Signal-Free Intersections and Automated Vehicles | A Case Study in Heraklion, Crete, Greece

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Extended abstract submitted for presentation at the Conference in Emerging Technologies in Transportation Systems (TRC-30)
September 02-03, 2024, Crete, Greece

April 15, 2024

Keywords: Connected and Automated Vehicles, Traffic Control, PTV Vissim

1 Introduction

In recent years, the society has seen remarkable technological advancements in transportation networks, especially in the realm of automation Mouratidis *et al.* (2021). Some of these innovations include optimal traffic light switching tailored to real-time traffic flow De Schutter & De Moor (1998), virtual speed limits Khondaker & Kattan (2015), adaptive cruise control Xiao & Gao (2010) etc. Collectively, these advancements have significantly enhanced the safety, comfort, and efficiency of the transportation system Shaheen & Finson (2013). A particular focus has been placed on connected and automated vehicles (CAVs), which have proven to be highly effective in diverse traffic scenarios, such as merging on-ramps, signal-free intersections, and speed reduction zones Rios-Torres & Malikopoulos (2016).

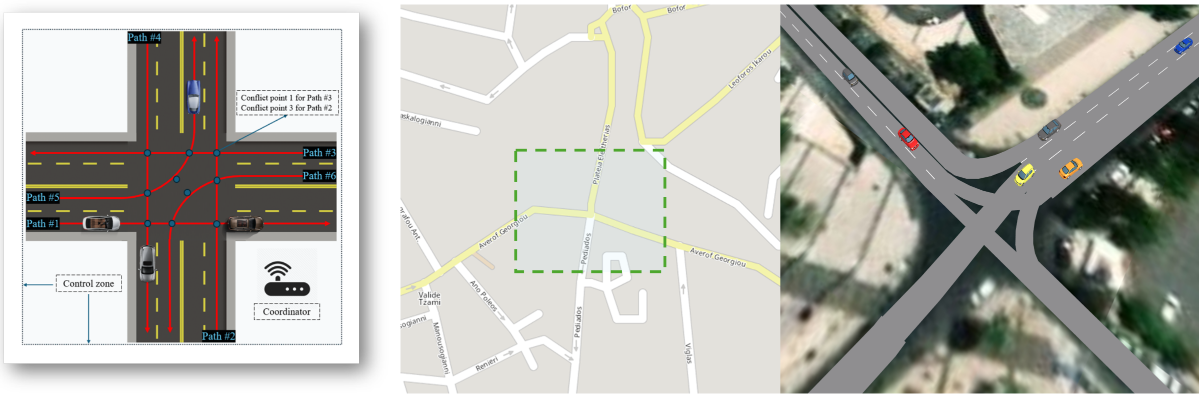
Along these lines, recent research has introduced a decentralized framework for operating CAVs at signal-free intersections, eliminating stop-and-go driving while maximizing throughput and fuel efficiency Malikopoulos *et al.* (2021). A subsequent study has explored the coordination of CAVs at adjacent intersections using a similar controller framework Chalaki & Malikopoulos (2021). Recently, an extension of this framework aimed to improve the feasibility domain of the controller when traffic volume increases, employing concepts from numerical mathematics Tzortzoglou *et al.* (2024).

In this paper, we integrate the previously defined problem formulation in Tzortzoglou *et al.* (2024) and demonstrate its effectiveness at a signal-free intersection in the center of Heraklion, Crete, Greece. We employed PTV Vissim to illustrate our approach and compare travel times and stop-and-go events between scenarios operating exclusively with human driven-vehicles (HDVs) and those with only CAVs.

The remaining of the paper proceeds as follows. In Section 2, we illustrate the problem formulation, then in Section 3, we present our findings provided by PTV Vissim software, and finally, in Section 4, we draw some concluding remarks.

2 Problem Formulation

We begin by introducing the control framework of an intersection as illustrated in Figure 1a. In our setup, we require a coordinator which handles communication between CAVs. We call the range of the coordinator as *control zone*. Then, we define $z \in \mathbb{N}$ paths along the intersection and define the set of paths as $\mathcal{L} = \{1, ..., z\}$. Note that in Figure 1a, we have defined 6 paths but this can easily be generalized to larger intersections. Let us denote the set of vehicles in the



(a) *Schematic of an intersection* (b) *Signal-free intersection at the center of Heraklion, Greece.*

Figure 1

intersection at time t as $\mathcal{N}(t) = \{1, ..., N(t)\}$. The dynamics and the physical constraints of each CAV $i \in \mathcal{N}$ are defined as:

$$\dot{p}_i(t) = v_i(t) \quad v_{\min} \leq v_i(t) \leq v_{\max}, \quad \forall i \in \mathcal{N}(t) \tag{1}$$
$$\dot{v}_i(t) = u_i(t) \quad u_{\min} \leq u_i(t) \leq u_{\max}, \quad \forall i \in \mathcal{N}(t)$$

where $p_i \in \mathcal{P}$, $v_i \in \mathcal{V}$, and $u_i \in \mathcal{U}$ denote the longitudinal position of the rear bumper, speed, and control input (acceleration) of the vehicle, respectively.

2.1 Safety Constraints

Before addressing safety constraints, we introduce notation for each path $z \in \mathcal{L}$, omitting subscript z to reduce ambiguity where possible. Define p_i^0, p_i^n, and p_i^f as the entry, conflict, and exit points respectively for each CAV i. Although in Figure 1a each path z crosses three conflict points $n \in \{1, 2, 3\}$, this can be generalized to any number of conflict points.

Define entry time t_i^0 and exit time t_i^f in $\mathbb{R}_{\geq 0}$ for CAV i at the control zone. Also, t_i^n is the time CAV i reaches each conflict point n. Note that $v_i(t) > 0$, $p_i(t)$ increases monotonically, allowing $t_i = p_i^{-1}$ to map positions to times, hence determining t_i^n.

Safety constraints include rear-end constraints on the same path guaranteed by (2), and lateral safety constraints on intersecting paths guaranteed by (3) and (4).

$$t_k(p) - t_i(p) \geq \tau_r, \tag{2}$$

$$t_i^n - t_i(p) \geq \tau_\ell, \quad \forall p \in [p_i^0, p_k^n], \tag{3}$$

$$t_k^n - t_k(p) \geq \tau_\ell, \quad \forall p \in [p_k^0, p_i^n]. \tag{4}$$

In (2) the subscript k denotes the vehicle in front of the vehicle i while τ_r denotes the rear-end time headway. In (3), we consider a CAV i that reaches the conflict point n after CAV k. Then, t_k^n denotes the time CAV k arrives at conflict point n. This constraint ensures that the time headway between CAV i and conflict point n is greater than or equal to τ_ℓ (lateral time headway) for the duration until CAV k has successfully passed through conflict point n. In (4), we follow the same logic as (3) for the case where CAV i reaches the conflict point n before CAV k.

2.2 Control Framework

Assuming known exit times t_i^f for all CAVs $i \in \mathcal{N}(t)$, we define Problem 1 as the energy-optimal control problem where v_i^0 is the initial speed at t_i^0.

Problem 1

$$\min_{u_i \in \mathcal{U}} \quad \frac{1}{2}\int_{t_i^0}^{t_i^f} u_i^2(t)\,\mathrm{d}t,$$

subject to:

$$(1), (2), (3), (4),$$

$$p_i(t_i^0) = p^0,\ v_i(t_i^0) = v_i^0, p_i(t_i^f) = p^f,$$

Problem 2

$$\min_{t_i^f \in \mathcal{T}_i(t_i^0)} \quad t_i^f,$$

subject to:

$$(1), (2), (3), (4),$$

$$p_i(t_i^0) = p^0,\ v_i(t_i^0) = v_i^0,\ p_i(t_i^f) = p^f, u_i(t_i^f) = 0.$$

Problem 1 aims for the minimum control input $u_i(t)$ from the entry to the exit of the control zone. The problem's solution is described in Malikopoulos *et al.* (2021), and utilizes Hamiltonian analysis to provide the optimal trajectories:

$$\begin{aligned} u_i(t) &= 6\phi_{i,3}t + 2\phi_{i,2}, \\ v_i(t) &= 3\phi_{i,3}t^2 + 2\phi_{i,2}t + \phi_{i,1}, \\ p_i(t) &= \phi_{i,3}t^3 + \phi_{i,2}t^2 + \phi_{i,1}t + \phi_{i,0}, \end{aligned} \qquad \begin{bmatrix} \phi_{i,3} \\ \phi_{i,2} \\ \phi_{i,1} \\ \phi_{i,0} \end{bmatrix} = \begin{bmatrix} (t_i^0)^3 & (t_i^0)^2 & t_i^0 & 1 \\ 3(t_i^0)^2 & 2t_i^0 & 1 & 0 \\ (t_i^f)^3 & (t_i^f)^2 & t_i^f & 1 \\ 6t_i^f & 2t_i^f & 0 & 0 \end{bmatrix}^{-1} \begin{bmatrix} p^0 \\ v_i^0 \\ p^f \\ 0 \end{bmatrix}. \quad (5)$$

However, note that Problem 1 assumes t_i^f is known. To find the optimal t_i^f for each CAV i, we utilize Problem 2. At the time t_i^0 of entering the control zone, let $\mathcal{T}_i(t_i^0) = [\underline{t}_i^{\mathrm{f}}, \overline{t}_i^{\mathrm{f}}]$ be the feasible range of travel times under the state and input constraints of CAV i computed at t_i^0. The CAV aims to solve the time-optimal control problem (Problem 2) to find the minimum feasible exit time t_i^f. The solution is iteratively refined by checking and adjusting t_i^f until all constraints are satisfied, achieving the optimal exit time and trajectory provided by Problem 1.

As discussed in Tzortzoglou *et al.* (2024), in scenarios where high congestion is present, solving Problems 1 and 2 may require piecing together arcs, a process that is computationally intensive. In such situations, the approach suggests that since the solution to Problem 1 is constrained to a third-order polynomial, employing a higher-order polynomial may provide a solution. To this end, we utilize theoretical results from numerical mathematics to construct such a higher-order polynomial. More specifically, it is proven that if we have $n+1$ distinct nodes $\{x_0, \dots, x_n\}$ and $n+1$ corresponding values $\{y_0, \dots, y_n\}$, there exists a unique polynomial $f(x)$ of degree n, such that $f(x_i) = y_i$ for all $i = 0, \dots, n$. Moreover, considering that we know for each CAV i the position of its entry p_i^0, the position of the conflict points p_i^n, and its final position in the control zone p_i^f, we have at least more than four standard fixed positions along its trajectory. The goal is to find corresponding times t_i^n and t_i^f at which a CAV passes through these positions without violating any safety constraints. After determining these times, we are positioned to construct a position trajectory polynomial extending the solution domain provided in Problem 1. For an analytical approach of how we select efficient times t_i^n and t_i^f for the construction of the trajectory polynomial, see Tzortzoglou *et al.* (2024), section III.

3 Results

In this section, we present our findings from simulations conducted at a signal-free intersection in the center of Heraklion, Crete, Greece. As depicted in Figure 1b, our scenario is designed based on the actual layout of this intersection, which accounts for one-way roads and lack of traffic signals. We defined a control zone with a 100-meter range and a traffic volume of 1,500 vehicles per hour. In Figure 2, we analyze the travel times of the first 20 vehicles passing through the intersection. The blue bars represent travel times for HDVs, while the orange bars show times for CAVs. The results clearly demonstrate a significant improvement in travel times with CAVs, typically around 20% . Additionally, we assessed the minimum speeds under different set of initial conditions. For HDVs, it was evident that the minimum speeds are generally lower, with several instances of full stops, leading to increased travel times and poorer fuel efficiency. Supplemental videos can be found on the paper's website: https://sites.google.com/view/casestudyheraklion.

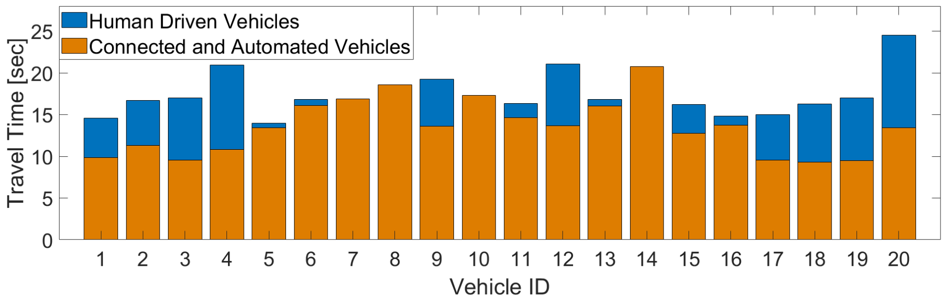


Figure 2 – *Vehicle Crossing Times*

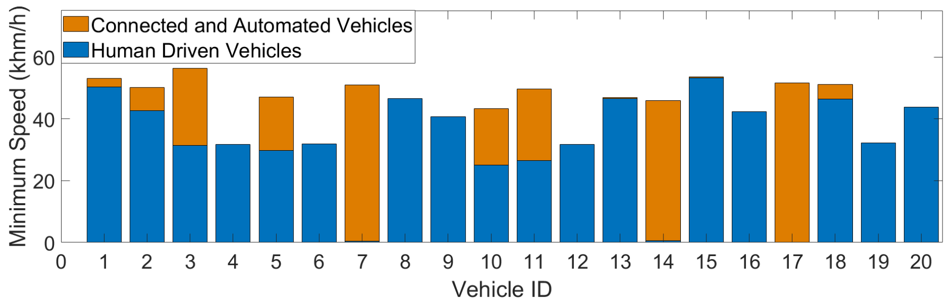


Figure 3 – *Vehicle Minimum Speeds*

4 Conclusion

We explored a controller framework presented in Tzortzoglou *et al.* (2024) and applied it to a signal-free intersection in Heraklion, Crete, Greece. We conducted simulation experiments using PTV Vissim software considering two cases. In the first case, we consider only HDVs, while in the second case, we consider only 100% penetration of CAVs. The results showcased a significant improvement in travel time when we have 100% penetration of CAVs while absorbing stop and go events, improving fuel efficiency.

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