their trajectory reaches at least one crossing during a usable green interval or within the waiting allowance before it.

Different crossings therefore serve different departure times. When the signal timings are coordinated so that every departure time is served at at least one crossing in each direction within the allowed waiting time, the corridor forms a temporal "net" over departure times.

We consider two- and three-crossing corridors under symmetric geometry. The walking distance between consecutive crossings, as well as between corridor ends and the nearest crossings, is assumed homogeneous. Let d denote this spacing, so that for a corridor of

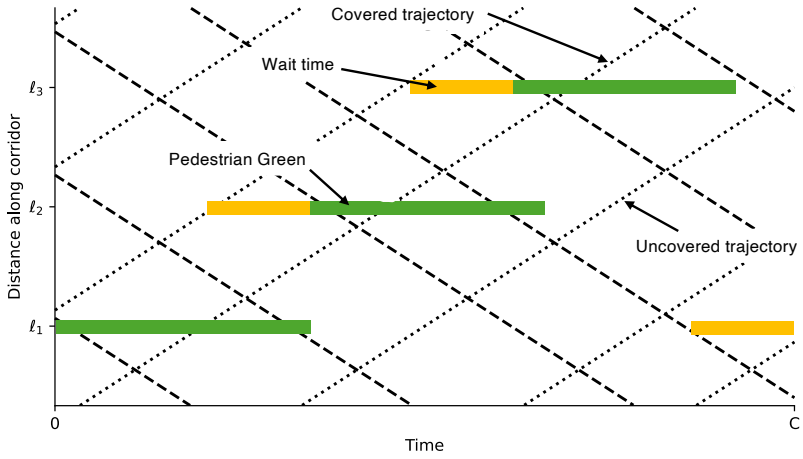


Figure 2: *Green Net coverage illustration with waiting allowance W.* Dashed and dotted lines show constant-speed pedestrian trajectories in opposite directions over a cycle C. Green bars denote pedestrian green intervals at crossings ℓ_1–ℓ_3, and yellow bars denote the waiting extension W before green. A departure is *served* if its trajectory reaches at least one crossing during green or within the waiting-extended service interval. Uncovered trajectories indicate gaps in departure-time coverage.

total length L with Z crossings, $d = L/(Z+1)$. This assumption ensures that differences in performance arise from signal timing rather than from variations in corridor geometry. The framework can be extended to heterogeneous spacing and asymmetric layouts.

Signal parametrisation and pedestrian arrival times

Let the cycle time domain be $\mathcal{T} = [0, C)$. Each parametrised crossing i is characterised by a pedestrian green interval defined by start time $s_i \in \mathcal{T}$ and duration $g_i \in (B, C]$. In all experiments, the safety-related minimum green time is set to $B = 3$ s.
The corresponding green set is

$$\mathcal{G}_i = \{\, t \in \mathcal{T} : (t - s_i) \bmod C \in [0, g_i) \,\}. \tag{1}$$

Without loss of generality, we fix the time origin by setting the first crossing to start at the beginning of the cycle,

$$s_1 = 0, \tag{2}$$

thereby reducing the number of decision variables. The remaining optimisation variables are the cycle length C, the green durations of the parametrised crossings, and the start times of all parametrised crossings except the first.
With constant walking speed, a pedestrian departing at time t reaches crossing i at time

$$a_i^d(t) = (t + \tau_i^d) \bmod C, \quad d \in \{\rightarrow, \leftarrow\}, \tag{3}$$

where τ_i^d denotes the walking time from the trip origin to crossing i in direction d.

Pedestrian service under bounded waiting

Pedestrian service is subject to a maximum allowed waiting time $W \geq 0$ upon arrival at a crossing. Only the part of a green interval that allows a pedestrian to fully complete the crossing is usable, excluding the last B s of the interval. A positive waiting allowance expands this usable window backwards in time, since a pedestrian may arrive before the start of service and wait up to W seconds. This yields the effective green set

$$\mathcal{G}_i^{\text{eff}} = \{\, t \in \mathcal{T} : (t - s_i) \bmod C \in [-W,\, g_i - B) \,\}. \tag{4}$$

Here, negative values are interpreted modulo C, i.e. as wrapping around the end of the cycle. The set of departure times covered by crossing i in direction d is then

$$\mathcal{D}_i^d = \left\{ t \in \mathcal{T} : a_i^d(t) \in \mathcal{G}_i^{\text{eff}} \right\}, \qquad \forall i \in \{1, \ldots, Z\},\ \forall d \in \{\rightarrow, \leftarrow\}. \tag{5}$$

These definitions describe the coverage provided by the effective service set of a crossing. For the optimised crossings, this set is parametrised by (s_i, g_i) as above; for the gap-filler crossing, it is constructed separately and may comprise multiple green intervals or none.

Feasibility and coverage gap-filler construction

To enforce feasibility efficiently, one crossing is designated as a gap-filler that covers any remaining uncovered departure times.
Let $k \in \{1, \ldots, Z\}$ denote the gap-filler crossing. The signal timings of all crossings except k are treated as decision variables, while the green intervals at crossing k are constructed ex-post to ensure full coverage.
Given timings for the non-gap-filler crossings, the uncovered departure-time set in direction d is

$$\mathcal{U}^d = \mathcal{T} \setminus \bigcup_{i \in \{1,\ldots,Z\} \setminus \{k\}} \mathcal{D}_i^d. \tag{6}$$

The gap-filler is then constructed such that

$$\mathcal{U}^d \subseteq \mathcal{D}_k^d, \qquad \forall d \in \{\rightarrow, \leftarrow\}. \tag{7}$$

This ensures that the Green Net feasibility condition is satisfied, namely full coverage:

$$\bigcup_{i=1}^{Z} \mathcal{D}_i^d = \mathcal{T}, \quad \forall d \in \{\rightarrow, \leftarrow\}. \tag{8}$$

It therefore acts as a repair step that deterministically assigns uncovered departure-time intervals to the gap-filler crossing. The gap-filler crossing is not subject to the integer discretisation imposed on the optimised decision variables, and may have zero green time if no uncovered departure times remain. For $Z = 2$, one crossing is optimised and the other acts as the gap-filler. For $Z = 3$, a *mid-cover* structure is adopted, in which the central crossing ($k = 2$) acts as the gap-filler while the outer crossings are optimised. Its central position enables efficient coverage of gaps arising from both directions. This approach reduces the dimensionality of the optimisation problem while guaranteeing feasibility whenever a solution exists.

Vehicular flow model

Vehicular dynamics are modelled using the Link Transmission Model (LTM) (Yperman, 2007). The corridor is partitioned into homogeneous links separated by signalised crossings that impose periodic capacity constraints. Traffic evolution is represented through cumulative vehicle counts at link boundaries, with flows determined by upstream sending and downstream receiving flows.
Signal control modifies link capacities over time. During pedestrian green, the boundary capacity is set to zero, while during vehicle green it equals the saturation flow. The LTM is simulated using a discrete time step Δt (0.1 s in our experiments), with continuous inflow rates applied at each time step. Signal timings are discretised at a 1-second resolution, which sensitivity tests showed to be sufficient for stable throughput estimates. The system is simulated over multiple cycles under periodic signal timings to allow transient effects to dissipate. Throughput $Q(\theta)$ is then defined as the total bidirectional outflow during the final cycle, which serves as a proxy for steady-state performance.

Optimisation problem formulation

Let θ denote the vector of decision variables, comprising the cycle length C and the signal timings (s_i, g_i) for each non-gap-filler crossing i. Define Θ as the set of admissible decision vectors for the non-gap-filler crossings, satisfying $s_1 = 0$, $s_i \in \mathcal{T}$, $g_i \in (B, C]$, and $C \in [C_{\min}, C_{\max}]$ (in all experiments, $C_{\min} = 30$ s, $C_{\max} = 240$ s). The optimised decision variables are discretised to integer seconds. For each candidate $\theta \in \Theta$, the gap-filler construction ensures feasibility, and the resulting signal plan is evaluated using the LTM to obtain vehicular throughput $Q(\theta)$.

$$\max_{\theta \in \Theta} \quad Q(\theta) \tag{9}$$

$$\text{s.t.} \quad \bigcup_{i=1}^{Z} \mathcal{D}_i^d = \mathcal{T}, \quad \forall d \in \{\rightarrow, \leftarrow\}, \tag{10}$$

$$\mathcal{U}^d = \mathcal{T} \setminus \bigcup_{i \in \{1,\ldots,Z\} \setminus \{k\}} \mathcal{D}_i^d, \quad \forall d \in \{\rightarrow, \leftarrow\}, \tag{11}$$

$$\mathcal{U}^d \subseteq \mathcal{D}_k^d, \quad \forall d \in \{\rightarrow, \leftarrow\}, \tag{12}$$

$$\mathcal{D}_i^d = \left\{ t \in \mathcal{T} : a_i^d(t) \in \mathcal{G}_i^{\text{eff}} \right\}, \quad \forall i \in \{1, \ldots, Z\}, \ \forall d \in \{\rightarrow, \leftarrow\}, \tag{13}$$

$$s_1 = 0, \tag{14}$$

$$s_i \in \mathcal{T}, \quad g_i \in (B, C], \quad \text{for all non-gap-filler crossings}, \tag{15}$$

$$C \in [C_{\min}, C_{\max}]. \tag{16}$$

For the gap-filler crossing, $\mathcal{G}_k^{\text{eff}}$ is understood as the effective service set induced by the ex-post constructed green intervals.
The problem is solved using a genetic algorithm (GA) (Goldberg, 1989). The GA iteratively evolves candidate solutions through selection, crossover, and mutation. In our experiments, 10 runs with different initial populations are performed to assess robustness to stochastic initialisation, using a population size of 200 and a maximum of 200 generations.

3 Results

Results are presented for two- and three-crossing corridors with $L = 900$ m. For two crossings, each link has length $d = 300$ m. For three crossings, each link has length $d = 225$ m. Pedestrian walking speed is set to 1.4 m/s. Vehicular dynamics follow typical LTM parameters: free-flow speed $v = 54$ km/h, backward wave speed $w = 18$ km/h, and jam density $\kappa = 120$ veh/km/lane. These values yield a theoretical unsignalised bidirectional capacity of 3240 veh/h, which is used as an upper bound for signalised corridor performance.

Baseline: No pedestrian waiting time

We first consider the case of zero waiting allowance ($W = 0$), corresponding to immediate service upon arrival.
For the two-crossing corridor, the optimisation converges to $(C^*, g_1^*) = (143\,\text{s}, 75\,\text{s})$, achieving a throughput of 1540.7 veh/h, corresponding to 47.6% of the theoretical unsignalised capacity. Enumeration over the feasible parameter space confirms that this solution is globally optimal under integer signal timings. Using finer timing resolutions yields improvements of less than 1%, indicating negligible loss from integer-resolution signal timings.
For the three-crossing corridor, the optimisation converges to $(C^*, g_1^*, s_3^*, g_3^*) = (123\,\text{s}, 45\,\text{s}, 0\,\text{s}, 45\,\text{s})$, achieving a throughput of 2049 veh/h (63.3% of theoretical unsignalised capacity). The

Table 1: GA robustness across waiting allowances. Gap: relative difference between best and mean objective values across 10 replications. Gen*: mean generation of first occurrence of the best solution.

	2 crossings			3 crossings		
W (s)	Mean±Std (veh/h)	Gap (%)	Gen*	Mean±Std (veh/h)	Gap (%)	Gen*
0	1538±8	0.17	11.6	2006±54	2.12	13.1
5	1585±19	0.94	7.8	2098±38	2.54	15.3
10	1733±46	1.94	10.6	2279±102	5.21	17.4
20	2209±49	2.17	2.4	2899±0	0.00	9.8
30	2822±0	0.00	2.7	3015±5	0.05	10.2

higher throughput reflects the increased flexibility provided by the additional crossing, which allows more efficient allocation of pedestrian service across the corridor.

Optimisation robustness

To assess optimisation robustness, Table 1 reports results from 10 independent GA runs for representative values of W. For two crossings, the GA recovers the optimum with little variation. For three crossings, variability is higher because of the larger search space, but the mean-best gap remains small, indicating that the GA consistently finds near-optimal solutions. In both cases, the best solutions are typically identified within the first few generations. Across different W values, runtime ranges from about 2 to 6 minutes for two crossings and from 11 to 34 minutes for three crossings, reflecting the increased computational complexity.

Different regimes under bounded waiting

We now examine how allowing a bounded waiting time $W > 0$ affects the structure of feasible pedestrian coverage, and hence the optimal cycle time and vehicular throughput. The results reveal three distinct regimes in the optimal signal plan, reflected in the changes in cycle time (Fig. 3) and throughput (Fig. 4).

Regime I - strict covering ($W \lesssim 8$ s):

For small waiting allowances, the pedestrian constraint remains close to a no-wait condition. In departure-time space, the projected green intervals must therefore almost exactly fill the cycle, leaving little arrival-phase mismatch. This favours long-cycle solutions. In the two-crossing case, the optimum remains near $C \approx 143$ s. Since the inter-crossing walking time is $\tau = 300/1.4 \approx 214$ s, this gives $\tau \approx 3C/2$, so pedestrians reach the next crossing after about one and a half cycles. This half-cycle alignment supports near-complete and symmetric coverage in both directions.

In the three-crossing case, the same strict-covering requirement also leads to long-cycle solutions, but the cycle lengths are less regular. Rather than lying on a single dominant branch, the optima move between several competing long-cycle solutions, each reflecting a phase relation to the inter-crossing walking time similar to that in the two-crossing case and enabling effective positioning of green intervals. This reflects the additional degrees of freedom introduced by the extra crossing and the gap-filler construction, which permit multiple feasible signal patterns under the constraints. Vehicular throughput remains limited in this regime, since the long pedestrian greens interrupt discharge for extended periods and increase queues.

Regime II - branch switching under relaxed covering ($8 \lesssim W \lesssim 20$–30 s):

Once a moderate waiting allowance is permitted, the feasible departure-time coverage of each green interval expands, so exact alignment between crossings becomes less necessary and shorter-cycle solution branches become feasible. In the two-crossing case, this produces a sharp transition from the long-cycle branch at $C \approx 143$ s to a short-cycle branch at $C \approx 33$ s. Since τ remains about 214 s, the new branch satisfies $\tau/C \approx 214/33 \approx 6.5$, so pedestrians again reach the next crossing after approximately a half-integer number of

cycles. The discontinuity therefore reflects switching between distinct cycle-time branches that each exploit alignment with the inter-crossing walking time, rather than the gradual deformation of a single optimum as W changes within Regimes I and II.

A similar but less abrupt reduction occurs in the three-crossing case, where optimal cycle times fall to approximately 31–34 s. Here, the inter-crossing walking time is $\tau = 225/1.4 \approx 160.4$ s, so the short-cycle branch satisfies $\tau/C \approx 5$, i.e., close to an integer number of cycles. Under symmetry, such an integer cycle relation also supports an efficient arrangement of green intervals across crossings. Because Regime I already contains several competing long-cycle structures, the transition is less cleanly expressed as a jump between two single branches than in the two-crossing case. Nevertheless, it still reflects a move toward shorter cycle-time branches structured by the inter-crossing pedestrian travel time. This regime yields the largest throughput gains, because long vehicle interruptions are replaced by shorter and more efficient blocking periods with smaller queues.

Regime III - waiting-dominated service ($W \gtrsim$ 20–30 s):

For larger waiting allowances, the solution structure changes qualitatively. Unlike Regimes I and II, where the optimal cycle times are shaped by alignment with the inter-crossing walking time, in Regime III waiting itself becomes the dominant mechanism maintaining feasible coverage. The resulting high-W structure differs between the two- and three-crossing cases.

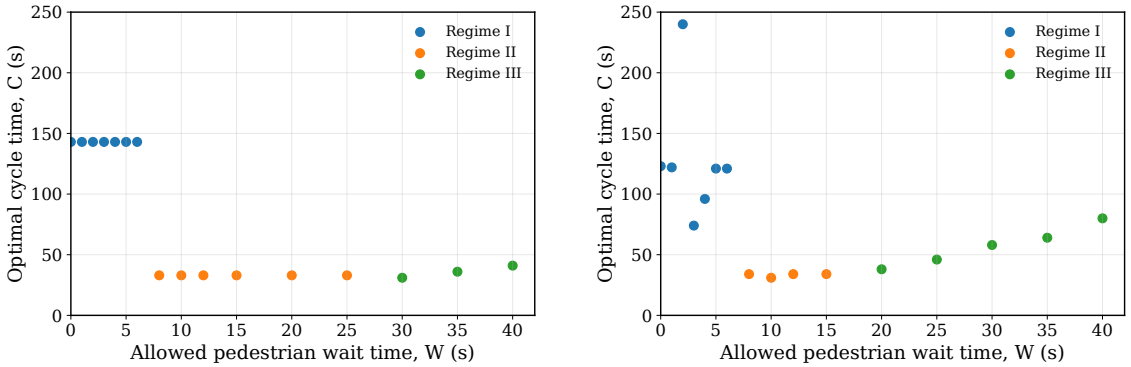
In the two-crossing case, the onset of Regime III is tied to the minimum admissible cycle length, $C_{\min} = 30$ s. Once W reaches approximately this value, the solution no longer needs coordinated coverage across both crossings. Instead, a single-active-crossing strategy becomes feasible: pedestrians can be served at one location within the allowed waiting time, while the second crossing becomes inactive. The optimiser therefore collapses to a waiting-dominated solution with zero pedestrian green time at the second crossing and the minimum green time at the first crossing ($g_1 = B + 1 = 4$ s). Beyond this threshold, the cycle time increases approximately in proportion to W (i.e., $C \approx W$), indicating that temporal waiting coverage directly substitutes for spatial coverage. Vehicle throughput then increases because pedestrian service is concentrated at a single crossing and occupies a progressively smaller fraction of each cycle.

In the three-crossing case, the transition is different. Rather than collapsing to a single active crossing, the solution retains two active end crossings. By approximately $W =$ 20 s, their greens reach the minimum admissible values ($g_1 = g_3 = B + 1 = 4$ s) and remain fixed there as W increases. The middle gap-filler crossing is unnecessary at $W =$ 20 s, and for larger W reappears only as a short residual single green interval to patch a small range of remaining uncovered phases. Further increases in W are then reflected mainly in longer cycle times. With the active greens remaining minimal, pedestrian service occupies a smaller fraction of each cycle, interrupts vehicle discharge less, and allows higher throughput. Since two optimised crossings remain active, each contributes an effective coverage width that increases with W, consistent with the observed cycle times increasing approximately linearly with W and remaining close to $C \approx 2W$. The transition between $W = 15$ and $W = 20$ s further suggests that this scaling becomes admissible once $2W$ exceeds the lower cycle bound $C_{\min} = 30$ s.

Comparison across regimes:

The transition between regimes is illustrated by the pedestrian signal plans in Fig. 5: increasing W into Regime III leads to a single active crossing in the two-crossing case, while the three-crossing configuration retains two active end crossings and uses the middle crossing only as a small residual gap-filler. In both configurations, throughput gains diminish in this high-W regime as performance approaches the unsignalised capacity limit.

Across all regimes, the three-crossing corridor consistently outperforms the two-crossing corridor, highlighting the role of corridor segmentation in improving pedestrian-vehicle coordination. The advantage is largest in Regimes I and II, where the additional crossing provides greater flexibility in constructing feasible pedestrian coverage patterns and pre-



(a) Two crossings

(b) Three crossings

Figure 3: Optimal cycle time C as a function of waiting allowance W for two- and three-crossing corridors. Colours denote the three regimes discussed in the text: strict covering (Regime I), branch switching under relaxed covering (Regime II), and waiting-dominated service (Regime III).

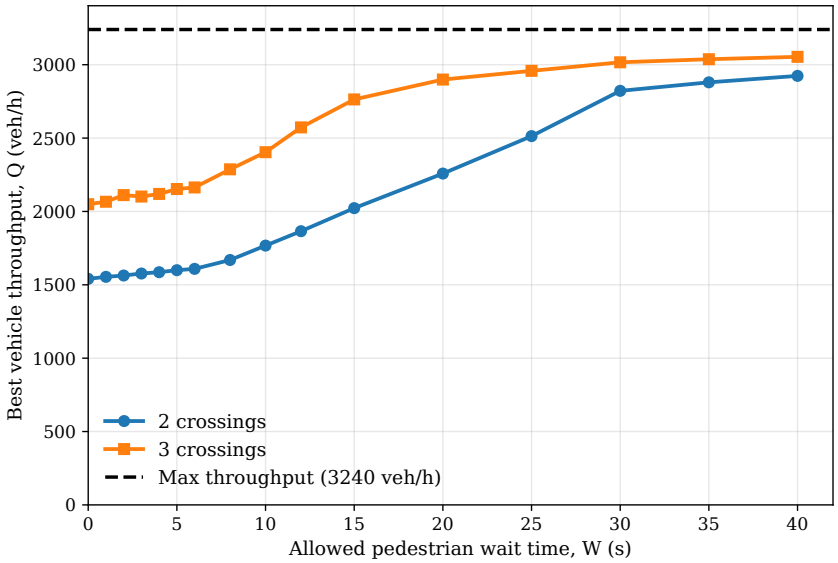


Figure 4: Bidirectional vehicular throughput as a function of waiting allowance W for two- and three-crossing corridors.

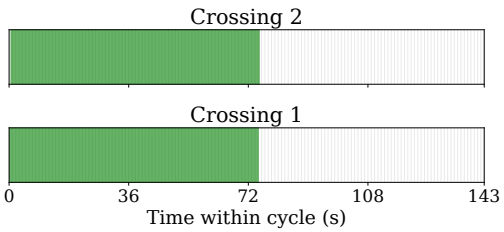
serving vehicle progression across successive links. In Regime III, this advantage narrows as both configurations approach the theoretical unsignalised capacity.

In summary, bounded waiting shifts the coordination problem from near-exact spatial-temporal covering across multiple crossings (Regime I), through switching between distinct aligned cycle-time structures (Regime II), to waiting-dominated service with different structural patterns in the two- and three-crossing cases (Regime III).

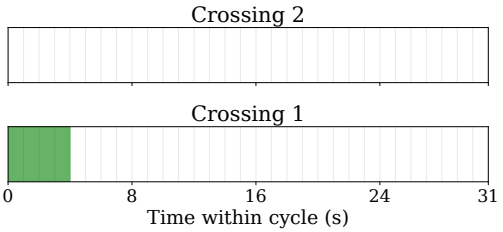
4 Conclusions

This paper introduced a Green Net formulation for corridor-level pedestrian coordination under bounded waiting. By reframing pedestrian progression as a temporal coverage problem, the approach departs from traditional arterial green-wave concepts and instead ensures that each pedestrian can be served at at least one crossing within a maximum waiting time.

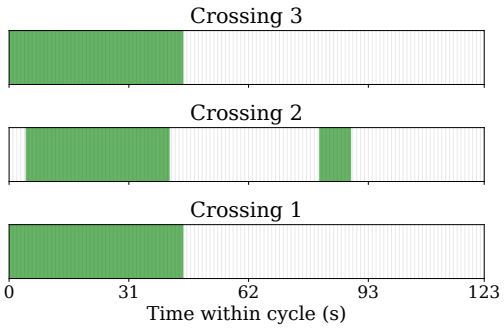
The results reveal a clear trade-off between pedestrian delay guarantees and vehicular



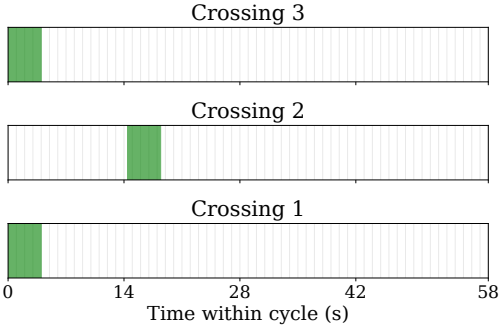
(a) Two crossings, $W = 0$.



(b) Two crossings, $W = 30$ s.



(c) Three crossings, $W = 0$.



(d) Three crossings, $W = 30$ s.

Figure 5: Representative optimal pedestrian green plans under zero and bounded waiting. Increasing W reduces the required pedestrian green time. In the two-crossing case, the gap-filler becomes inactive at higher W, while in the three-crossing case multiple crossings remain active.

throughput. Allowing even small waiting times substantially relaxes the coverage constraint, with the largest throughput gains occurring at low waiting allowances.

A key insight is that bounded waiting fundamentally alters the coordination mechanism. At low waiting allowances, performance relies on spatial coordination across multiple crossings. As the waiting allowance increases, the optimal solution transitions between distinct cycle-time regimes. For small W, long cycle times are required to provide distributed spatial coverage across crossings. As W increases, shorter cycle times become feasible, and pedestrian service then relies on waiting at fewer locations rather than coordinated coverage. In the two-crossing case, this transition leads to a regime in which one crossing becomes inactive and pedestrian service is effectively concentrated at a single location. In contrast, the three-crossing configuration retains distributed service and continues to provide higher throughput across all waiting times.

Future work will extend the framework to heterogeneous pedestrian speeds and asymmetric corridor geometries. In addition, rather than accommodating waiting times up to W, pedestrians could be encouraged to adapt their walking speed to meet the start of a green window. This could increase vehicular capacity without impacting pedestrian delay. Another important extension is to relax the fixed-cycle assumption and consider actuated control, where pedestrians in low demand scenarios request service via button presses and are guaranteed a green phase within at most W seconds of arrival. Lastly, analytical characterisation of optimal timing structures for general multi-crossing systems, as well as alternative gap-filling strategies, also remain important directions.

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