A HYBRID TRAFFIC RESPONSIVE INTERSECTION CONTROL ALGORITHM USING GLOBAL POSITIONING SYSTEM AND INDUCTIVE LOOP DATA

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ABSTRACT

This paper compares the performance of a traffic responsive intersection controller which combines vehicle Global Positioning System (GPS) data and inductive loop information, to fixed-time, inductive loop, and GPS based controllers. The INRIX Global Traffic Scorecard reports that vehicles spent up to 42% of their travel time in congested traffic in 2016. Inefficient signal timing choices by isolated intersection controllers contribute to traffic delays, causing severe negative impacts on the economy and environment. Signal timings can be improved using vehicles' GPS information combined with vehicle flow information from inductive loops to overcome the control action deficit at isolated intersections. This proposed new signal control algorithm is beneficial for traffic engineers and governmental agencies, as optimised traffic flow can reduce fuel consumption and emissions.

The proposed traffic responsive Hybrid Vehicle Actuation (HVA) algorithm uses position and heading data from vehicle status broadcasts, and inferred velocity information to determine vehicle queue lengths and detect vehicles passing through the intersection to actuate intersection signal timings. When vehicle broadcast data are unavailable, HVA uses inductive loop data. Microscopic simulations comparing HVA to fixed-time control, inductive Loop Based Vehicle Actuation (Loop-VA) and GPS Based Vehicle Actuation (GPS-VA) on four urban road networks were carried out to see how the proposed HVA algorithm performs compared to existing control strategies. The results show that HVA is an effective alternative to traditional intersection control strategies, offering delay reductions of up to 32% over Loop-VA, for networks with $0-100\%$ connected vehicle presence.

Keywords: Intelligent Transportation Systems, Traffic Control, Connected Vehicles

INTRODUCTION

Traffic delays are a significant problem in developed vehicle markets. In the UK, Germany, and US alone, traffic congestion cost their economies a combined $450 billion in lost time and wasted energy (*1*). Traffic congestion can be mitigated through responsive control of signalised intersections. From simple control schemes such as fixed-time (e.g. TRANSYT (*2*)) or vehicle actuation, to more sophisticated adaptive control schemes such as SCOOT (*3*) and MOVA (*4*), signalised intersection control is important for managing the network demand (*5*).

Intelligent Transport Systems (ITS) are the integration and application of communication systems, data driven control strategies, and large-scale information processing to transport systems. Many of the hypothesised traffic control schemes for ITS assume ideal communication between vehicles and infrastructure, or require the dominant presence of connected and/or autonomous vehicles in the network (*6–8*).

Connected and Autonomous Vehicles (CAVs) are predicted to be introduced from 2020 onward and it will take time for the vehicle fleet to turnover (*9*). Therefore, there is a need for strategies that can modify existing infrastructure and support the transport network as it becomes increasingly connected and/or automated. CAV centric control schemes will be needed eventually. However, as vehicles are incrementally modernised, it is important that traffic control strategies adapt according to the vehicle fleet composition, and fairly consider multiple types of vehicles.

This paper focuses on control strategies for connected vehicles (CVs). CVs are those which transmit and receive information from vehicles and infrastructure equipped with communication systems. Multi-modal traffic flow has been shown to have negative effects on traffic flow stability in (*10, 11*). As a result, this paper investigates networks with CV levels from $0-100\%$.

This paper proposes a traffic responsive Hybrid Vehicle Actuation (HVA) algorithm to reduce traffic delays at isolated intersections. The contributions of this paper are as follows:

- Vehicle Global Positioning System (GPS) data and inductive loop information are combined and used to actuate signal timings at isolated intersections.
- Traffic delays for networks with $0-100\%$ connected vehicle presence are calculated for the proposed HVA algorithm, and compared against the traffic delay times for two conventional traffic control algorithms (fixed-time control, inductive Loop Based Vehicle Actuation (Loop-VA)) on four urban road networks (Simple T-Junction, Twin T-Junction, Corridor, Manhattan grid).
- The HVA traffic delay times are also compared to a GPS Based Vehicle Actuation (GPS-VA) algorithm on the four urban road networks.

The proposed HVA algorithm uses position and heading data from vehicle status broadcasts, and inferred velocity information to actuate signal timings. These are adjusted by predicting vehicle queue lengths in stopped lanes, and detecting vehicles passing through the junction on lanes in their green cycle. When information vehicle status broadcasts is sparse, data from inductive loops are used to actuate the signal timings. The data are transferred from the vehicles to the intersections using the IEEE 802.11p communication protocol (*12*), and the European Telecommunications Standards Institute (ETSI) Cooperative Awareness Message (CAM) framework (*13*) in order to ensure interoperability among CV implementations.

This paper is organised as follows: The first section discusses the background literature regarding existing intersection control strategies. Then, the fixed-time, Loop-VA, GPS-VA, and HVA intersection control algorithms are defined. Next, the simulation procedure used to compare the algorithm to existing methods is outlined, and the simulation results are presented and discussed.

Finally, conclusions are drawn and avenues for further research are discussed.

BACKGROUND

An abundance of signal control strategies have been developed with the intent of improving traffic flow and reducing delays at signalised intersections. Table 1 outlines a selection of control strategies commonly used in urban environments under the three key classes of intersection controller. Namely isolated, coordinated fixed-time, and coordinated traffic-responsive control. For each class of controller, the operation of the control strategy is summarised, and references to the key literature for the strategy are given. Table 1 builds upon the review of traffic control strategies by (*5*), and is followed by a review of ITS control strategies. The common distinctions of signal control strategies are:

- The strategy controls an intersection, or network of intersections.
- An intersection comprises several approaches, each of which contain one or more lanes.
- Each lane has an associated queue and vehicle flow.
- Measurement of the vehicle flow typically occurs locally via inductive loops, or video systems.
- A phase is an indication of movement priority on a particular lane (i.e. green to go, or red to stop for example).
- A stage defines a set of non-conflicting phases.

Additionally, there are four key terms needed to understand intersection control:

- *Isolated control* - The intersections in the network are controlled independently. This can be useful for small or sparsely distributed networks.
- *Coordinated control* - Coordinated strategies control multiple junctions. The idea is to create *'green waves'* so that traffic lights go green along several routes in the same direction to maximise vehicle throughput along a particular road section.
- *Fixed-time control* - Fixed-time strategies use pre-determined stages and timings that can be equally or proportionally split between routes, or based on calculations done off-line using historical vehicle data. The timings may vary according to time of day (during rush hours for example).
- *Traffic-responsive control* - Strategies of this class control multiple junctions, performing on-line optimisation of signal timings and stage configurations based on network demand using real-time traffic data.

Intersection control is a widely studied area. The current developments in the area of connected and/or autonomous vehicles and ITS technologies offer a renewed opportunity to improve on the prevalent control strategies discussed previously, and even develop new strategies that harness ITS data streams.

Table 2 compiles references to notable ITS intersection control strategies, some of which are discussed in detail in (*14*), and it summarises how the proposed control strategy works and harnesses the ITS data stream. It can be seen that communication is a key feature of all of the strategies and that shared information facilitates the development of strategies that do not rely solely on loop data.

It can be seen that the prevalent strategies do not harness the ITS data stream at all, and it remains to be investigated whether this information is beneficial for traffic control. Furthermore, the ITS based strategies typically rely on idealised communications and high penetrations of CAVs, not considering the challenges of multi-modal fleets. Their reliance on communication

TABLE 1: Summary of key urban traffic control strategies.

Controller Class	Control Strategy	Strategy Information	References
Isolated Intersection	Fixed-Time	• Cycles through pre-determined stage times • Inflexible to varying demand • Examples include SIGSET and SIGCAP	(*15*, *16*)
	Traffic-Responsive	• Uses real-time inductive loop data to actuate stage times • Most notably, Miller's strategy implemented as part of MOVA	(*4*, *17*, *18*)
Coordinated Fixed-Time	MAXBAND/ MULTIBAND	• Selects signals from a set of possible signals such as to maximise the number of vehicles that can pass through the intersection without stopping • Chooses the signal and stage time to maximise the system bandwidth	(*19*–*21*)
	TRANSYT/ TRANSYT-7F	• Calculates a performance index based primarily on delays and stops • Optimises the signal timings to minimise the performance index based on historical inductive loop data.	(*2*, *22*)
	PASSER IV	• Aims to optimise progression band with for multi-arterial road traffic • Optimizes cycle lengths, offsets, and phase sequencing.	(*23*)
Coordinated Traffic-Responsive	SCOOT/SCATS	• Uses real-time data to optimise traffic flow between multiple intersections	(*3*, *24*)
	Model-Based Optimisation	• Uses real-time traffic data to dynamically optimise the switching values for the next few stage times • Examples include OPAC, PRODYN, CRONOS, RHODES	(*25*–*28*)
	Store-and-Forward	• Describes traffic flow without discrete variables allowing for more efficient optimisation routines to be used • Implemented in the TUC traffic controller	(*29*–*32*)
	REALBAND	• Identifies and predicts the movement of vehicle platoons through the transport network • Signals times are allocated to the predicted platoons based on the optimisation of a performance criterion	(*33*)
	ALLONS-D	• Real-time decentralised traffic-responsive delay minimiser with implicit coordination • Can generate non-cyclic paths. Allows arbitrary phase sequencing/splits within the constraints of a minimum and maximum green time.	(*34*)

TABLE 2: Summary of key ITS traffic control strategies.

Key Literature	Control Strategy Information
(*6, 35*)	• Traffic-responsive decentralized isolated intersection control strategy • Determines vehicle queue length using GPS data from vehicles • Sets green time based on the time to clear the queue or for the queue to reach a target speed
(*7, 36*)	• Traffic-responsive isolated centralized strategy • Vehicles make reservations with a central server that directs them through the intersection • Vehicles are directed on a first-come-first-served basis • Does not require traffic lights in a fully autonomous system, traffic lights are only used to direct human drivers
(*8*)	• Uses V2V communication to relay signal phase and timing (SPaT) information to vehicles • Connected vehicles with sufficient automation adjusts their velocity so as to still be in motion when the traffic light turns green
(*37, 38*)	• The authors present Platoon-based Arterial Multi-modal Signal Control with Online Data (PAMSCOD) • An intersection manager receives travel mode, position, speed, and desired phase information from the vehicle • The requests are then optimised to determine the next phase and timings
(*39*)	• Uses vehicle speed and position data to optimise the phase every 5 seconds • The optimisation procedure attempts to reduce the queue length over 20 forecasted seconds • Provisions priority access strategies for special vehicles or traffic streams
(*40*)	• The authors present the IntelliGreen Algorithm • Uses k-means clustering to determine when the phase should change (k=2, enumerated red/green) • Vehicles are grouped into clusters based on their time-to-intersection (based on received speed, position data) • Green time is set based on the largest time-to-intersection of all the vehicles in the green cluster
(*41*)	• A traffic responsive method that uses cumulative travel time (CTT) data from connected vehicles • CTT accumulated from when vehicles begin their approach to the intersection • Sets the signal phase and green time based on the phase with the highest total CTT
(*42*)	• A connected vehicle intersection coordination scheme is proposed that requires 100% connected vehicles • Vehicles may proceed through the intersection without stopping by determining safe gaps between itself and the other vehicles
(*43*)	• Proposes an algorithm requiring minimal driver assistance that results in self-organised, decentralised traffic flow. • Vehicles synchronise their approaches so as to pass through the intersection without collision

systems leaves them ill-prepared to deal with mixed human driver-CAV fleets, and their robustness to communication errors unknown.

INTERSECTION CONTROL STRATEGIES

In this section, the four developed intersection control schemes are described. First, some terminology is introduced and the algorithms for the fixed-time and Loop-VA benchmark intersection controllers are presented. An algorithm which uses GPS data to perform vehicle actuation is then proposed. Finally, an algorithm that incorporates elements from both the loop based and GPS based control is developed.

Traffic stages are defined as the traffic lights configuration at an intersection. Table 3 defines the possible phases a traffic light can have and their meanings. Here, a stage comprises the set of traffic phases that give priority green to a single side of an intersection. The side of the junction showing priority green will be referred to as the 'active side', the others are considered 'inactive'. Inactive lanes display permissive green on routes that are not in conflict with any priority green streams, and red on streams that conflict with priority stream(s). Pedestrians are not considered in this study so the stages only account for vehicle movements.

TABLE 3: Traffic light phase definitions.

Phase	Description
Red	Vehicles must stop
Yellow	Vehicles stop if it is safe to do so
Permissive Green	Vehicles proceed if the road is unoccupied by vehicles in a priority green stream
Priority Green	Vehicles proceed if it is safe to do so

All of the algorithms presented in this paper make control decisions every 1 s. Where CVs send data, the data are sent at a rate of 10 Hz based on the ETSI CAM (*13*) specification. Messages are sent over an IEEE 802.11p (*12*) Dedicated Short-Range Communication (DSRC) channel. Research on IEEE 802.11p networks shows that signal strength within a 250 m range is high enough that messages can be received correctly (*44, 45*), and that packet latencies of approximately 50 ms are achievable at vehicles speeds up to 90 km/h (*44*). In this paper CAMs are received by the intersection controller with ideal information content, but with a delay of 100 ms.

Fixed-time Control

In a fixed-time control algorithm, each side of the intersection is set active for a predetermined amount of time, and the controller cycles through the stages sequentially. Algorithm 1 is the pseudocode description of a fixed-time control process. Fixed-time control is relatively simple to implement but is not inherently adaptive or responsive, and cannot be optimised beyond calibrating the timings using historic traffic flow data.

Loop Based Vehicle Actuation

Loop-VA uses inductive loops (*46*) to detect traffic and responsively adjust stage durations according to the traffic demand detected at the intersection.

ALGORITHM 1: Fixed-Time Control Algorithm Pseudocode

```
begin Fixed-time control
    if elapsedTime < stageDuration then
        elapsedTime ← elapsedTime + timeStep
    else
        DO: change to next traffic stage
        elapsedTime ← 0
```

ALGORITHM 2: Loop-VA Algorithm Pseudocode

```
begin Vehicle Actuation
    DO: get flow data from inductive loops
    flow ← activeLaneFlow
    if flow > flowThreshold then
        stageExtendTime ← defaultExtendTime
    else
        stageExtendTime ← 0
    stageDuration ← max(stageDuration + stageExtendTime, minGreenTime)
    stageDuration ← min(stageDuration, maxGreenTime)
    if elapsedTime < stageDuration then
        elapsedTime ← elapsedTime + timeStep
    else
        DO: change to next traffic stage
        elapsedTime ← 0
        stageDuration ← 0
```

In this paper, a fully-actuated intersection control strategy is implemented under Federal Highways Administration Signal Timing Manual (STM) (*47*) guidelines for Loop-VA. Loop-VA systems can skip stages if they do not detect vehicles in the lane(s) corresponding to those stages; however, in order to make the Loop-VA scheme comparable to the GPS-VA scheme, a minimum green time is defined. The STM specifies that the minimum green time of between $7-16\,\mathrm{s}$ for major arterial roads, and between $4-10\,\mathrm{s}$ for minor arterial roads satisfies driver expectancy and queue clearance criteria for speed limits up to $50\,\mathrm{km/h}$. As the models used in this study contain both minor and major arterial roads, the driver expectancy and queue clearing criteria for both road types is satisfied by a minimum green time of $10\,\mathrm{s}$.

Maximum green times of $40-60\,\mathrm{s}$ for major arterials, and $30-50\,\mathrm{s}$ for minor arterials, are recommended on roads with speed limits up to $50\,\mathrm{km/h}$. As major arterials take precedence, a $60\,\mathrm{s}$ maximum green time satisfies the condition for major arterials, and does not greatly exceed the maximum green time upper limit for minor arterials.

The stage green time is extended in response to vehicle flows greater than 80% of the lane's saturation flow in any priority green lane. The measured saturation flow for all lanes is $S = 2160\ veh/h$. Therefore, vehicle flows above 80% of the saturation flow can be detected if the last detection time between the detectors is less than 2 s ($0.8S/3600 = 0.48\ veh/\mathrm{s} \mapsto \sim 2\ s/veh$) and the green time can be extended if the maximum green time is not exceeded. An extend time between $0.1-2$ s is suggested by the STM based on the work of Bonneson and McCoy (*48*), so an extend time of 1 s is used in this study.

Algorithm 2 describes the Loop-VA implementation. In practice, adaptive algorithms such as SCOOT (*3*) and MOVA (*4*) are widely used to provide isolated and connected control to signalised intersections.

GPS Based Vehicle Actuation Algorithm

GPS-VA proposes the utilisation of GPS data extracted from CAMs broadcast by CVs to actuate signal timings. Inductive loop flow data are deliberately ignored so that the algorithm's performance relies solely on information from CAMs communicated over a DSRC channel.

The proposed GPS-VA algorithm (*49*) adapts and extends the work of Goodall et al. (*6*) by using the more accessible open access ETSI CAM standard rather than the closed access SAE J2735 standard. Additionally, instead of only using queuing information, GPS-VA incorporates dynamic vehicle tracking to actuate the stage timings.

Algorithm 3, which describes the GPS-VA implementation, can be understood in two parts, vehicle data acquisition, and intersection control.

Vehicle data acquisition

Vehicle data acquisition determines which CAMs originate from vehicles in the junction's control region, determining the queue length on routes that are not inactive, and the locations and velocities of the vehicles on the active lane.

The junction control region is defined as the 250 m radius surrounding the junction. If another junction exists inside the control region, the boundary is cropped to 10 m less than the conflicting junction's location. The boundary reduction ensures as large a control region as possible while allowing data from vehicles associated with other junctions to be ignored.

The junction controller receives CAMs from all vehicles inside its control region, ignoring those that are not. The CAMs are broadcast by vehicles at a rate of 10 Hz over a DSRC network. For these experiments, it is assumed that the junction controller receives an accurate snapshot of the network at a delay of 0.2 s.

The junction controller stores data regarding the vehicle positions and headings. The vehicles' velocities can be inferred from CAM data from previous time steps, and their lanes and approaches can be inferred from their headings. The junction controller has knowledge of its own layout/map and is able to determine the headings that correspond to an approach on each of its lanes. Vehicles in range of the junction and travelling with headings matching one of the known approaches ($\pm$ a certain tolerance to allow for GPS positioning error) are considered to be approaching the junction.

Intersection Control

Inactive lane queue lengths are determined as the distance of the furthest queuing vehicle from the intersection. A vehicle is queuing if it is travelling at less than 5% of the road speed limit (inferring that vehicles travelling so slowly are at or approaching the end of the queue). In this experiment, all vehicles are 5 m long and maintain a minimum gap of 2.5 m, therefore their effective vehicle length is $l_{\text{eff}} = 7.5$ m. In the minimum green cycle of 10 s, the vehicle flow is estimated to be

1080 veh/h corresponding to 0.3 veh/s, therefore the time to clear 1 vehicle is $3.\dot{3}\,\text{s}/veh$. As the effective vehicle length is known, the time for a vehicle to clear 1 m is $3.\dot{3}\ /7.5 \approx 0.45\,\text{s}$. The vehicle clearance time per meter is calculated over the minimum green cycle. Therefore, the time loss due to stop-and-go wave effects (*50*) resulting from finite driver reaction times is incorporated, and thus provides a slightly larger than required value. The vehicle clearance time per meter can be multiplied by the distance between the intersection and the last vehicle in the queue to get the queue clearance time.

If oncoming vehicles in the active lane are within 25 m of the intersection, the time it will take the vehicle to reach the intersection (centre point) is added to the stage duration if it will take longer than the remaining stage time to clear the intersection (up to the maximum green time). The time for a vehicle to reach the intersection is calculated as its distance from the intersection divided by its velocity if known. Otherwise, it is calculated based on its distance from the intersection times the clearance time per meter.

ALGORITHM 3: GPS-VA Algorithm Pseudocode

```
begin GPS-VA
    DO: get CAM data
    for laneID ∈ approachLaneIDs do
        if laneIsActive then
            if nearestVehicleSpeed ≠ NULL and nearestVehicleIsInRange then
                queueClearTime ← nearestVehicleDistance / nearestVehicleSpeed
            else
                queueClearTime ← nearestVehicleDistance × clearTimePerMeter
            stageDuration[laneID] ← max(queueClearTime, remainingTime)
            stageDuration[laneID] ← min(stageDuration[laneID], maxGreenTime)
        else
            if lastVehicleDistance ≠ NULL then
                queueClearTime ← lastVehicleDistance × clearTimePerMeter
                stageDuration[laneID] ← max(queueClearTime, minGreenTime)
                stageDuration[laneID] ← min(stageDuration[laneID],
                  maxGreenTime)
            else
                stageDuration[laneID] ← minGreenTime
    if elapsedTime < stageDuration[activeLaneID] then
        elapsedTime ← elapsedTime + timeStep
    else
        DO: change to next traffic stage
        elapsedTime ← 0
        stageDuration ← 0
```

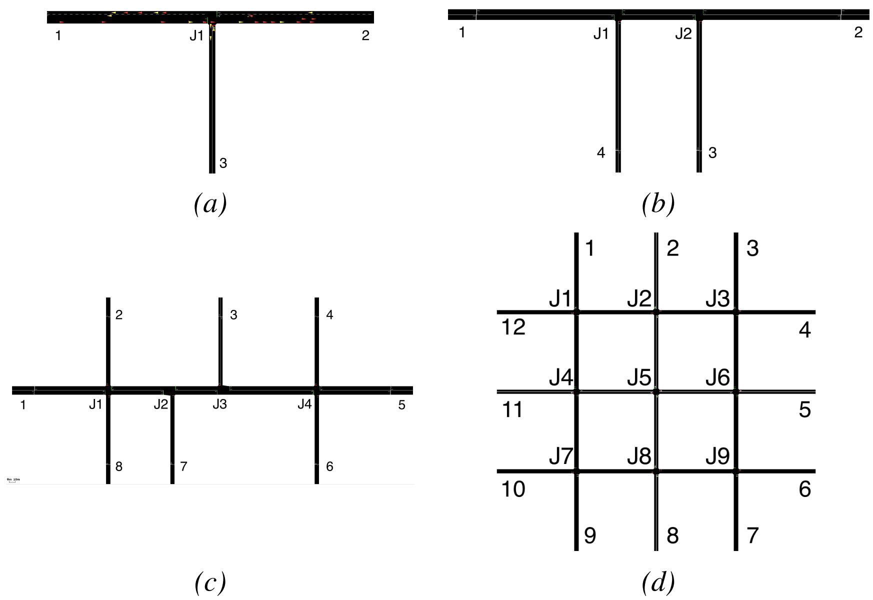

FIGURE 1: The four road topologies used in the simulations. (a) Simple T-Junction, (b) Twin T-Junction, (c) Corridor, (d) Manhattan grid.

Hybrid Vehicle Actuation Algorithm

The HVA algorithm uses dynamic real-time information from CAMs received from vehicle broadcasts as in GPS-VA, and extends the control algorithm by incorporating flow data from inductive loops for robustness when the presence of CVs is low. Algorithm 4 details the implementation of HVA. HVA uses the same queue length estimation and moving vehicle tracking mechanism as GPS-VA. However, the key improvement HVA makes over GPS-VA is that if no CVs are detected then it will try to make a stage time estimation using Loop-VA. There is also the case at low CV penetrations where CVs are present but not within the 25 m near-intersection catch area. If no CVs are detected near the intersection, the controller will also check the inductive loop data for vehicle presence, and if vehicles are detected Loop-VA is used to extend the stage time.

SIMULATION

Here, microsimulation is used to test whether intersection management can be improved using information from standardised ITS data streams. The HVA strategy is compared to the cases where intersections are managed by fixed-time, Loop-VA, and GPS-VA controllers. The HVA algorithm was tested using data from 1 (stop line) and 2 (stop line and upstream) inductive loops. The simulations are performed using the *SUMO (version 0.30.0)* microsimulation environment (*51*). The simulation is controlled using a Python API (*52–54*) that interfaces with *SUMO* and contains four intersection models (see Figure 1). All roads in the models operate at a 50 km/h speed limit, and the intersections contain inductive loops at 6 m and 18 m from each stop-line per UK Highways Agency standard MCE 0108 (*55*).

Car-following Parameters

The Krauss (*56*) microscopic car-following model was chosen as it produces stable collision-free traffic flow, and is well validated. As GPS-VA depends on information from CVs, the performance of the control strategies will depend on the penetration of CVs in the fleet. In order to model

ALGORITHM 4: HVA Algorithm Pseudocode

```
begin GPS-VA
    DO: get CAM data
    for laneID ∈ approachLaneIDs do
        if laneIsActive and detectedCVs then
            if nearestVehicleSpeed ≠ NULL and nearestVehicleIsInRange then
                queueClearTime ← nearestVehicleDistance / nearestVehicleSpeed
            else
                queueClearTime ← nearestVehicleDistance × clearTimePerMeter
            stageDuration[laneID] ← max(queueClearTime, remainingTime)
            stageDuration[laneID] ← min(stageDuration[laneID], maxGreenTime)
        else if laneIsActive and not detectedCVs then
            DO: get flow data from inductive loops
            flow ← activeLaneFlow
            if flow > flowThreshold then
                stageExtendTime ← defaultExtendTime
            else
                stageExtendTime ← 0
            stageDuration ← max(stageDuration + stageExtendTime, minGreenTime)
            stageDuration ← min(stageDuration, maxGreenTime)
        else
            if lastVehicleDistance ≠ NULL then
                queueClearTime ← lastVehicleDistance × clearTimePerMeter
                stageDuration[laneID] ← max(queueClearTime, minGreenTime)
                stageDuration[laneID] ← min(stageDuration[laneID],
                  maxGreenTime)
            else
                stageDuration[laneID] ← minGreenTime
    if elapsedTime < stageDuration[activeLaneID] then
        elapsedTime ← elapsedTime + timeStep
    else
        DO: change to next traffic stage
        elapsedTime ← 0
        stageDuration ← 0
```

increasing CV penetration, two vehicle types are defined: Unconnected vehicles which do not support ITS functionality, and CVs capable of communicating CAMs. It is assumed that CVs do not have any driving advantages over unconnected vehicles. Therefore, both vehicle types have identical car-following parameters as described in Table 4. The only difference between the vehicle types is that CVs can broadcast ITS CAMs. The parameters in Table 4 are typical of a passenger car.

TABLE 4: The Krauss car-following model parameter values for both unconnected vehicles and CVs.

Parameter (*unit*)	**Value**
Acceleration $(\mathrm{m/s^2})$	0.8
Deceleration $(\mathrm{m/s^2})$	4.5
Driver Imperfection - σ	0.5
Reaction Time - $\tau(\mathrm{s})$	1.0
Length (m)	5.0
Min. Gap (m)	2.5
Max. Speed $(\mathrm{m/s})$	25

Traffic Generation

Vehicle routes are randomly generated for each simulation run based on the probability of a vehicle travelling along a given route at rates of $\sim$1500 veh/h for approximately 3 hours. The vehicles are randomly assigned a type (unconnected or CV) based on a CV penetration ratio from 0 to 1. The CV presence in the network is incremented from 0% to 100% in steps of 10%. As the proportion of CVs and the routes are defined at random, the experiments are repeated 15 times for each CV penetration to achieve reliable mean delays and confidence intervals. All random samples are uniformly distributed, and the random number generator for the route generation process is seeded using the run number so that the results are repeatable.

Free-flow Travel Times

Free-flow travel times are the basis for delay calculations. In this study, free-flow travel time is established by setting all intersection lights to green and passing 50 cars along each route in all the models. The average free-flow travel time for each route is then established. The vehicle departures are spaced in time so that the vehicles do not interact. Additional time is added between the calculation of a subsequent route's free-flow time to allow vehicles from the previous test to clear the network.

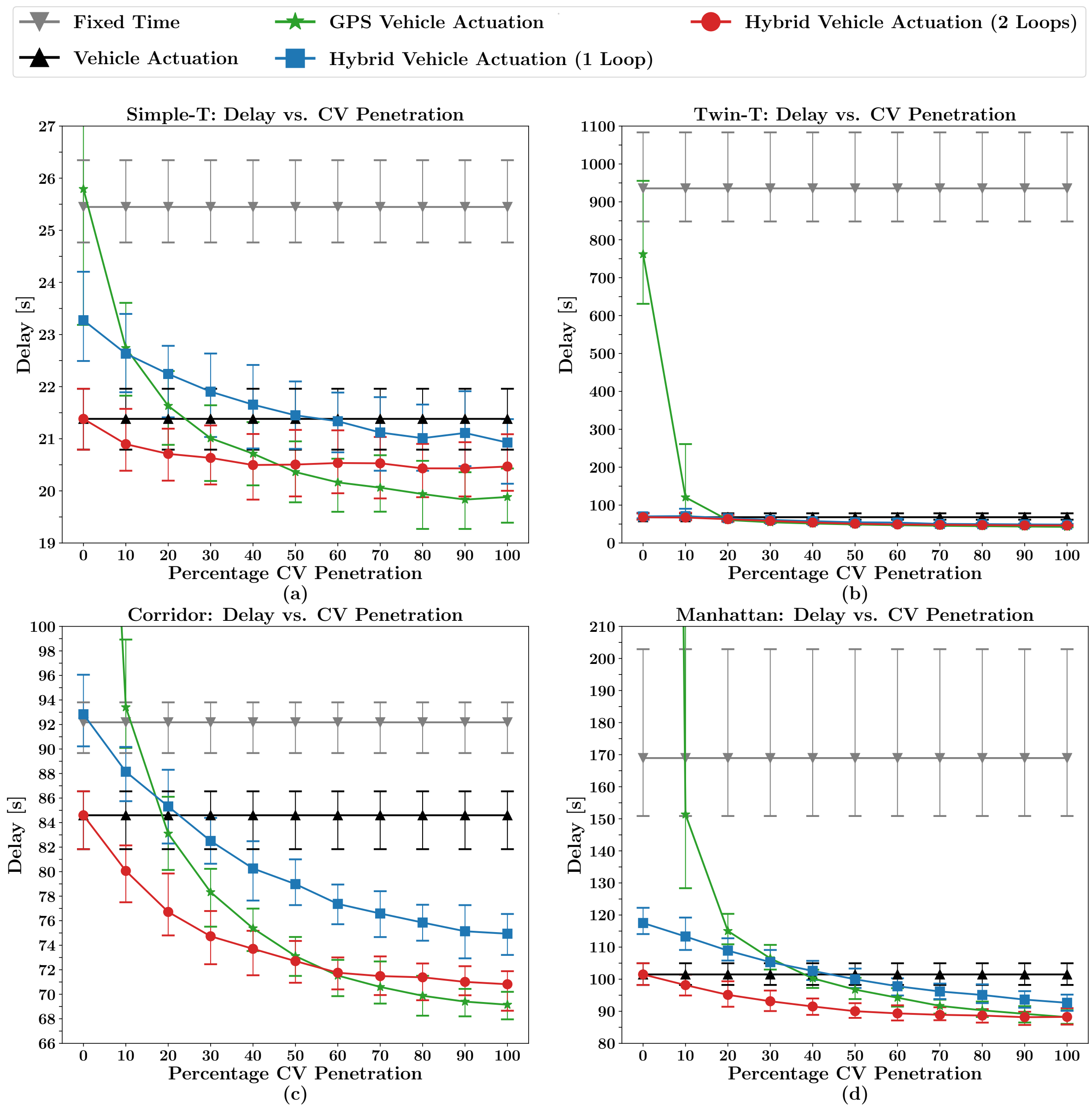

FIGURE 2: Travel-time delay for the intersection control strategies on the four urban road networks. The solid lines denote the mean delay over all the simulation runs. The error bars encapsulate the 5th and 95th percentiles of the data as an indicator of travel time variability.

RESULTS AND DISCUSSION

The proposed HVA algorithm is tested against fixed-time, Loop-VA, and GPS-VA control algorithms on four road network models at increasing levels of CV penetration. Figure 2 shows a comparison of the delay times for each intersection control strategy on each road model. Here, CV penetration is the percentage of vehicles in the network that are connected.

Travel-time delay characterises the excess time a vehicle takes to complete its journey compared to the free-flow travel time for the same journey. The simulation time T_{sim} is:

$$T_{\text{sim}} = T_{\text{out}} - T_{\text{add}} \tag{1}$$

where T_{add} is the time the vehicle is added to the simulation, and T_{out} is the time the vehicle exits the simulation. Time delay T_{Delay} can therefore be given by:

$$T_{\text{Delay}} = T_{\text{sim}} - T_{\text{freeflow}} \tag{2}$$

where T_{freeflow} is the time it takes the vehicle to make its journey on an unobstructed route. Delay time indicates the amount of time actually saved compared to the complete journey time, and highlights the performance limitations of each method.

Figure 2 shows a comparison of the delay times for each intersection control strategy on each road model. It can be seen that in all cases, the traffic responsive actuated control strategies reduce delays better than the fixed-time algorithm. GPS-VA degenerates to fixed-time with minimum green time cycles and performs poorly at low CV penetrations. However, at CV penetration rates exceeding 30%, GPS-VA reduces delay comparably to or better than the implemented Loop-VA strategy for different traffic levels. GPS-VA's poor performance at low CV penetrations is expected, as the strategy degenerates to fixed-time control with minimum green cycle stage lengths. The poor performance at low CV penetrations is a direct result of a control action deficit.

The HVA algorithm was tested with input from both 1 and 2 inductive loops. The 1 loop case partially overcomes the control action deficit present in GPS-VA but still requires CV penetrations of approx 30% or greater to improve on VA. HVA with 2 loops performs at least as well as VA in all cases and typically outperforming GPS-VA for CV penetrations between $0-50\%$. However, the performance of HVA is not as good as GPS-VA in most cases for CV penetrations between $50-100\%$. The reduced performance at high CV penetrations is a result of the detected flow at the loops triggering an extension after a CAV has crossed the stop line, unnecessarily extending the stage time. This false triggering is less prevalent in the topologies where there are more junctions, and the vehicle queues have less chance of accelerating to the speed limit. Ideally, the all of the delay trends would be similar to the Manhattan grid case. The conflict in control information suggests that future work should investigate a system that can estimate the CV penetration and determine when it is beneficial to ignore loop data. HVA should also be tested at different traffic levels to see how its performance varies with number of vehicles. The travel times for CVs and normal vehicles should also be assessed separately to ensure the algorithm is not heavily biased towards one class of road user.

The Loop-VA and fixed-time strategies do not show as large a delay difference in the corridor model as in the other three. This is due to the short road segments connecting each junction inhibiting traffic flow. A coordinated strategy is more appropriate than isolated control in this case.

CONCLUSIONS AND FUTURE WORK

This paper explores the performance of a hybrid traffic responsive intersection control algorithm using GPS and inductive loop data in comparison to traditional intersection control strategies. The HVA algorithm uses position and heading data received from CV status broadcasts to actuate intersection signal timings by determining vehicle queue lengths and detecting vehicles passing through the intersection. Where CV data is unavailable, the HVA algorithm uses data from inductive loops to perform Loop-VA.

Microscopic simulations were performed to see how the proposed HVA algorithm using 1 and 2 inductive loops performs compared to fixed-time, Loop-VA, and GPS-VA control strategies on four common urban road topologies. The results show that HVA with 2 loops is a compelling alternative to traditional intersection control strategies, showing delay reductions up to 32% on average over traditional Loop-VA. HVA also demonstrates better performance than GPS-VA at CV penetrations below 50% and in all cases for the Manhattan grid road network. By using both GPS and loop data, HVA provides an enhanced signalised intersection control afforded by ITS data streams, while remaining robust at low CV penetrations. The proposed HVA algorithm shows how traffic data sources can be used together to achieve better traffic signal control than either in isolation. HVA also demonstrates how multiple algorithms can be used and selected based on which provides the best solution for the current traffic demand. In practice, the algorithm is ideal for deployment within urban areas in the near future, as the control improves as people progressively adopt CVs. The robustness of HVA for all CV penetrations contrasts many of the current ITS based control algorithms which rely on high CV penetrations.

Algorithms that incorporate data from CVs and that consider low CV fleet penetrations are still an underdeveloped research area. Further work needs to be done to investigate which ITS data streams are the most effective for signalised intersection control, and increase the robustness of control algorithms at low CV penetrations. Work also needs to be done to establish the effects of errors on the HVA algorithm. Communication packet loss, GPS measurement noise, and disparate GPS measurement rates all must be considered if the algorithm is to be robust in real road networks and reliably provide reduced travel times to drivers.

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