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Connected e-Bicycle Platoons at Unsignalised Intersections

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***Abstract*— This paper presents a concept of an unsignalised intersection control system for connected bicycle platoons. The system is motivated by a real case study of an unsignalised intersection at Tsinghua University, in China, where bicycle jams and accidents frequently occur. The proposed system is assumed to utilise CACC and V2V to coordinate platoon formation and following distance, in order to facilitate and increase traffic filtering at the unsignalised intersection. In this paper, the proposed system is validated using SUMO by emulating four different scenarios, and improvements in bicycle traffic flow and speed, compared to the nominal scenario, are measured. It is seen that the proposed platoon-based system significantly increases intersection flow and speed by 150% and 764%, respectively, for west-bound bicycle traffic, in comparison to the nominal scenario. The simulations demonstrate that there exists opportunity in further investigating and developing connected bicycle platoon technology and unsignalised intersection control systems, to make bicycle travel more safe and appealing, and facilitate improvements to transportation options to keep cities moving.**

I. INTRODUCTION

Globally, travel restrictions due to the coronavirus disease 2019 (COVID-19) pandemic have seen people making more bicycle trips locally. Around Melbourne in Australia, for instance, a 270% increase in bicycle usage on key bike paths has been observed according to a survey from [1], with 73% of respondents planning to use a bicycle to access essential services. Bicycle sales have surged as people are pursuing sustainable and socially-distanced transportation, with a particular growing popularity in electric bicycles (or e-bikes) due to their comfort and efficiency compared to ordinary bikes. Furthermore, with smartphone integration and smart connectivity technology, e-bikes have increased in appeal to wider customer bases that wish to keep track of their health and cycling activity.

As these mobility trends continue, cities will likely see more people commuting by bicycle to avoid crowded public transport and roads congested with single-occupant vehicles. Currently, in many cities, there is not enough space to facilitate cycling, and many cyclists do not feel comfortable riding on the road among traffic. Prior to COVID-19, a cycling boom had already happened in large cities in Europe and the Americas due to the health benefits, travel flexibility and speed, especially when bicycles are not affected by traffic congestion. However, this may change in the post-pandemic recovery, as more bicycle volumes are expected according to [1]. Increased bicycle traffic will decrease infrastructures' efficiency and overflow infrastructure capacity, forcing cyclists to ride in traffic lanes, adding more conflicts to the continuous street fight with motorists [2].

Safety and traffic interruption at intersections are some of the barriers to using a bicycle, as cyclists are extremely vulnerable in mixed traffic conditions, with 43% of bicycle crashes happening at intersections and crashes being most common during peak hours [3], [4]. Furthermore, traffic interruption at intersections increases the need for cyclists to stop and accelerate, which can be physically tiring and frustrating, especially when exposed to the elements while waiting at the intersections [5]. Meanwhile, with the surging popularity of e-bikes, fitness will no longer necessarily be a barrier to enjoying cycling. E-bike technology provides an opportunity for integration with smart bicycle technology to make bicycle infrastructure smarter and connected. Not only might this improve intersection safety and efficiency through detection and inter-vehicular communication, but may make cycling more appealing for daily use and build resilience for future transport infrastructure.

In this paper, a problem observed by one of the paper's authors during his exchange to Tsinghua University in Beijing, China, is considered. On campus at Tsinghua University, bicycles have become one of the most essential modes of transportation given that the distance between student dormitories and teaching buildings has exceeded a reasonable walking distance for many students. As a result, bicycle numbers have exceeded the road capacity, and bicycle jams are frequently observed at multiple intersections and on road sections during the class transition period. Furthermore, due to a lack of proper bicycle infrastructure, students ride in mixed-traffic conditions and bike accidents have become a norm.

Vehicular platoon research is receiving much attention in the Intelligent Transportation Systems (ITS) community, as it offers the potential to reduce delays and improve operational safety through Cooperative Adaptive Cruise Control (CACC) and inter-vehicular communication (V2V). An aim of platooning is to increase traffic flow and density by reducing the headway between vehicles, and thus offers cities a solution for increasing road capacity without the need for infrastructure expansion [6], [7]. The aim of this paper is to consider an intersection at Tsinghua University as inspiration, and investigate whether a connected bicycles platoon system would offer a solution for mitigating accidents and improving traffic flow at unsignalised intersections in general

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through filtering gap adjustment. Specifically, in this paper, Simulation Urban MObility (SUMO) is utilised to evaluate connected bicycles platoon system adaptations through four different traffic scenario designs, and necessary future work is consequentially identified for making this system a reality.

The remainder of this paper is structured as follows. In Section II, a brief background on the intersection location of interest is given. This is followed by a literature review in Section III to identify the gaps in the current research and technology. The proposed system architecture is presented in Section IV. Then, the simulation scenario and parameters are presented in Section V. The results of the simulation are presented and discussed in Section VI. Finally, concluding remarks and future work is discussed and proposed in Section VII.

II. Background

Tsinghua University, located in Beijing, is a leading research university in China, with a total of 50,394 students living and studying on campus, and a land area encompassing over 395 hectares [8]. It is common for students to travel around the campus on a bicycle or e-scooter. These are considered essential modes of transportation, as the distance between the student dormitories and the teaching buildings exceed a walkable distance for many students.

In cities in China, the majority of traffic operates in mixed-traffic conditions, and there exist conflicts at unsignalised intersections due to lack of infrastructure and facilities to segregate bicycles, pedestrians and vehicles [9]. Furthermore, bicycle path planning differs to lane-based vehicles due to characteristics in size and manoeuvrability. Therefore, when crossing an intersection, cyclists behave more similar to pedestrians by modifying speed and adjusting their trajectories to avoid conflict [10]. This behaviour, discussed in [9], is called *gap acceptance behaviour*.

One of the most problematic intersections at Tsinghua University is the Zhishan-Xuetang intersection located between the student dormitories and teaching buildings. Zhishan road runs east to west, while Xuetang road runs in a north to south direction; see Fig. 1. As illustrated in Fig. 2, large volumes of bike traffic can be observed on Xuetang road during a typical 15 minute class transition period. A lack of gaps in this continuous stream of bicycles causes traffic congestion on Zhishan road (see Fig. 2a). Students running late for class will thus sometimes attempt to break through the Xuetang road bicycle stream by slowly moving across the intersection, as in Fig. 2b, and thus impede the traffic on Xuetang road, forcing other cyclists to slow down and pass around them. Accidents at the intersection occur when cyclists fail to notice a crossing bike hidden by the crowd, or upon hesitating when negotiating who has the right of way.

III. State of the Art

The following brief literature review examines current state of the art in regard to connected vehicular platooning, autonomous intersection systems, and connected electric bikes (or e-bikes).

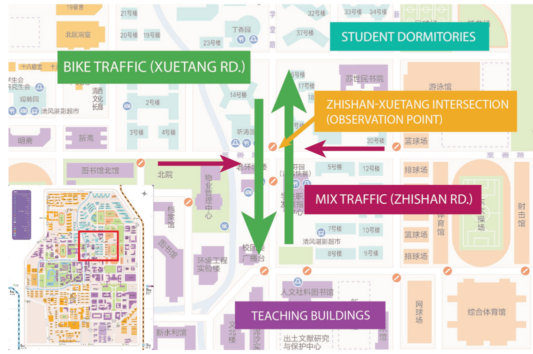


Fig. 1: Indication of the traffic direction at the Zhishan-Xuetang intersection during the class transition period at Tsinghua University, in Beijing, China.

(a) Continuous traffic on Xuetang road.

(b) Cyclists attempting to cross the intersection.

Fig. 2: Frames of a video recording of the Zhishan-Xuetang intersection (facing SW) at Tsinghua University, at 09:42, on 23 December 2019.

A. Vehicular Platooning

Automated platooning systems have been receiving increasing attention in the Intelligent Transportation Systems (ITS) world. It is envisioned that vehicular platooning will improve road capacity and ease traffic congestion, while increasing safety and comfort while driving, and reduce energy consumption and emissions [6]. Vehicular platooning utilises vehicle-to-vehicle (V2V) communication to coordinate multi-vehicle manoeuvring and establish close formations by decreasing headway time between vehicles through information exchange. A focus of the last decade has been on the development of Connected Adaptive Cruise Control (CACC) for vehicular platooning systems. CACC is enabled by V2V communication and permits the exchange of vehicle acceleration for dynamic driving scenarios to minimise speed differences among vehicles and guarantee higher safety and smaller inter-vehicular distances [11]–[13].

While developments in automated platooning systems have been robust in motorised vehicles [14], there is currently a lack of extensive connected platoon systems or CACC research for bicycles. In [7], a prototype of a connected bicycle platoon was developed. Illustrated in Fig. 3, the prototype utilised three components: a control, a communications and an interface module. The control module acquires Global Positioning System (GPS) information through an Android-based smartphone, and utilises a simple reed switch on the bicycle rim to calculate speed and acceleration. The information is passed to the communications module via an antenna covering the whole bicycle platoon. Information such as bicycle ID, latitude, longitude, speed and time is shared; in addition, follower bicycles communicate distance to the platoon leader, and acceleration data for the overall platoon CACC calculation [15]. Finally, the human-bicycle interface module utilises the information collected by the control module, and a haptic display with coloured lighting indicates to cyclists to accelerate or decelerate to keep up with the platoon speed and formation.

B. Autonomous Intersection Systems

Since its emergence, GPS technology has been used for intersection control, in traffic signal preemption for emergency vehicles, for example. Currently, emergency vehicles are fully integrated with Vehicle-to-Infrastructure (V2I) capabilities through 3G-based communication systems for tracking and detecting emergency vehicles' positions, and controlling the traffic light signals, to give the emergency vehicles green light priority along all intersections to their destinations [16]. GPS has many advantages in distributed sensing because it is inexpensive and flexible to integrate with communication modules such as mobile phones. This bolsters existing vehicle-to-everything (V2X) technology in intersection control applications for coordination of traffic at or near the intersection for smoother and fuel-efficient traffic flow [17].

Polling systems are novel to all autonomous traffic intersections [18]. The majority of intersection control addresses aspects in assigning viable time schedules or priorities to

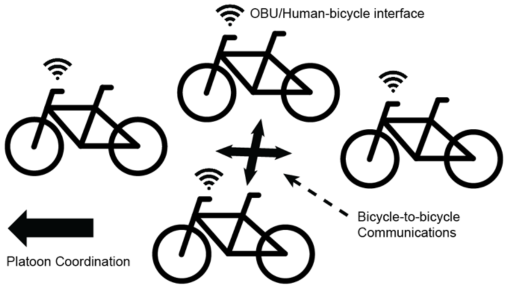


Fig. 3: A model for a coordinated smart bicycle platoon.

vehicles and designing safe vehicle trajectories for the fulfilment of intersection assignments. Much of the literature contains trajectory-focused protocols which focus on the safety of the vehicle and optimise traffic performance; however, delay, throughput and fairness are not easily available to analyse though mathematical models for intersection performance.

Traditional queuing systems provide service one-by-one to customers arriving in a single queue. Polling systems are an extension of the queueing system, consisting of a single resource or service shared by multiple queues [19]. Vehicles approach an intersection in a similar manner, where the intersection determines the schedule time of the vehicle and gives clearance by using policies such as the exhaustive policy and the k-limited policy. In the exhaustive policy, the server will service the queue until empty, while the k-limited policy will service at most k customers from one queue per visit [18].

The algorithm for autonomous intersection developed by Miculescu and Karaman [18] can be implemented in autonomous vehicles to determine the optimal crossing order of vehicles at an intersection. Vehicle sensing can be fully utilised to acquire real-time information such as vehicle acceleration, platoon length and number of vehicles in the control area. Information can also be passed along to consecutive intersections to reserve clearance for the vehicle cluster.

Similar bicycle intersection control utilised the adaptive polling system through smartphone-based software to control the traffic lights using GPS and the cellular network [20]. The software uses the cyclist's position to calculate the time to reach the intersection and determine the intersection traffic conditions using GPS nodes within a control area. The information is processed and output as a phase request at the traffic light; however, the downsides of this system are transmission speed, data privacy and power efficiency from high precision GPS [20].

Similarly, a bicycle intersection control smartphone application, called Schwung, has been developed by the city of 's-Hertogenbosch in the Netherlands. The city council hopes to reduce bicycle waiting times at intersections by requesting green signals early using smartphone GPS sensors to detect approaching cyclists. Schwung is effective when cycling within a group, as the system tries to cluster cyclists at intersections and gives green priority to bicycle clusters during the peak hours. Moreover, the software is developed to counteract the inductive loop's inability in detecting multiple cyclists [21]. This is done by using Bluetooth technology to determine the number of cyclists within its close proximity. The data collected by the software is exchanged with an Intersection Control Unit (ICU), and the 's-Hertogenbosch city council addressed privacy concerns by disassociating GPS data with the smartphone user. The data is erased as soon as the cyclist reaches to their destination [5].

C. Connected e-Bikes

Electric bicycles (also known as e-bikes) are bicycles equipped with an electric motor. E-bikes are enjoying popularity in the current market as they are generally less noisy and are more comfortable to ride given their smooth acceleration and the less physical demands required of the cyclist when riding on rough terrain. There are currently two types of e-bikes: the first is controlled by the throttle, by the user, depending on the user's intention; and the second is pedal-assisted with input from both the cyclist and the electric motor [22].

In order to keep up with a platoon, cyclists are required to accelerate at the same rate as the platoon. Using regular bikes, cyclists may struggle to keep up with the platoon due to differences in fitness levels resulting in different acceleration rates. An electric drive unit can be used to compensate for these differences in power output when accelerating, and currently there are e-bike options on the market that can provide power assistance for cyclists to accelerate faster without too much effort.

Moreover, the Internet of Things (IoT) has gained increasing attention in regard to the integration of smart devices, sensors and mobile phones for acquiring information and communicating [23]. E-bike technology can be beneficial in any connected bicycle platoon system implementation. Currently, Bosch has an onboard computing unit for the purpose of displaying speed and gear recommendation; while also offering the capability of using Bluetooth communication with a mobile phone and fitness tracking app. to display navigation, power and cadence [24]. While Bosch designed the computer to be suited for sport use, the unit has not yet been integrated with the drive unit for the purposes of speed regulation or inter-vehicular communication. Therefore, another existing gap before platoon implementation can be realised is that the power drive unit currently still requires manual gear shifting, which indicates that the drive unit is yet to be integrated with the on-board interface.

This provides an opportunity for future work towards implementing CACC and V2V communications with the on-board computer, and having the ability to control the drive unit autonomously. This means that the gear shift unit needs to integrate into automatic gear shifting to be able to regulate with the on-board computer. Having on-board computer control of the drive unit is important because CACC will be able to adjust the power output when accelerating and maintaining the speed. In fact, deceleration needs to be controlled by the computer due to the close formation of the platoon and an inconsistent deceleration will increase the chance of collision. This can be controlled by using an on-board computer to control the drive unit power output and maintain a constant speed to prevent the e-bike going over speed limits. For example, if a cyclist is producing 260 W of power but only requires 200 W to maintain the speed, the excess 60 W will be stored to the battery to maintain the speed limit.

IV. CONNECTED BICYCLE PLATOON SYSTEM ARCHITECTURE

As discussed in Section III, there currently exist gaps in the realisation and development of connected bicycle platoons and the integration of inter-vehicular communications between bicycles and intersection control. This is due to current limited connected bicycle development and the integration of CACC for speed fine adjustment. Therefore, as a first step in the direction of realising connected bicycle platooning, the subject of this paper is to simulate connected bicycle platoon traffic filtering through an unsignalised intersection assuming CACC and V2V capabilities. The simulations demonstrate whether generating acceptable gaps between continuous bicycle traffic streams will increase traffic flow. And moreover, whether generating adaptable gaps between bicycle platoons, assuming V2V and CACC through speed control, traffic conditions and intersection priority within the control region, will further improve the traffic flow and reduce conflicts at the intersection.

The proposed system flowchart illustrated in Fig. 4 utilises multiple communication methods. Within the connected e-bike system, CACC is achieved using the GPS and speed information from the drive unit. The on-board computer sends out the command to control the acceleration and deceleration speed of the bicycle. This information is broadcast wirelessly through the communication module to the platoon leader, who will share the data with other bicycles in the platoon and the Roadside Unit (RSU) or 5G cell tower at the intersection control area.

Fig. 5 illustrates the local network control area for the connected bicycle platoon. A RSU gathers the information on the platoon's approaching speed, length and location within the control area, to store on the intersection database. The platoon leader's time to reach the intersection (denoted by t_{int}), and the time of the platoon to clear the intersection (t_P), which are both unknown, can be calculated using platoon speed, distance to the intersection, and following distance between the leader and followers, all generated from GPS data. The intersection will use the polling system to determine the access priority and arrival order based on First Come First Serve (FCFS) and k-limited policy (see Section III-B) to coordinate intersection schedules to operate at high efficiency. The performance is measured by the number of delays and average traffic flow rate.

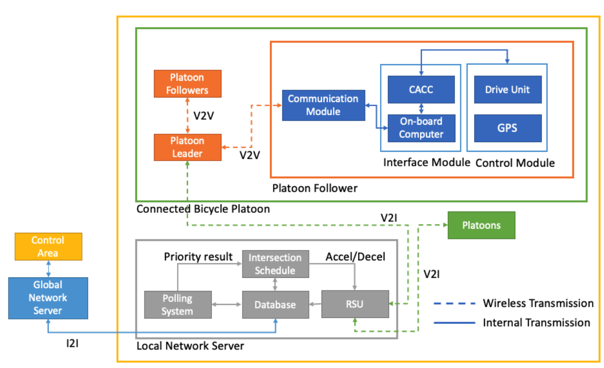


Fig. 4: Autonomous Intersection Control and Connected Bicycle Platoon System architecture flow chart.

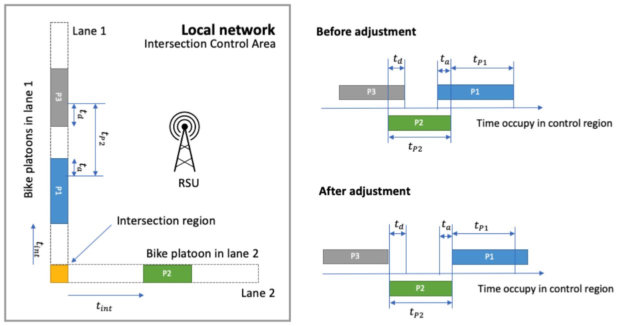


Fig. 5: Illustration of local network intersection control area (left) and speed adjustment schematic (right).

Once the order of arrival is established, the intersection will schedule a time slot based on the time the platoon will occupy the intersection region. For example, in Fig. 5, platoon P2 is determined to have conflict with P1 and P3. In order to clear the conflict, P1 and P3 need to accelerate and decelerate, respectively, in order to give P2 a sufficient gap to filter between these two platoons. The speed command is passed to the RSU to send to the platoons within the control region, and the platoon leader's drive unit output will automatically adjust based on the command. After the platoons have left the intersection region, the information will pass on to the global network, where this information can be used to coordinate other intersections in advance of the platoon arrival until the platoon reaches its destination.

V. System Simulation

In this section, the connected bicycle platoon system proposed in Section IV will be validated using Simulation of Urban MObility (SUMO). SUMO is an open-source multi-modal traffic simulation developed by the German Aerospace Centre (DLR) and community users since 2001 [25]. SUMO has evolved into a full featured suite of traffic modelling with the capability to read different source formats, routing utility, demand generation, a high-performance junction simulation, and a "remote control" interface (TraCI) to adapt the simulation online. It is worth noting that an exclusive movement model for bicycles has not been implemented in SUMO yet, and is thus still subject to development. In this paper, for simplicity, we therefore assume that the simulated system has full control of the speed and maneuvering of each e-bicycle, and therefore the only difference between simulating the connected e-bicycles in this work, and connected vehicles in general, will be the addition of sub-lanes to allow the bicycles to travel parallel to each other.

A. Simulation Scenarios

All traffic scenarios simulated will imitate a 15-minutes class transition period as described in Section II. At the real-world geographical location, the system proposed in Section IV would be operating under mixed-traffic conditions. However, in the preliminary simulations conducted for this paper, to reduce complexity, only bicycles, and two traffic streams in particular (i.e., west bound and south bound) are considered. Network performance between four different simulated scenarios, defined below, is measured by traffic flow using inductive-loop detectors on Zhishan and Xuetang roads. The four simulated scenarios are as follows.

- *Nominal traffic condition (base)*: This model will be used as the base model to simulate the baseline or nominal bicycle traffic conditions at the intersection. It is expected that the south-bound traffic stream will have limited gaps for west-bound traffic to cut through. The baseline scenario is based on the 5 minute video that the primary author took during a class transition period while he was on exchange at Tsinghua University (see Fig. 2). When creating the baseline scenario, the number of bikes in the video were counted in the south- and west-bound directions to determine the flow rates and speeds. However, in the simulation, environmental factors such as weather conditions, details of road geometry (e.g., vegetation, pavement, speed bumps), etc. were not considered, which could be the subject of future work to enhance realism.
- *Defined-gap allocation (fix-gap)*: This model will simulate south-bound bicycle traffic with a defined fixed gap to allow west-bound traffic to cut through. This model will be used to determine whether introducing gaps in continuous bicycle streams can improve west-bound traffic flow.
- *Platoon allocation (platoon)*: This model will involve the generation of bicycle platoons in the south-bound traffic by using simpla, a configurable platooning plugin for SUMO's TraCI Python client. This model will be compared to the fix-gap model to determine whether bicycle clustering (i.e., platooning) can further improve west-bound traffic flow.
- *Platoon interactive allocation (interaction)*: This model will simulate platoon interactions with the west-bound traffic. Depending on the west-bound traffic conditions, the south-bound platoons will alter their following distances to create a time gap to allow west-bound traffic to cut through, thus mimicking CACC and V2V communication. This model will be used to compare whether platoon interaction at the intersection will further improve traffic flow in both directions.

B. Simulation Assumptions

1) Traffic Conditions: Bikes will initially travel at a speed limit of 20 km/h (i.e., 5.56 m/s). To simulate the tendency of a rider to impede traffic at the intersection of interest, an impatience probability attribute of 0.45 is added to the vehicle based on the gap acceptance behaviour survey by [9], [26]. This value is derived using the impatience formula $\max(0, \min(1.0, I_b + t_w/t_{I.\max}))$, where base impatience, $I_b = 0.1$; waiting time, $t_w = 42$ s; and time to maximum impatience, $t_{I.\max} = 120$ s.

SUMO's sublane model is used to simulate bicycle riding abreast during the peak time. A lateral resolution of 0.8 m is used to allow three bikes riding abreast on a single lane

(3.2 m). An acceleration of 1.25 m/s^2 is added to the platoon vehicle attribute to mimic the Bosch drive unit specification to provide acceleration assist and speed control (see Section V-B.4 below).

2) Trip Generation: For all simulation models, it was assumed that the distribution of traffic generation passing through the intersection was 1/3 demand per second travelling south bound and 1/7 demand per second travelling west bound. Trip generation is given as the probability of a bicycle be generated for each simulation time step. There are several ways to generate traffic in SUMO: flow definition was initially used but this function spaced bicycles evenly out which is highly unrealistic. Alternatively, adding a departure position and a departure lateral position parameter to SUMO's "random" placement resolves the evenly spaced bicycle generation, but introduces an influx of saturation flow, causing a bottleneck at the intersection, thus decreasing the headway and limiting the number of bikes passing through the intersection.

Therefore, integrating trip generation with Python via TraCI was determined to give more control over traffic generation in SUMO. This was done by generating random floats between 0-1, and comparing these with the probability of the trip demand as the condition to execute the route generation function during each time step. Higher demand associates a higher chance that the function will be executed.

3) Bicycle Platoons: The platoon is generated through the simpla platoon manager using TraCI. Simpla offers four modes of platoon control: Platoon leader mode (vehicle travelling at the front of the platoon); Follower mode (vehicle travelling behind another vehicle within the platoon); Catch-up mode (vehicle in range of a platoon and able to join the platoon); and Catch-up follower mode (vehicle travelling in a platoon with a leader in catch-up mode). Bicycle platoon separation and organisation is based on common destination and/or direction of travel of each platoon. Future work is required to determine the grouping policy and route determination.

In the simpla configuration file, bikes have to be within 10 m from the following bike to be considered as a platoon (maxPlatoonGap) and 15 m catch-up distance is given for the bicycle to join the platoon in front (catchupDist). A speed factor is given to different platoon modes to ensure the follower bicycle can catch up with the platoon by modifying the speed. A leader of the platoon is assigned every 10 s in the trip generation function, and simpla will dynamically assign the platoon mode depending on the traffic condition in the simulation. Different colours are assigned to the cyclists to better distinguish between the different platoon modes being used for the platoon and interaction model. The colours are: white (unassigned), green (leader), red (follower), yellow (catchup), magenta (catchup-follower), and blue (west-bound traffic). Refer to Fig. 6b as an example.

4) Connected e-Bikes CACC: As mentioned in Section III-C, in order to utilise the full potential of CACC for a better speed and acceleration control, similar e-bike systems to the Bosch e-bike will be used for the platoon and interaction simulation model. There is a difference in maximum acceleration between e-bikes and ordinary unassisted bicycles. To distinguish the acceleration effect between models, the maximum acceleration for e-bikes within the platoon will be set to 1.25 m/s^2. This acceleration is calculated using the technical specification of the Bosch Active Line Plus drive unit in Turbo mode where it can generate 50 Nm torque with 250% support level. This data was acquired from the Bosch e-bike system website [24] and from Moustache bikes [27] (see Table I).

TABLE I: Specification Data of Moustache Urban Friday 28.5 e-Bike

Urban Friday 28.5 e-Bike	**Value**
Total Weight[3] (kg)	100
Wheel Size (cm)	40
Torque (Nm)	50
Force (N)	125
Acceleration (ms^{-2})	1.25

VI. SIMULATION RESULTS

The four models proposed in Section V-A are generated in SUMO using the assumptions from Section V-B. Traffic data of the average flow (veh/h), $\bar{q}$; average speed (km/h), $\bar{v}$; and percentage change (Δ) compared with the base model, are presented in Table II as mean values over the five minute simulation run times.

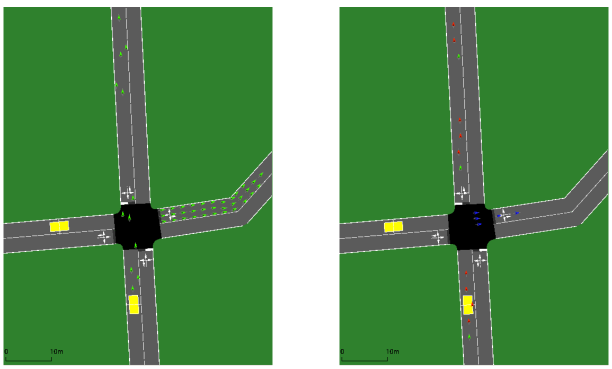
In the base model, the west-bound traffic flow was affected by the continuous stream of bicycle traffic travelling south bound, with insufficient gaps for cyclists to filter through. Traffic jam was observed on the east side of the intersection (see Fig. 6a), and cyclists were attempting to cross the intersection by interrupting the south-bound traffic as they reached the maximum patience time. This model resembled the real-life traffic condition at the Zhishan-Xuetang intersection described in Section II, and thus will be used as the base model to compare the other scenarios to.

In the fix-gap model, there was an increase in traffic flow and speed in the west-bound traffic as more frequent and sufficient gaps were provided for cyclists to filter in between the south-bound traffic streams. Compared with the base model, a 73% increase in west-bound traffic flow was observed after fixed 10 s time gaps were introduced in the south-bound traffic. However, south-bound traffic flow decreased 26% because a reduced number of bikes were being generated over the five minute simulation run time. Nonetheless, it provided sufficient gaps for west-bound cyclists to react, accelerate and filter through the traffic. The fix-gap model confirms the hypothesis of introducing frequent gaps to increase west-bound traffic flow at the intersection.

[3] Assume 20 kg bike weight plus 80 kg rider weight.
[4] Mean traffic flow (veh/h) over five minute simulation timestep.
[5] Mean traffic speed (km/h) over five minute simulation timestep.

TABLE II: West-Bound and South-Bound Inductive-Loop Simulation Results

	West Bound			
	Flow[4], $\bar{q}$	$\Delta\bar{q}$	Speed[5], $\bar{v}$	$\Delta\bar{v}$
Base	196.80	-	1.44	-
Fix-Gap	340.80	73%	3.38	135%
Platoon	487.20	148%	10.81	653%
Interaction	492.00	150%	12.40	764%
	South Bound			
	Flow[4], $\bar{q}$	$\Delta\bar{q}$	Speed[5], $\bar{v}$	$\Delta\bar{v}$
Base	1161.60	-	16.48	-
Fix-Gap	860.40	-26%	16.47	0%
Platoon	1138.80	-2%	9.51	-42%
Interaction	1140.00	-2%	9.11	-45%



(a) (b)

Fig. 6: SUMO screenshots of Zhishan-Xuetang intersection, Tsinghua University. Inductive loops (in yellow) can be seen on the west and south side of the intersection. (a) Normal traffic conditions model. (b) Platoon mode model.

The platoon model resulted in a significant increase in traffic flow in the west-bound direction when bicycle platoons were used. Compared with the base model, there was a significant 148% increase in west-bound traffic flow and a 653% speed increment (see Table II). This was due to the south-bound bicycle platoons creating more frequent gaps by decreasing their headway and shortening their platoon lengths (see Fig. 6b). The south-bound platoons were taking less space on the road due to their tight formations, allowing west-bound traffic to filter through without as many interruptions and speed reductions. As a result, south-bound traffic still maintained a high flow rate while accommodating traffic filtering despite a 42% decrease in average speed and 2% decrease in traffic flow (see Table II). It is an improvement from previous models and validates the advantages of CACC and V2V implementation in the connected bicycle platoon system.

Finally, the interaction model introduces a feedback loop between both west- and south-bound traffic, adapting both directions' speeds to align with the platoon gaps. The interaction model does not yield a significant improvement compared to the platoon model. This is due to an imperfect gap alignment algorithm where the speed acceleration adjustment has yet to be fine tuned. Nonetheless, despite a small 2% improvement in traffic flow compared with the platoon model, there is a significant 764% improvement in travelling speed west bound due to less interruption and delays with the south-bound traffic compared to the base model. Thus, the interaction model shows promising results if further improvements to the speed adjustment algorithm are made in the future.

VII. CONCLUSIONS AND FUTURE WORK

In conclusion, this paper aims to investigate whether a connected bicycle platoon system could address existing traffic congestion on the Zhishan-Xuetang intersection at Tsinghua University, China. Through a review of the literature on connected bicycle platoons, connected intersection control and connected e-bikes, research gaps in coordination between intersection control and connected bicycles at unsignalised intersection were found, along with a technology gap concerning CACC in connected e-bikes for precision speed adjustments and synchronisation between on-board computers and drive units, which must be filled in order to achieve connected bicycle platoon filtering at unsignalised intersections.

A conceptual unsignalised intersection system for connected bicycle platoons was proposed. This system is based on current technology developments in autonomous driving and intersection control, with CACC and V2V used to coordinate approach order for bicycle platoons at the intersection through speed adjustment. Autonomous intersection coordination requires a high level of speed tuning to ensure platoons and connected bicycles pass the intersection safely, by providing the necessary gap in between the vehicles. In order to control the variation in speed due to different fitness levels, connected e-bikes will provide power assistance to balance the difference in power output to provide a consistent acceleration or to maintain a consistent speed. Integrating the drive unit with control systems will be a key step to achieving CACC and V2V coordination within the platoon and the intersection control region.

SUMO simulation through the four scenario models has validated the hypothesis, that introducing adaptive gaps in continuous traffic streams between the connected bicycle platoons will improve intersection traffic flow. A significant improvement in the west-bound traffic flow (150%) and speed (764%) was observed, with only a minor effect on south-bound traffic flow. This was because the bicycle platoons increased road capacity by decreasing headway between the bicycles, and adaptable gaps encouraged more traffic filtering at the intersection. Note that steadiness and turbulence of e-bicycle platoons should be analysed in future work, in parallel with improved models of bicycle behaviour in SUMO. Furthermore, one could determine the platoon critical density and analyse fundamental diagrams to find optimal travelling speeds. Nonetheless, at least in this preliminary work, the results indicate that the proposed conceptual system will improve traffic flow and speed without a need for implementing physical intersection controls, and be able to improve intersection safety as less conflicts and delay were observed at the intersection during the simulation. Compared with the base model, it demonstrates a huge improvement in safety and intersection efficiency.

Bicycle mobility trends will continue to grow as cities transition and recover from COVID-19 effects. Cities are encouraging more people to ride bikes by addressing current safety and infrastructure barriers for bike use. Fortunately, this project has opened a huge potential in connected bicycle platoons, unsignalised intersection controls, and e-bike connectivity development. In the future, it is envisioned that the system will operate autonomously without traffic controls and seamlessly coordinate bicycles passing intersections using the advantages of CACC, V2V and 5G technologies. Hopefully, these future developments will make cycling more appealing, and help shape the future of local mobility.

Further investigation needs to be put forth to validate and construct the connected bicycle platoon system in reality. The next step will be implementing multi-direction traffic flow with turning traffic, and improving upon the speed adjustment algorithm and platoon detection in SUMO. After perfecting the system algorithm, the ultimate system capacity and optimum system performance level can be determined by modifying traffic demand and speed limits in all directions, creating new models such as bicycle platoons interacting with other transport modes (e.g., public transport, motorised vehicles) and pedestrians. For hardware, intersection communication infrastructure and on-board units can be developed using available hardware and smartphones with GPS capability. On the other hand, to implement CACC and V2V in e-bikes, the next step is to develop an automatic gear shifting electric drive unit, integrating it with the on-board interface, and be able to control and offset power control and acceleration rate through wireless control with the on-board interface.

References

[1] Bicycle Network, *More People out on Bicycles: Recreational Activity Surveys During COVID-19 and Comparison with Pre-Lockdown Activity Levels*, Report, May 2020. [Online]. Available: https://www.bicyclenetwork.com.au/wp-content/uploads/2020/05/COVID_report_final.pdf

[2] J. Pucher and R. Buehler, "Making cycling irresistible: lessons from the Netherlands, Denmark and Germany," *Transport Reviews*, vol. 28, no. 4, pp. 495-528, 2008.

[3] Bicycle Network, *Bicycle Network Crash Report 2012-2016*, Report, July 2017. [Online]. Available: https://www.bicyclenetwork.com.au/wp-content/uploads/2017/08/Bicycle-Network-Crash-Report-2012-2016.pdf

[4] H. Gonzalo-Orden, A. Linares, L. Velasco, J. M. Díez, and M. Rojo, "Bikeways and cycling urban mobility," *Procedia - Social and Behavioral Sciences*, vol. 160, pp. 567-576, 2014.

[5] Bicycle Dutch, "Get a green light quicker with Schwung," unpublished. [Online]. Available: https://bicycledutch.wordpress.com/2018/03/20/get-a-green-light-quicker-with-schwung/

[6] D. Jia, K. Lu, J. Wang, X. Zhang, and X. Shen, "A survey on platoon-based vehicular cyber-physical systems," *IEEE Communications Surveys & Tutorials*, vol. 18, no. 1, pp. 263-284, 2016.

[7] S. Céspedes, J. Salamanca, A. Yañez, C. Rivera, and J. C. Sacanamboy, "Platoon-based cyclists cooperative system," in *Proceedings of the 2015 IEEE Vehicular Networking Conference*, 2015, pp. 112-118.

[8] Tsinghua University. Facts and Figures. [Online]. Available: https://www.tsinghua.edu.cn/xxgk/tjzl.htm

[9] L. Huang and J. Wu, "Cyclists' path planning behavioral model at unsignalized mixed traffic intersections in China," *IEEE Intelligent Transportation Systems Magazine*, vol. 1, no. 2, pp. 13-19, 2009.

[10] M. Huber, Y.-H. Su, M. Krüger, K. Faschian, S. Glasauer, and J. Hermsdörfer, "Adjustments of speed and path when avoiding collisions with another pedestrian," *PLOS ONE*, vol. 9, no. 2, 2014.

[11] V. Milanés, S. E. Shladover, J. Spring, C. Nowakowski, H. Kawazoe, and M. Nakamura, "Cooperative adaptive cruise control in real traffic situations," *IEEE Transactions on Intelligent Transportation Systems*, vol. 15, no. 1, pp. 296-305, 2014.

[12] B. van Arem, C. J. G. van Driel, and R. Visser, "The impact of cooperative adaptive cruise control on traffic-flow characteristics," *IEEE Transactions on Intelligent Transportation Systems*, vol. 7, no. 4, pp. 429-436, 2006.

[13] Y. Zhou, S. Ahn, M. Chitturi, and D. A. Noyce, "Rolling horizon stochastic optimal control strategy for ACC and CACC under uncertainty," *Transportation Research Part C*, vol. 83, pp. 61-76, 2017.

[14] C. Englund, L, Chen, J. Ploeg, E. Semsar-Kazerooni, A. Voronov, H. H. Bengtsson, and J. Didoff, "The Grand Cooperative Driving Challenge 2016: boosting the introduction of cooperative automated vehicles," *IEEE Wireless Communications*, vol. 23, no. 4, pp. 146-152, 2016.

[15] J. Salamanca, S. Céspedes, D. Vinasco, and A. Yañez, "Demo: a prototype for a platoon-based cyclist cooperative system," in *Proceedings of the 2016 IEEE Vehicular Networking Conference*, 2016.

[16] H. K. Gedawy, M. B. Dias, and K. Harras, *Dynamic path planning and traffic light coordination for emergency vehicle routing*, Thesis, School of Computer Science, Carnegie Mellon University, Pittsburgh, PA, USA, 2009.

[17] P. Tallapragada and J. Cortés, "Hierarchical-distributed optimized coordination of intersection traffic," *IEEE Transactions on Intelligent Transportation Systems*, vol. 21, no. 5, pp. 2100-2113, 2020.

[18] D. Miculescu and S. Karaman, "Polling-systems-based autonomous vehicle coordination in traffic intersections with no traffic signals," *IEEE Transactions on Automatic Control*, vol. 65, no. 2, pp. 680-694, 2020.

[19] H. Levy and M. Sidi, "Polling systems: applications, modeling, and optimization," *IEEE Transactions on Communications*, vol. 38, no. 10, pp. 1750-1760, 1990.

[20] T. Anagnostopoulos, D. Ferreira, A. Samodelkin, M. Ahmed, and V. Kostakos, "Cyclist-aware traffic lights through distributed smartphone sensing," *Pervasive and Mobile Computing,* vol. 31, pp. 22-36, 2016.

[21] R. M. Shanteau, "Bicycle detection at traffic actuated signals," presented to the AB 1581 Subcommittee of the California Traffic Control Devices Committee, March 4, 2008. [Online]. Available: http://www.bikewalknc.org/wp-content/uploads/2016/01/Bicycle-Detection-at-Traffic-Actuated-Signals.pdf

[22] D. S. H. Abhilash, I. Wani, K. Joseph, R. Jha, and K. M. Haneesh, "Power efficient e-Bike with terrain adaptive intelligence," in *Proceedings of the 4th International Conference on Communication and Electronics Systems*, 2019, pp. 1148-1153.

[23] D. Aguiari, G. Delnevo, L. Monti, V. Ghini, S. Mirri, P. Salomoni, G. Pau, M. Im, R. Tse, M. Ekpanyapong, and R. Battistini, "Canarin II: designing a smart e-bike eco-system," in *Proceedings of the 2018 15th IEEE Annual Consumer Communications and Networking Conference*, 2018.

[24] Bosch. The Heart of eBikes: Drive Units. [Online]. Available: https://www.bosch-ebike.com/au/products/drive-units/

[25] P. A. Lopez, M. Behrisch, L. Bieker-Walz, J. Erdmann, Y.-P. Flötteröd, R. Hilbrich, L. Lücken, J. Rummel, P. Wagner, and E. Wießner, "Microscopic traffic simulation using SUMO," in *Proceedings of the 2018 21st International Conference on Intelligent Transportation Systems*, 2018, pp. 2575-2582.

[26] R. Zhang, J. Wu, L. Huang, and F. You, "Study of bicycle movements in conflicts at mixed traffic unsignalized intersections," *IEEE Access*, vol. 5, pp. 10108-10117, 2017.

[27] Moustache Bikes. Friday 28.5. [Online]. Available: https://moustachebikes.com/velos-electriques/friday-28/friday-28-5/