Car-following constraints to link multiple independent intersection managers

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1 Introduction

Automated Intersection Management (AIM) techniques have been proposed to replace traffic light signals at intersections for Connected Automated Vehicles (CAV) in numerous studies reviewed in [1]. Approaches can be divided into different heuristics and those based on optimization. An early heuristic put forward by Dresner and Stone [2] required each vehicle to submit a motion plan across the intersection a which could either be accepted or rejected. This improved capacity in some traffic situations and is suitable for real time operation with many vehicles but in certain traffic could produce worse throughput than traffic signals. Others have suggested extending distributed controllers for longitudinal platooning with virtual vehicles [3].

A recent review reveals that most AIM designs have been modelled in isolation [4]. This means the optimal methods do not consider departing traffic, which may need to slow for the next intersection. This may be important in urban roads and also indoor material handling sites, where the intersections are quite close together. A two-layer control scheme gives the zone around each intersection a fixed capacity determined by experiment [5]. The capacity is used in the routing algorithm to prevent queue spillback becoming important. In this scheme routes across the intersection are reserved for one vehicle, so another will not follow in the same lane until it is clear. This reservation system is common in industrial automation controls but may lead to lower capacity than car-following.

Another study looking at multiple intersections, in this case for on-road Connected Autonomous Vehicles (CAV) is [6]. Here a scheduling top layer finds the right speeds to avoid crossing collisions, while a longitudinal Model Predictive Control (MPC) layer minimizes the speed tracking error at the entry to each segment. Nearby intersections exchange Intersection-to-intersection (I2I) messages to assist traffic distribution. Another approach using a similar hierarchy and Model Predictive Control for the lower layer but optimising the scheduling for minimum travel time as a mixed integer linear program (MILP) is given by [7]. The scheduling layer was modified to minimize energy consumption in [8].

The potential of forward guidance approaching intersections has been studied for human operated vehicles where it can lead to significant fuel economy improvements [9].

2 Aim

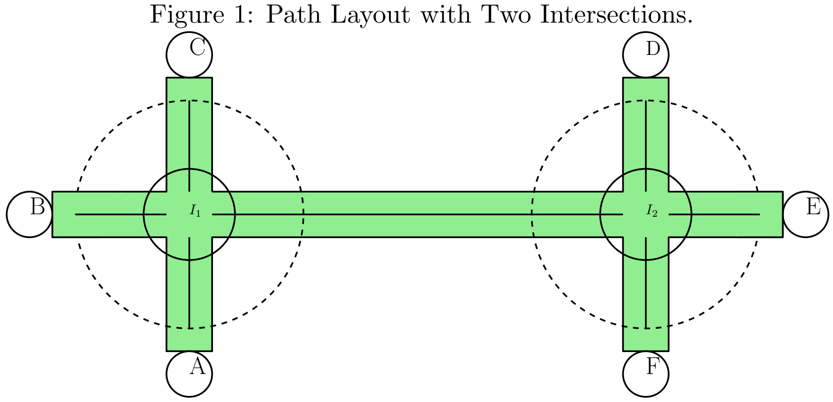
To evaluate Multiple independent intersection managers as a decentralized fleet control approach on a selection of site maps from literature. The selected criteria are site-wide task completion rate, energy consumption and execution time on each agent. Guaranteed safety in the face of communications dropout, isolated mobile robot failure and path obstruction is also considered as is the potential for deadlocks and livelocks.

3 Hypothesis

The coupled AIM approach is expected to achieve a higher task completion rate on every site than earlier approaches based on roadmap reservations. The energy consumption should also be lower due to a reduction in stop-start motion. With the caveat that car-park areas lacking fixed lane directions are unlikely to benefit and may need to be treated by a different motion-coordination scheme.

4 Method

Figure 1: Path Layout with Two Intersections.



The first test takes place on the synthetic path layout shown in Figure 1. This comprises six location nodes labelled A-F which a mobile robot may need to visit. This could represent a small pick-pack-and-ship warehouse, where nodes A-C are in the picking aisles and nodes D-F are packing stations where customer orders are assembled.

4.1 Assumptions

- All the lanes have a fixed direction.
- Mobile robots follow the centre line of these lanes exactly.
- Every mobile robots begin at a unique node.
- Every mobile robot ends at a unique destination node.
- Mobile robots only communicate with intersection managers according to the specified interface.
- Mobile robots reach their issued time critical waypoints.
- The lanes are only used by robots, there are no mechanical faults and there are no unexpected obstacles.

5 Car Following Constraints

The constraints should be enforced at every sample point with an associated free variable. They ensure the front bumper (control point $s_F + L_B/2$) of the follower vehicle arrives at each sample point τ_h seconds later than the rear bumper of the leader (control point s_L - $L_B/2$).

Considering only the first point on arrival at the conflict s_{AB} the constraint can be written as follows:

$$\begin{bmatrix} s^F_{AB} - L_B/2 & 0 & -s^L_{AB} - L_B/2 & 0 \end{bmatrix} \begin{bmatrix} \phi^F_{AB} \\ \phi^F_{BC} \\ \phi^L_{AB} \\ \phi^F_{BC} \end{bmatrix} > \tau_h \tag{1}$$

Once the instructions are committed to the leader, so it is no longer controllable but will arrive at time T_L Equation 1 can be rewritten

$$\begin{bmatrix} s^F_{AB} - L_B/2 & 0 \end{bmatrix} \begin{bmatrix} \phi^F_{AB} \\ \phi^F_{BC} \end{bmatrix} > T_L + \tau_h \tag{2}$$

As implemented the constraints are rarely active because the cross collision constraint ensures the conflict zone must be clear before another can enter. With a conflict zone of at least 5 metres this tends to be more conservative.

6 Crossing Constraints

To guarantee collisions will be avoided in the case of a fault in one AGV, it is useful to explicitly separate the crossing and following constraints.

Consider a fault limited to one AGV. It stops communicating with the rest of the system. Furthermore it may stop moving or exhibit some undesirable motion. This type of fault may be mechanical due to wear and tear, or environmental due to an obstacle dropped into a path, blocking it. In itself this occurrence causes some downtime and possibly material damage. If people are nearby they could be injured. In order to avoid the site control system amplifying the damage, following vehicles must have sufficient headway time to reduce their speed to avoid another collision. One way to ensure this is to reserve geometric segments much larger than the vehicle body.

The constraints above are point-based rather than area-based. At a certain distance along the path, the vehicle must arrive at a set time. This offers greater fidelity as the safety margin for vehicles travelling in the same direction at similar speed can be reduced compared to that for crossing vehicles.

The fail safe distance L for a vehicle to approach the conflict zone is discussed in [6]. Many AIM papers assume $L \to 0$ so the approaching vehicle $R1$ enters the conflict zone at the exact moment $R0$ leaves the zone. With real hardware this is not fail-safe, as $R0$ may fail to meet it intended departure time, perhaps due to a hardware fault. It is desirable for AIM to be fail-safe so that an isolated fault will not propagate throughout the fleet.

A fail-safe speed profile allows $R1$ enough time to come to a complete stop before entering the conflict zone. This can be expressed as the position $p_1(t)$ relative to the start of the conflict D in terms of the reaction time $d\tau$, the braking distance du and the space occupied by the robot and conflict zone dz equation 3.

$$D - p_1(t) \geq d\tau - du + dz \tag{3}$$

Or in terms of the speed profile of $R1$, Equation 4.

$$D - p_1(t) \geq v_1(t)\tau - \frac{v_1(t)^2}{2\underline{u}_1} + I_c + I_1 + s_1 \text{ with } t \in [t_{0,enter}, t_{0,exit}] \tag{4}$$

Assuming maximum deceleration and worst case maximum speed, the time headway for a complete stop $\tau = v_{max}/a_{max}$. For the AGV model parameters introduced in chapter 3, this gives τ =2.0s.

References

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