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. Reservation based control improved capacity in some traffic situations and is suitable for real time operation with many vehicles. However, certain traffic scenarios could suffer reduced throughput compared to appropriately prioritised traffic signals [**?**]. In the same paper on-ramp merging as modelled in SUMO merging led to lower delay than FCFS in a highway scenario. One way this could be addressed is by the use of pressure based policies [**?**]. 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 (upper) 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]. This is a result of the combination of vehicles travelling at lower speeds (reducing air resistance) and avoidance of the sharp acceleration after giving way at many junctions.

Another approach from Tettamanti et al combines Autonomous Intersection Management with network wide traffic control [10]. A macroscopic fundamental diagram (MFD) relating traffic density on a link to the average speed is approximated with a second order by repeated runs of the Krauss car-following microsimulation model used in the intersection layer. This differs from the MFD used in [6] which was a piecewise linear modified Greenshields model. In [11], a piecewise linear model is used for motorway traffic, this time a Godunov-discretized LWR (Lighthill and Whitham, 1955) model. Autonomous Intersection Management V2I comms and seems likely to substantially alter the relationship between density and speed, so estimating the link capacity and speed response by repeated runs of the intersection controls might be necessary to ensure the upper layer can make the appropriate routing decisions.

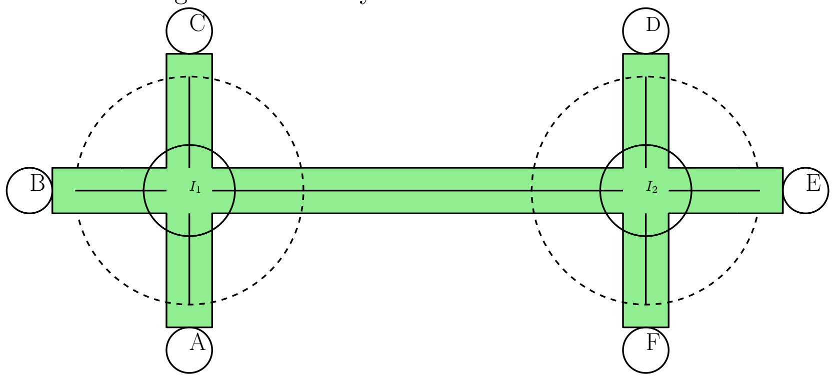
2 Aim

The use of coupled AIM at every intersection to resolve motion conflicts in a locally optimal way by speed adjustment may lead to significantly different link performance that other control systems or human drivers. In this study the aim is to characterise the link performance in a roadmap network of a size where downstream effects of control is one intersection affect its neighbour. The macroscopic fundamental diagram will be estimated for each link based on a multi-agent simulation and compared with the classical linear model for human drivers and a piecewise linear model proposed to capture automated vehicle behaviour.

3 Hypothesis

The piecewise linear fundamental diagram is expected to be more accurate at capturing the dynamics of automated vehicles, with the correct parameters. There is no 'speed choice' behaviour for the automated vehicles in the simulation, they all travel at full speed unless their exit is blocked. It may be possible to model the speed on a lane by considering traffic on conflicting lanes at the same intersection.

Figure 1: Path Layout with Two Intersections.



4 Method

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.
- A new mobile robot appears at an arrival node only when there is S metres clear in that lane.
- Mobile robots only communicate with intersection managers according to the specified interface.
- Mobile robots reach their issued time critical waypoints within some tolerance ϵ.
- 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:

$$\left[\begin{array}{cccc} s^F_{AB} - L_B/2 & 0 & -s^L_{AB} - L_B/2 & 0 \end{array}\right] \left[\begin{array}{c} \phi^F_{AB} \\ \phi^F_{BC} \\ \phi^L_{AB} \\ \phi^F_{BC} \end{array}\right] > \tau_h \tag{1}$$

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

$$\left[\begin{array}{cc} s^F_{AB} - L_B/2 & 0 \end{array}\right] \left[\begin{array}{c} \phi^F_{AB} \\ \phi^F_{BC} \end{array}\right] > T_L + \tau_h \tag{2}$$

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.

7 Numerical Experiment

A simulation of 14 vehicles was performed on the two intersection layout shown in Figure 1.

The longitudinal position s of every AGV in the coordinatate from defined by its own route over time is shown in the left panel of Figure 2. The corresponding position traces in cartesian coordinates are shown in the right panel.

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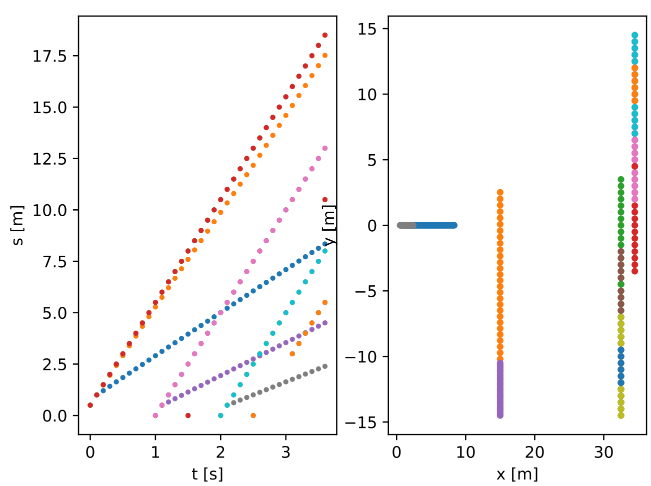
Figure 2: Distance s in path coordinates and X-Y position Trace for all AGV in test



The speed-occupancy plots produced are shown in Figure 3-6. The first two showing move $s1$ and move $s2$ can be discounted as there were never more than one vehicle on either lane (surpisingly *check this*). The second two show identical performance on moves $s3$ and $s4$ for one to four occupants: All are able to proceed at full speed. (**This is definitely inconsistent with Figure 2, which shows a range of speeds).

Figure 3: s1

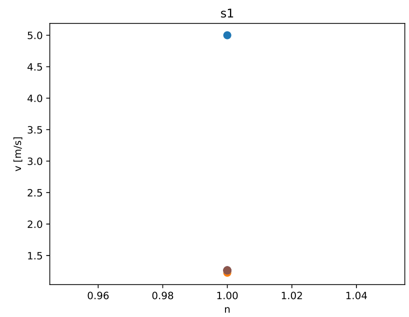


Figure 4: s2

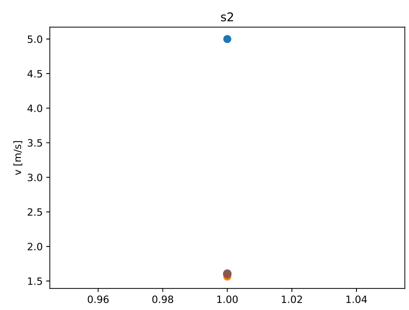


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Figure 5: s3

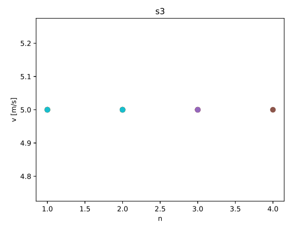
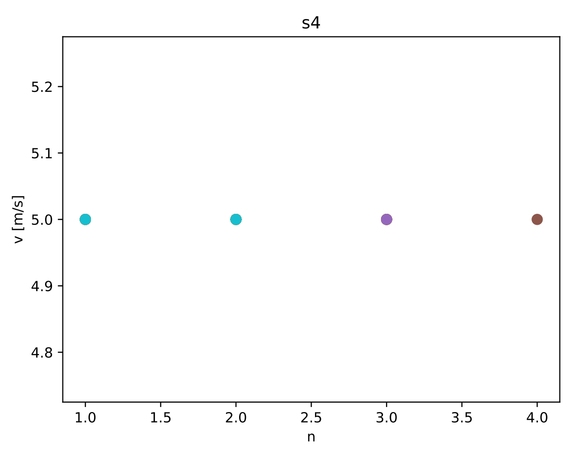


Figure 6: s4



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