

Group Cycling meets Technology: A Cooperative Cycling Cyber-physical System

Sandra Céspedes, *Senior Member, IEEE*, Juan Salamanca, Alexis Yáñez, and Daniel Vinasco

Abstract—The initiatives of cycling infrastructure enhancements around the world reveal a consistent interest in promoting cycling to transition toward sustainable lifestyles and safe multi-modal commuting. Accordingly, proposals for cyber-physical systems for smart cycling are also growing, providing solutions to make cycling safer and a better experience for cyclists. However, most existent solutions address *single cyclist* problems rather than group cycling issues. It is evident that further work is needed to improve safety and comfort for groups of cyclists traveling on busy urban bicycle paths or dedicated bicycle highways. In this paper, we position the concept of technology-assisted cooperative cycling. We introduce a platoon-based cyclist cooperative system that provides safe and efficient coordination for groups of cyclists. We present the results of an experimental prototype tested on real cyclists, as well as comprehensive simulations that test the performance of our solution in different scenarios. We demonstrate that our system is feasible to be implemented and tolerates the human error factor while it is still able to achieve a constant spacing policy. Coordinated platoons of bicycles can be extremely useful to maximize the positive impact of green waves of traffic lights for cyclists and can be extended to groups of two-wheeled vehicles, including mopeds and self-balanced electric vehicles.

Index Terms—Bicycles, Cyber-physical system, Human-to-machine interfaces, Platooning, Wireless networks.

I. INTRODUCTION

The problems of urban mobility caused by the densification of metropolitan areas, citizens preference for personal vehicles, presence of obsolete or insufficient transportation network infrastructure, and the dominance of polluting motor technologies require mobility policies that promote the transition from car-based transportation to walking, cycling, and high quality public transport [1]. Intelligent transportation systems play a pivotal role in such a transition, supporting sustainable lifestyles, enabling safe multi-modal commuting, and informing data-driven land use planning and urban infrastructure development.

Whereas in some European cities the promotion of cycling has been a governmental policy for decades, in other cities around the world it is a recent initiative. Overall, cycling's share of total urban traffic has been rising with positive effects on motorized congestion and pollution around the world [2], [3]. But in some cases, the promotion has been so successful

that commuters overflowed the bicycle-dedicated infrastructure [4]; for example, according to the Secretariat for The Cycling Embassy Of Denmark¹, Copenhagen commuters ride 1.340.000 km every day on 454 km cycle lanes experiencing traffic congestions at intersections. Other cities with extensive bicycle paths, like Bogota, still need to engage a big portion of city dwellers to ride to work or school.

As cities around the globe enhance their cycling infrastructure (e.g., London's East-West Cycle, Melbourne's Veloway, Chicago's 606, and Copenhagen's suburban Cycle Super Highways), the number of cyclists grows, and the initiatives of cyber-physical systems for smart cycling are more numerous. Some projects are focused on making cycling safer by detecting hazards and warning riders [5]–[7], others on improving the cyclist experience by automating gear change [8], boosting riders' power [9], or guiding them through unfamiliar routes [10]. Some take advantage of wireless communications to access navigation services [11], [12], report environmental and traffic conditions in real-time [9], [12], or determine circulation speed to efficiently reduce power consumption of e-bicycles [13]. In order to keep cyclists' attention on the road, some research initiatives are focused on tactile human-machine interfaces to display contextual information [10], [14], [15]. But most of these solutions address *single cyclist* problems rather than group cycling issues. It is evident that further work is needed to improve safety and comfort for groups of cyclists travelling on crowded urban bicycle paths and cycle highways.

In this paper we position the concept of technology-assisted cooperative cycling and characterize an envisioned solution of platoon coordination as a cyber-physical system. In particular, the work reported herein builds on top of our preliminary research findings [16]–[18] and aims at making the following novel contributions:

- Present a platoon-based cyclists cooperative system that provides safe and efficient coordination for emergent groups of cyclists traveling together. It involves a cyber-physical system with a customized design of a human-bicycle interface and a control scheme following a cooperative adaptive cruise control algorithm (CACC).
- Demonstrate the feasibility of implementation of our system through an experimental prototype and data collected from real cyclists receiving instructions from the cooperative scheme. The preliminary experimental results enabled improvements to the system's design to avoid the overreaction of cyclists to the instructions provided by the system.
- Provide analysis from extensive simulations to verify the performance of the system under different riding conditions, showing the recommended operational ranges for our solution.

Manuscript received on Dec 6th 2017, revised on July 13th 2018, accepted on Sep 8th 2018.

S. Céspedes is with the Department of Electrical Engineering, Universidad de Chile, Santiago, Chile; with the NIC Labs Chile; and with the Universidad Icesi, Cali, Colombia. Email: scspedes@ing.uchile.cl

J. Salamanca is with the School of Art and Design, University of Illinois at Urbana-Champaign, Champaign, USA, and with the Universidad Icesi, Cali, Colombia. Email: jsal@illinois.edu

A. Yáñez is with the Department of Electrical Engineering, Universidad de Chile, Santiago, Chile, and D. Vinasco is an independent researcher located in Cali, Colombia.

This work was funded by: Universidad Icesi; CONICYT Chile Project FONDECYT 11140045; and the Complex Engineering Systems Institute, ISCI (CONICYT: FB0816)

¹<http://www.cycling-embassy.dk/facts-about-cycling-in-denmark/statistics/>

The method used in this research combines an empirical approach with a simulation-based approach. We offer a detailed description of three experiments used to test our system. The first experiment evaluates the performance of follower cyclists in a real scenario with a multimodal human-bicycle interface that combines a haptic and a visual display. The second experiment evaluates, through extensive simulations, the platoon behavior for different group sizes, taking into account the human misinterpretation of signaled acceleration found in the first experiment. We analyze the cyclists' response to acceleration cues with two metrics: accuracy and consistency. In the third experiment, we propose a mechanism to prevent subject's cue misinterpretation by filtering acceleration signals. We conclude with recommendations about the recommended platoon size and sets criteria to determine acceptable leader's behavior.

The rapid adoption of electric two-wheeled mobility (E2W) around the world has direct implications in this discussion. China is the extreme case, with 35 million units produced per year and 100 million e-bicycles in use [19]. E2W fits the scenarios of future mobility because e-bicycles pollute less [20], are more practical than motor vehicles, are fashionable, can easily connect to a smart city's infrastructure, and save effort compared to regular bicycles [19]. Our research is focused on regular bicycle mobility, but our findings could be extended to the domain of e-velomobility [21] because e-bicycles only engage electric motors to accelerate up to 25 km/h, and their power is less than 250W. Such power assistance reduces but does not replace cyclists' acceleration efforts and helps them maintain speed, the two main kinetic variables of our adaptive system. Note however that any E2W vehicle that exceeds the assisted speed and motor power requirements mentioned above is not considered a bicycle, according to the European standards, but a scooter or moped vehicle that is subject to mobility licensing [21].

The remainder of this paper is organized as follows: In Section II we provide a review of technological advances for smart cycling. In Section III we describe the system model, its mathematical foundations and the experimental prototype. Then we provide extensive evaluations with the prototype and computer simulations. Future applications and challenges are also discussed in this section. Finally, we present the concluding remarks in Section IV.

II. RELATED WORK

In this section, we review current technological projects that involve sensing systems, wireless communications, control mechanisms, and innovative human-machine interfaces for the integration of cycling in smart transportation systems.

Several projects from industry and academia have launched a variety of solutions that integrate sensing systems and wireless communications with cycling. Authors in [5] propose a human-centered collision warning system to improve cycling safety. The bicycle is equipped with an active sensing system that detects and tracks vehicles behind it. This solution does not require any connectivity enabled at vehicles or bicycles. Another warning system, proposed by Hernandez et al. [6], sends notifications to the vehicles via a wireless network to alert of the presence of a bicycle nearby. Other commercial solutions supported by initiatives such as the EU Horizon 2020, include a proposal to develop cyclist-friendly traffic control algorithms to help them stay on synchronized sequence

of traffic lights that allows them to flow without having to stop at the signals, known as *green waves*; another proposal is to equip the road with an experimental warning system composed by cameras and sensors using data analysis to detect safety-critical events, such as trucks turning into the paths of cyclists [22].

If wireless communications are enabled for bicycles, the technologies that provide such a connectivity may be 4G, WiFi, IEEE 802.15.4, Bluetooth, and IEEE 802.11-OCB (a.w.a. 802.11p). Communications for bicycles may happen in an ad-hoc fashion (among nearby bicycles, vehicles, and pedestrians) [12], in an infrastructure-based fashion to enable the exchange of information with external networks [6], [9], or as a combination of ad-hoc and infrastructure-based communications.

In terms of control strategies for interaction between traditional and alternative forms of transportation, high resolution data is a rich source for traffic modeling and control purposes. Two decades ago, control mechanisms were oriented to control isolated bicycles, in some cases autonomous bicycles for applications such as trajectory tracking control, balancing, and speed control [8], [23]. More recent work, such as the one proposed by Portilla *et al.* [24], propose a model-based predictive approach that represents the dynamic interaction between bicycles and vehicles. The scheme is able to control traffic lights at intersections based on predictions of both vehicles demand and bicycles demand. To account for electric bicycles, Tal *et al.* propose a speed advisory system when bicycles are approaching a signaled intersection to avoid high-power-consumption scenarios [13].

In the area of human-machine interaction, unlike drivers of smart cars, smart bicycle riders cannot completely delegate the navigation and behavior of the vehicle to the on-board computing and communication technologies. During a bicycle ride, the cyclist-smart bicycle unit is an indivisible cybernetic system constantly sensing, acting, and processing information. The stability of the system highly relies on the interface design that articulates both parties. Therefore, the use of vibration-based displays on the handle, the saddle, the helmet or wearable accessories are commonly used to signal binary messages, warnings, and navigation hints [10], [14], [15], leaving the auditory and visual channels uncompromised. The caveat of haptic perception is that humans hardly correlate time and length magnitudes to vibration frequencies, reducing the vocabulary of potential tactons to simple vibration patterns. Wireless enabled in-ear-devices, known as *hearables*, are alternative auditory displays that whisper sounds and synthesized spoken instructions to the user [25].

Different from the aforementioned solutions devoted to the *single cyclist* case, our system explores the use of control mechanisms and ad-hoc communications for providing co-ordinated driving to a group of bicycles. Furthermore, our approach for the design of the human-bicycle interface is bimodal. It scratches, instead of vibrates, on cyclist's hand palms to convey positive or negative acceleration and confirms the signal through a visual display. Details of this scheme are provided in the following section.

III. INTERVENTION OF GROUP CYCLING WITH TECHNOLOGY: A COOPERATIVE CYCLING CYBER-PHYSICAL SYSTEM

When cycling lanes are overflown, spontaneous platooning often becomes a circulation strategy. Although it uses roads

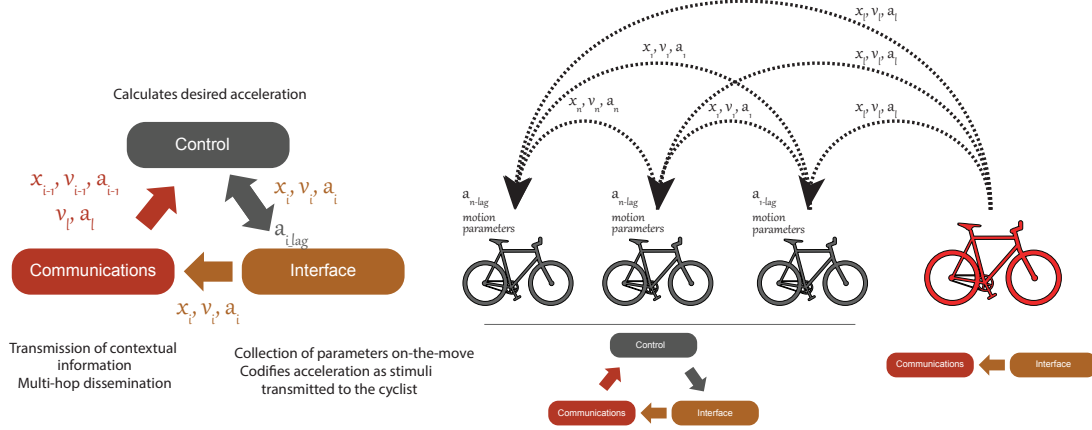


Fig. 1. A three-module system for coordinated group cycling

efficiently, it derives in safety risks and gridlocks due to the lack of explicit coordination [26]. This kind of scenario has motivated our proposal to coordinate the collective behavior of a platoon of cyclists. Similar to a platoon of vehicles, the purpose of this system is for cyclists to form or subscribe to a platoon, such that members of the group are able to move at a target speed while maintaining a safe distance to one another. Our solution aims to help the platoon formation process in a scenario in which cyclists, unacquainted with each other, are willing to join to or initiate a platoon but have not coordinated to do so. They are unaware of which cyclist, ahead or behind, is already subscribed to the platoon, or might not have visual contact because they are too far away. The target speed may be defined by group consensus or simply determined by the pace at which the group leader is riding.

A. System Model

Three main components form the proposed cyber-physical system: control module, communications module and interface module. The Fig. 1 shows the interaction between the modules for the leader of a bicycle platoon and its followers.

The *control* module processes the information received from other participants according to the policies (e.g., safety distance and leader's speed) and suggests acceleration adjustments according to a Cooperative Adaptive Cruise Control (CACC) logic. The module follows Rajamani et al. CACC model, which is designed to maintain a constant spacing between vehicles while it ensures string stability of the platoon [27]. It is based on a sliding surface method of controller design. The controller determines the desired acceleration, a_{i_des} , for the i^{th} vehicle in the platoon thanks to the motion information received via wireless communications. a_{i_des} is calculated as follows [28]:

$$a_{i_des} = (1 - K)a_{i-1} + K(a_l) - (2\xi - K(\xi + \sqrt{\xi^2 - 1}))(\omega_n(v_i - v_{i-1})) - (\xi + \sqrt{\xi^2 - 1})\omega_n K(v_i - v_l) - \omega_n^2 \varepsilon_i, \quad (1)$$

where K , ξ , and ω_n are design constants. K is a weight factor for the leading vehicle, ξ is the damping ratio, and ω_n is the bandwidth of the controller. v_i , v_{i-1} , and v_l are the i^{th} vehicle,

the $i - 1$ predecessor, and the leading vehicles' velocities, respectively.

The spacing error ε_i that accounts for the difference between the platoon's constant target spacing d_{i_des} and the real spacing between vehicles i and $i - 1$ is defined as:

$$\varepsilon_i = x_i - x_{i-1} + d_{i_des}, \quad (2)$$

where x_i and x_{i-1} are the positions of the i^{th} vehicle and its predecessor, respectively.

Define the sliding surface as:

$$S_i = (v_i - v_{i-1}) + \frac{\omega_n}{\xi + \sqrt{\xi^2 - 1}} \frac{1}{1 - K} \varepsilon_i + \frac{K}{1 - K} (v_i - v_l), \quad (3)$$

then, the sliding surface law ensures that $S_i - S_{i-1}$ is equal to zero. The magnitude of the transfer function obtained by taking the Laplace transforms of $S_i - S_{i-1}$ is less than 1 under the conditions that $\xi \geq 1$ and $K < 1$, and ensures the system is string stable. A detailed demonstration of the string stability property of the system is provided in [28].

The outputs and inputs of this module are illustrated in Fig. 1: the *control* receives position, speed, and acceleration information from the preceding bicycle ($x_{i-1}, v_{i-1}, a_{i-1}$) and leading bicycle (v_l, a_l). The calculation of a_{i_des} is then passed through a low pass filter to account for the actuation lag [17] resulting in acceleration a_{i_lag} . The output of the module is the suggested acceleration a_{i_lag} . When each participant of the platoon automatically adapts its acceleration according to the CACC logic, an automated platooning system is formed. Instead, we call it a semi-automatized platoon, because the *control* module suggests the acceleration needed to conform to the rules, but it is a human, the cyclist, the one executing the suggestion. The behavior of human drivers in car following models and corresponding control theoretic models were proposed by Bekey et al. [29]. In previous works, human driven platoons have been studied; however, the platoon leader is assumed to be a professional driver and the followers are completely automated vehicles under longitudinal and lateral control [30], [31]. More recent works address the scenario of heterogeneous platoons comprised of human-driven and connected cruise control vehicles [32]. In our case, cyclists participating in the platoon respond to the CACC with indications delivered through the *interface* module.

The *communications* module is there for transmitting the cyclist motion parameters, i.e., location x_i , speed v_i , and acceleration a_i , and for receiving contextual information from neighboring bicycles. We introduce in this module a dissemination mechanism that takes advantage of beacon messages to append information from the leader, so the bicycles out of the one-hop range of coverage can still receive information through multi-hop communications.

Finally the *interface* module enables the cyclist and her bicycle to work as a unit. It connects with sensors that collect motion parameters on-the-move (i.e., x_i, v_i, a_i) and actuators that display information to the cyclist. The data collected through sensors is delivered to the *communications* module for transmission to neighboring bicycles and to the *control* module for processing. Once a suggested acceleration is computed by the *control* module, it is displayed to the cyclists through a human-bicycle interface (HBI).

Cyclists in an actual platoon formation are constantly monitoring moving direction, proximity to others, and collision avoidance. Our *interface* module is designed to help cyclists to achieve and maintain a given spacing policy. Other important signals such as braking, unsubscribing to the formation, or warning propagation (e.g., backwards alerts of puddles or holes, or slow down requests sent to cyclists ahead), could also be incorporated in this module, but are left for future development.

An example of the cooperative cycling scheme is illustrated in Fig. 2, where the leader is setting a target speed for the group (hence, no control is being employed) and the followers determine the suggested acceleration based on the exchange of information with the other platoon members. Note that acceleration a_{i_lag} is only a suggestion, since the cyclist will apply his own interpretation of acceleration based on the stimuli received from the *interface* module.

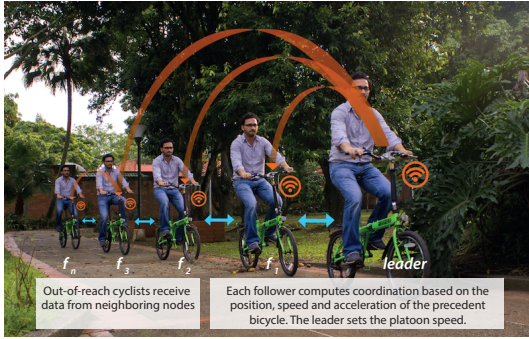


Fig. 2. Coordinated cycling through ad hoc communications, control mechanisms, and a human-bicycle interface

B. System Prototype

We built a prototype of the complete system to evaluate the performance in a real scenario [18]. The bicycles used in the prototypes are regular urban bicycles with no major modifications except for the handlebar that houses a mini geared motor for the hardware of the *interface* module, as illustrated in Fig. 3. The cyber-physical system components are prototyped in each bicycle as follows:

Control module. This module is built on a Romeo V2-All-in-one board: a robot controller based on Arduino Leonardo that uses Arduino's libraries and IDE, and also includes two servo



Fig. 3. Prototypes of a cooperative cycling cyber-physical system

motor controllers, one XBee Socket, and full compatibility with Arduino shields. It hosts the logic of the CACC algorithm and calculates the acceleration according to (1).

Communications module. This module uses an XBee Pro 60mW PCB Antenna Series 1 that, although it does not support mesh network architecture, achieves 1500 m with line of sight (LOS), covering the entire platoon. All the bicycles transmit their ID, latitude, longitude, speed, and the global time from the A-GPS every second. In addition to these data, each follower also sends its CACC calculation, acceleration, and the distance to the bicycle ahead for post-hoc analysis.

Human-bicycle Interface module (HBI). The HBI relies on haptic stimuli on the hand palm to convey acceleration information [17]. The stimulator is a rough texture eccentric cylinder spinning forward or backwards at a frequency of 3.91 Hz that scratches the subject's hand palm conveying positive or negative acceleration respectively. The haptic signal is complemented with a colored lighting on a visual display because former tests on the actual field revealed the need for multimodal signaling confirmation. If the *control* module suggests accelerating, the haptic display spins forward indicating to speed up and the visual display turns green. Conversely, if the *control* module suggests decelerating the haptic display spins backwards indicating to slow down and the visual display turns red. If the cyclist goes at the right speed the haptic device is off and the visual display turns blue. In addition, this module collects parameters on-the-move to feed the *control* module. Two sources of contextual information are gathered:

i) position: our initial approach was to use a standard Arduino-compatible GPS shield, but it yielded large errors, unreliable coordinate updates, and poor GPS signal. The solution was to replace the GPS shield with an Android-based smartphone running an app that sends the phones' assisted GPS (A-GPS) position in NMEA format via Bluetooth to the controller's serial port; and ii) speed and acceleration: a simple reed switch attached to a digital port serves to calculate the bicycle speed based on the time it takes to interrupt the controller at each wheel cycle.

Data Recording. In order to record the behavior of each bicycle and cyclist, the leader control module carries a Micro SD Shield that uses FAT 16 file system to record in a text-based file the beacons of all the bicycles in a platoon for further analysis.

C. Preliminary experiments testing acceleration cue

In [17] we describe a preliminary experiment aimed to determine to what extent amateur urban cyclists, prompted with positive or negative acceleration signals displayed on a combined visual (non verbal) and tactile display, adjust their acceleration to match three target speeds (2.77 m/s (10 km/h), 4.16 m/s (15 km/h), and 5.0 m/s (18 km/h)). For that experiment we staged the scenario of one cyclist following a computer simulated leader in a laboratory setting. To any speed change of the leader the subject tried to match and maintain it for at least 20 seconds. The apparatus consisted of a large format screen displaying a road in front of a static urban bicycle equipped with a *control* and *interface* modules as described above. Positive acceleration was signaled if the subject speed was below the target's lower bound, negative acceleration if it was above the target's upper bound. No haptic signal was displayed when the subject speed matched the target with a tolerance of ± 0.5 m/s. The subject perceived the leader's speed and her speed as a sequence of dots flowing along the road.

For each subject we measured time-to-goal and speed, sampled every 0.5 seconds. Based on the results we computed the response acceleration magnitude and acceleration direction at each sampling event. Overall we observed that across target speeds, above 70% of the signals conveying acceleration direction were interpreted correctly, and on average, 61% of sampled speeds fall within the target. Subjects were less consistent matching slow and fast speeds (2.77 m/s or 5 m/s) than cruise speed (4.16 m/s), and they took 15 seconds on average to reach the target speed when prompted with acceleration cues.

We conclude that subjects had a hard time determining the appropriate response magnitude when perceiving acceleration signals on visual and haptic displays, but they had a fair performance interpreting the signals acceleration direction.

D. Experiments with the working prototype

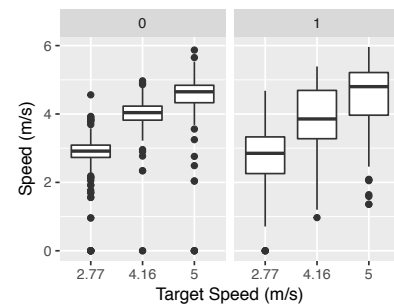
Based on the results of the previous experiment, we conducted a second study aimed to assess cyclists response to acceleration signals, but this time we tested two bicycles enabled with the *control*, *communications*, and *interface* modules in an actual urban street. Both leader and follower had to adjust their speed following the signals displayed by the interface module, preserving a 4 m inter-bicycle gap. This means that the leader was not freely determining the platoon speed, but it was following a ghost leader moving at three target speeds. The independent variable was the target speed with three values {2.77, 4.16, 5} m/s repeated three times. To increase the validity of the experiment and prevent responses due to fatigue we sorted the target speeds in a 3×9 latin-square design. The dependent variables were speed, acceleration response, and bicycle proximity. The sampling rate was one record per second, recorded from the leader's communications module.

As for the leader, the *control* module retrieved the first target speed, constantly computed the speed difference from its current speed for one minute, and the *interface* module signaled acceleration correction if necessary. Then it moved to the following target speed. Therefore, the duration of each trial spanned for 9 minutes, plus half minute spent at the beginning reaching minimal balancing speed. In the case of the follower, the *communications* module received the leader's position and velocity, the *control* module computed its optimal

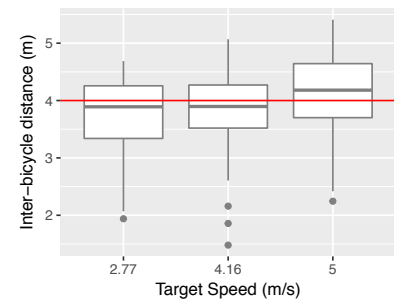
acceleration to maintain the gap, and the *interface* module constantly signaled the acceleration correction to the cyclist.

Five pairs of leader-follower amateur urban cyclists between 18 and 23 years old rode on the shoulder of a flat paved straight road. All cyclists were guarded by a escort car, and participated in the experiment only once. Both leader and follower were unaware of the target speeds and inter-bicycle gap, but they knew who was following who. For each trial, we picked one of the three latin-square sequences and asked both subjects to follow the displayed haptic and visual acceleration signals.

During the analysis, each data point was marked HIT when the acceleration direction response matched the *control* module suggestion, else it was marked MISS. The experiment revealed that across target speeds the follower's speed was on average very close to the leader's (2.8, 3.88, and 4.42 m/s respectively) but its standard deviation almost double the one of the leader (0.7, 0.84, and 1.04 respectively) as shown in Fig. 4a. In terms of inter-bicycle distance, Fig. 4b shows that on average the followers matched the expected proximity (mean 3.77 m, sd 0.6; mean 3.84 m, sd 0.59; mean 4.13 m, sd 0.74, respectively). As for the response to acceleration prompt, illustrated in Fig. 5a, we observe that across target speeds the percentage of signals interpreted correctly is 63.3%, 63.9%, and 66.4%, respectively, resembling the behaviour observed in the experiment conducted in the laboratory. As expected, the average magnitude of acceleration across conditions is consistently close to zero, but it exhibits a considerable variance as showed in Fig. 5b (mean 0.03 m/s², sd 0.45; mean 0.0 m/s², sd 0.42; mean 0.01 m/s², sd 0.39, respectively), meaning that followers were constantly and progressively adjusting their speed instead of making abrupt changes regardless of how fast or slow they rode.



(a) Speed response in empirical study. Leader 0, follower 1



(b) Gap preservation between bicycles at different target speeds

Fig. 4. Results of empirical studies on actual urban roads. Speed and inter-bicycle distance response

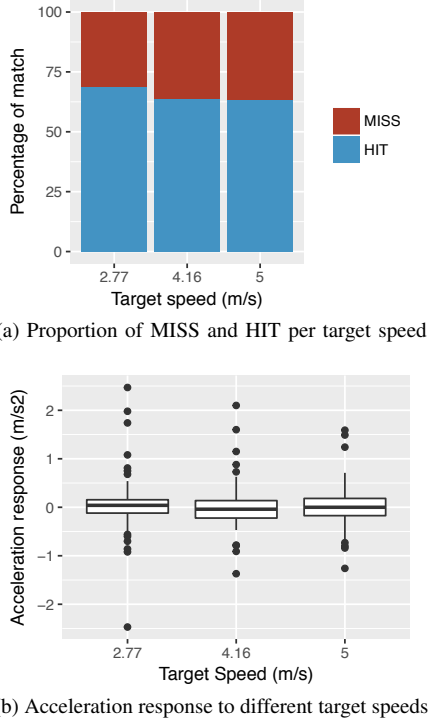


Fig. 5. Results of empirical studies on actual urban roads. Acceleration response

From this study we observed that although their considerable speed variation, on average the followers' responses follow the acceleration suggestion. This means that followers do not ride at the exact target speed, but they are always close to it. We realized that this is due to leaders not accurately maintaining the target speed, and HBI repetitive signaling that prompted cyclists to overreact because it signaled acceleration corrections even if followers were few centimeters above or below the proximity target.

From the two empirical studies explained in this section we conclude that the cyclists' response to HBI signals was sufficient to preserve a cohesive group of cyclists although 60% of acceleration adjustment responses were true positives. Hence, we estimate that a portion of acceleration signaling could be filtered out aiming to reduce the variation of the cyclist's speed response in a way that it is still possible to maintain an acceptable inter-bicycle gap. In order to prevent subjects' hand palm numbing and cue misinterpretation, we included a filter that signals acceleration corrections only if the follower's proximity to the leader overpasses a target's tolerance boundaries. A complete evaluation of the proposed filter is presented in Section III-E.

E. Experiments from simulations

In order to understand the system's behaviour in a more controlled environment, we have employed computer simulations. We use the OMNeT++ simulation tool and the unit cyclist-smart bicycle is represented by a mobile node equipped with an IEEE 802.15.4 wireless interface. Signals attenuate according to a LogNormal shadowing model. Bicycles move along a straight path and are considered to be 2 meters long. A node collects its motion information (speed, acceleration, and position) and transmits it with a frequency of 10 Hz to

neighboring nodes. The control module in each bicycle selects the latest information received from neighboring and leading bicycles, determines which one is the preceding bicycle based on the reported location, and employs the CACC logic to calculate a_{i_des} and a_{i_lag} according to the model described in Section III-A.

To emulate the (mis)interpretation of the cyclist of the signaled acceleration (i.e., the one transmitted through haptic and visual stimuli), we alter the acceleration with a human error factor ϵ . Such a factor allows the simulation to be an imperfect system. To have a realistic ϵ factor, we analyzed the information from the empirical studies with actual cyclists and the bicycle prototypes concluding that human error closely follows a normal distribution [17]. The mean μ and deviation σ for human error distributions are extracted from the same experiments. The acceleration as perceived by the cyclist including the human error is implemented as follows:

$$a_{i_err} = a_{i_lag} + \epsilon, \epsilon \sim N(\mu, \sigma). \quad (4)$$

Besides inter-bicycle distance, we introduce two metrics to characterize the platoon behavior: *accuracy* and *consistency*. *Accuracy* is defined as the absolute value of the distance between the suggested acceleration and the cyclist's acceleration response. The lower the value the highest the accuracy. *Consistency* accounts for the correspondence between the acceleration direction prompted by the control system and the cyclist's acceleration response. It is estimated by dividing the number of HIT over all the signals displayed.

In a first stage, we employed the *accuracy* and *consistency* to check if the simulation behaves similarly to the empirical experiment, so that we can assure that the computer simulations resembles the human factor of the cyber-physical system. We calculated *accuracy* and *consistency* for the followers of 5 leader-follower empirical observations, and for the followers of 30 leader-follower simulated runs. In both empirical observations and simulations, samples were taken during 530 seconds and the leader changed the target speed to {2.77, 4.16, 5} m/s at different times.

Table I shows that on average the reaction of simulated cyclists to acceleration prompts is 7% more consistent than the one of actual cyclists, but the accuracy of their acceleration reaction is almost the same. A two-tailed t-test with independent samples was used to compare the difference between the average accuracy of empirical and simulator datasets. It shows that there is not a significant difference between the two samples, $t(598) = 0.07$, $p < 0.05$, $CI = 0.21 < \mu_1 - \mu_2 < 0.27$. Moreover, the confidence intervals suggest that there is a high probability of not rejecting the null hypothesis ($\mu_1 - \mu_2 = 0$) if the average accuracy of the simulator falls between 0.21 and 0.27. Thus, we conclude that the simulator results are reliable and close enough to the empirical observations.

Condition	Hit	Miss	Avg.Cons	Avg.Accu.	SD Accu.
Empirical	363.0	207.0	0.637	0.241	0.310
Simulator	354.7	141.8	0.714	0.242	0.033

TABLE I
COMPARISON OF CONSISTENCY AND ACCURACY FROM EMPIRICAL STUDIES AND SIMULATIONS

1) *Behavior of large platoons:* We ran simulations to establish the behavior of our system when different target velocities, platoon sizes, and leader's speed variability (LSV) were in place. The inter-bicycle target distance was set to 4

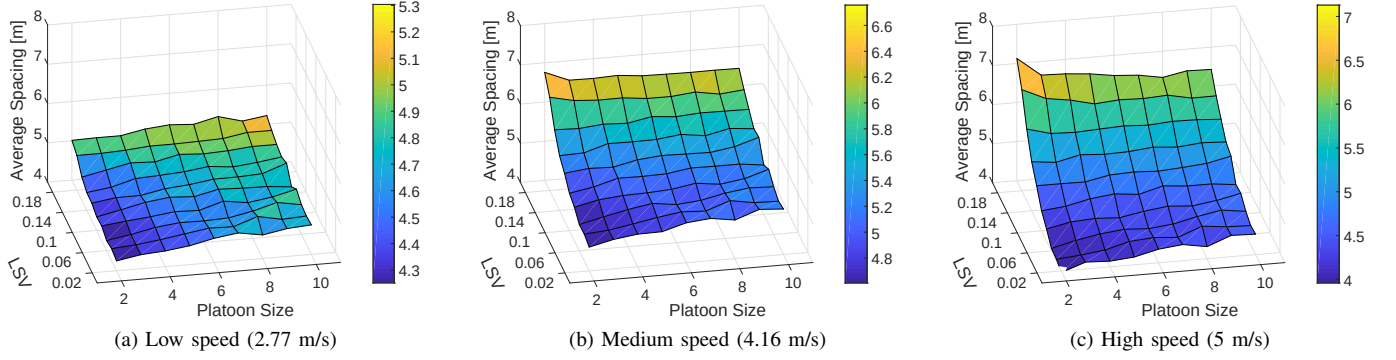


Fig. 6. Gap preservation for different platoon sizes and leader's speed variability (LSV) at three reference speeds.

meters and bicycles rode over a straight route for 530 seconds. We considered a leader's speed variability between 5% and 30% that accounts for the leader's inability to maintain a stable velocity along the ride. We have observed this behavior in the empirical study, where the leader's performance was highly variable from subject to subject (presumably due to the physical capacity of the cyclists or his/her driving abilities). The velocities were the three reference speeds $\{2.7, 4.16, 5\}$ m/s employed in the empirical study. Consistently, the human error distribution parameters were also calculated from the empirical results with $\mu_{\text{low}} = -0.0164$, $\sigma_{\text{low}} = 0.3829$, $\mu_{\text{med}} = -0.0437$, $\sigma_{\text{med}} = 0.4173$, and $\mu_{\text{high}} = 0.0091$, $\sigma_{\text{high}} = 0.3975$. The platoon size was increased from 2 to 10 participants. Each combination of parameters was run 20 times for a total of 5400 runs.

Fig. 6 illustrates the average spacing for all three speeds. Overall, larger platoons show the lowest performance when the leader becomes more unstable (LSV=0.20). At 5 m/s, cyclists are able to closely match the target distance when the LSV < 0.10. Nevertheless, in all three target speeds it is observed that small inter-bicycle gaps tend to be avoided by the system. This means that, under leader's instability and high human error conditions, follower bicycles usually distance from the one ahead, which is a desired behavior to preserve safety.

A detailed inspection of the individual results showed that the greater impact for a poor performance of platoon participants comes from the human error factor ϵ . The less familiar are cyclists with the signaling system, the more likely to misinterpret the acceleration cue. Therefore, we ran a simulation to explore the platoon behavior with reduced levels of human error, to account for different levels of training of the platoon participants. Fig. 7 shows the behavior for platoon sizes from 2 to 10 participants, with four levels of training (i.e., lower σ values indicate more familiarity of participants with the system). Results demonstrate a consistent improvement across all platoon sizes: lower σ values show not only distances closer to the 4 m target gap but also a reduced deviation from the average spacing.

To inspect the improvements due to participants training, we compared the results of the last two participants in a 6 bicycles platoon, with no training ($\sigma = 0.39$) and with intermediate levels of training ($\sigma = 0.3$ and $\sigma = 0.25$). As the Fig. 8 depicts, the last followers obtain an average distance closer to the target spacing for the higher levels of training. In addition, the variance decreases and the maximum and minimum inter-bicycle gaps get closer to the expected spacing, which improve

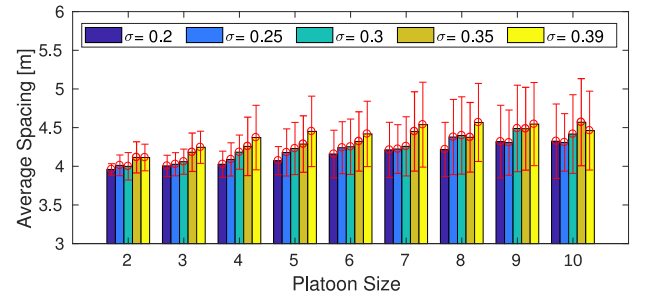


Fig. 7. Average inter-bicycle distance at different levels of training of platoon participants. Speed=5 m/s, LSV=0.065

cohesion and safety, in the majority of cases. Note that due to the human error few values out of the 10600 points plotted in each box-plot in Fig. 8 fall beyond the minimal spacing gap (i.e., points below 0 m spacing). However, there is a natural correction that do occur in the real world but does not occur in the simulation: the human reaction to override any prompt that may seem unsafe. This is observed if we compared Fig. 8 with Fig. 4b, where the natural correction does take place and extreme values only get near to 1 m.

Our evaluation of training levels works under the assumption that training across platoon participants is homogeneous. This feature could be controlled by a platoon subscription module, in a way that a potential participant is only allowed to join platoons with a level of training similar to hers. The individual level of training is a parameter that changes according to the cyclists performance in previous platoon participations.

Fig. 9 is an illustration of the acceleration obtained for one follower in a single simulation run, where the blue line corresponds to the desired acceleration resultant from the implementation of (1), whereas the red line corresponds to the acceleration affected by the human misinterpretation of the system signals.

2) *Filter of acceleration signaling:* According to the results of the empirical study, we concluded that although the system accurately prompts the suggested acceleration, repetitive signaling might impel cyclists to overreact, resulting in the amplification of their acceleration response variance. To improve such a behavior, we propose a filter to determine whether a suggested acceleration is displayed. The filter would conceal acceleration signals if their magnitude is not large

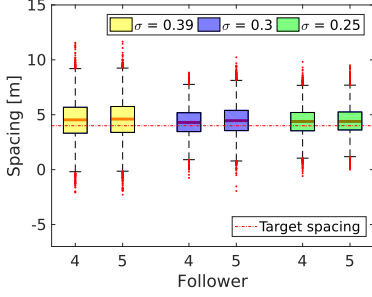


Fig. 8. Gap preservation between bicycles at different levels of training. Last two nodes of a simulated platoon of 6 participants (1 leader, 5 followers). Speed=5 m/s, LSV=0.065

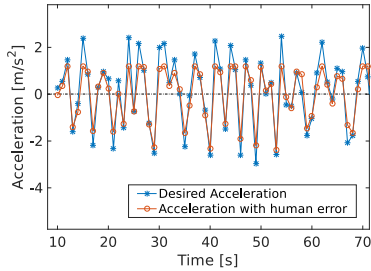


Fig. 9. Desired acceleration vs. acceleration with human error, $\sigma = 0.25$

enough to provoke a significant reaction of the cyclists. In the simulations we employed three different filters that correspond to 1/4, 1/3, and 1/2 of the standard deviation of accumulated acceleration response of a cyclist in a platoon. The accumulated acceleration was collected from previous simulations.

By simulating different boundaries, we were able to define which filter yields an acceptable acceleration and prevents cyclists overreaction without compromising the platoon, in particular the inter-bicycle distance. The introduction of a filter in the system is illustrated in Fig. 10.

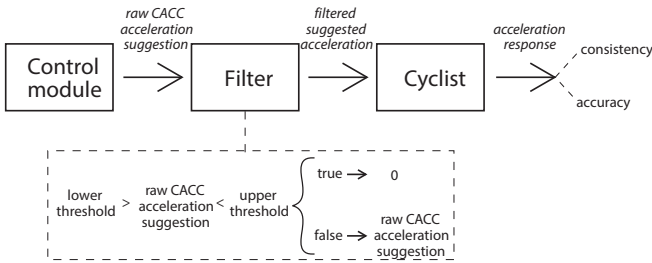


Fig. 10. Filter scheme to improve acceleration response

We ran the simulator 30 times for each of the filters with a platoon size of 4 members (i.e., one leader and three followers). The results of followers 1, 2, and 3 are presented in Table II. Undefined values correspond to data points where the *suggested acceleration* was filtered out, thus the cyclist was prompted to maintain the current speed.

In terms of *consistency* we observe that for each follower the wider the filter the larger the consistency except for the closest follower to the leader. As expected, the number of undefined data points increases and the number of HIT and MISS data points decreases. An ANOVA analysis for each

follower, examining the effect of the filtering condition over consistency, reveals that for all of them the effect is significant (all $p < 0.001$). The post-hoc Tukey tests showed that all filtering conditions differ significantly from the Unfiltered condition regardless of the node position (all $p < 0.02$). There is no significant difference between 1/2, 1/3 and 1/4 filters except for Follower 1. In this case applying the 1/2 filter is significantly worse than applying 1/4 or 1/3 filter (both $p < 0.00$). An interesting observation is that across followers the F value gets lower as their position in the platoon distances from the leader (all $F(3,116)$, follower 1 = 459.1, follower 2 = 16.87, follower 3 = 10.12). This means that the closer the follower is to the leader, the narrower the filter to be applied.

In conclusion, not filtering yields over-signaling that hinders follower's consistent interpretation of acceleration suggestions. Filters 1/4 and 1/3 perform similarly, and filter 1/2 performs poorly with follower 1.

In terms of *accuracy* we observe that there is a consistent response around 0.24 m/s^2 . Our interpretation is that nodes always take a similar time (around 15 secs) adjusting their acceleration to reach the target speed. In this analysis we did not differentiate the accuracy by target speed, but in previous results [17] we observed that for the slowest and fastest target speeds the accuracy of cyclist response was less than for the intermediate one. There are not salient effects of filter over accuracy except for a deep valley of the 1/2 filter in accuracy of Follower 1.

The effects of filtering on the inter-bicycle distance of the group under study are illustrated in Fig. 11. The results confirm that the application of a filter has a greater effect over the first follower than the rest of the group, and reinforces our observation that differentiated filters should be employed depending on the position of the follower in the platoon.

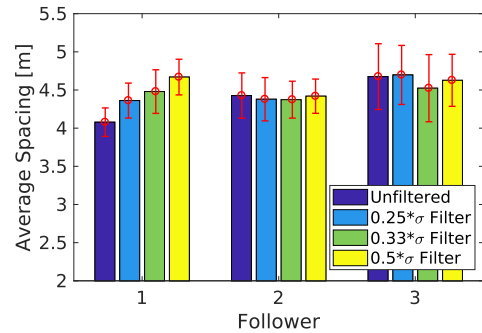


Fig. 11. Spacing between followers and the bicycle ahead with three signal filters. Speed=5 m/s, LSV=0.065

The goal of this experiment was to improve the reliability of our findings derived from the OMNeT++ simulation platform by increasing the sample size of node response to acceleration signals. Our approach was a *within subjects analysis* in which we averaged all entries that correspond to the same node and experimenting condition. The results show that the *consistency* of acceleration response of nodes in a platoon to unfiltered signals falls between 71.4% and 76.5%, and the *accuracy* of such response is about 0.24 m/s^2 . But the *consistency* could be improved in about 4% for all follower nodes if for each node we filter out acceleration signals within 1/3 of the standard deviation of its accumulated acceleration response.

Follower	Filter	Hit	Miss	Undefined	Consistency	SD Cons.	Accuracy	SD Acc.
1	Unfiltered	354.867	141.833	0.000	71.4%	0.322	0.242	0.033
	1/4	322.867	106.800	67.033	75.0%	0.318	0.243	0.025
	1/3	313.600	98.700	84.400	76.0%	0.319	0.240	0.031
	1/2	195.367	182.733	118.600	51.7%	0.524	0.426	0.027
2	Unfiltered	346.800	116.733	0.000	75.1%	0.317	0.240	0.035
	1/4	318.034	86.690	56.517	78.8%	0.319	0.239	0.034
	1/3	310.034	81.655	74.414	79.1%	0.320	0.242	0.032
	1/2	286.467	69.467	107.600	80.5%	0.323	0.245	0.019
3	Unfiltered	311.000	97.167	0.000	76.5%	0.316	0.242	0.039
	1/4	282.536	75.393	46.536	79.4%	0.323	0.246	0.046
	1/3	283.000	70.667	54.500	80.6%	0.314	0.239	0.040
	1/2	262.600	59.800	85.767	82.5%	0.319	0.241	0.049

TABLE II
AVERAGE CONSISTENCY AND ACCURACY FOR FOLLOWER 1, 2 AND 3

F. Future applications

The technology reported herein could be applied in the coordination of a group of two-wheeled vehicles including e-bicycles and self-balanced electric vehicles. The assistance of electric motors could benefit the performance of the proposed system because e-bike riders exhibit a more sustained acceleration and speed. However, further testing with data from e-bicycle riders needs to be conducted because E2W drivers take more risks, are less disciplined, and have high traffic-related number of accidents [33].

In particular, coordinated platoons of bicycles can be extremely useful to maximize the positive impact of green waves for cyclists when it is implemented in conjunction with vehicle-to-infrastructure technologies. The contribution of our solution to such green waves is twofold: *i*) smart bicycles using our control system would inform cyclists permanently when they were subscribed to a green wave, instead of being informed when they pass by the traffic light; and *ii*) it would trigger the green waves on collective demand. Copenhagen, and soon Dublin, have embedded smart cat's eye displays in the ground along shared bike-lanes to signal bikers when they ride synchronized with green waves [34]. Our solution conveys the same information to the HBI interface on the bicycle handlebar, simplifying the implementation of green waves in cities with limited infrastructure budget. Regarding green waves on demand, some solutions for single riders are being tested with the use of smartphone applications [35]. Our solution offers the benefit of attracting uncoordinated cyclists to platoons, which upon reaching a sufficient number of riders may evolve into a dedicated green wave, maximizing the benefit of prioritizing the traffic on demand.

Some of the challenges that impact the development of future applications based on coordinated cycling include the low accuracy of positioning-based systems, since most safety and control mechanisms rely completely on accurate positioning. In addition, a better multi-radio support from bicycles will boost their integration to Intelligent Transport Systems, for example, an alternative version of IEEE 802.11p may become necessary to enable bicycle-to-bicycle and vehicle-to-bicycle communications as a true integrated system. Finally, further research needs to be done in terms of safely and accurately displaying operational and contextual information to cyclists whether traveling by themselves or collectively. In cooperative systems such as the one presented herein, it is necessary to alert members of reckless behaviours that compromise the stability of the group through hybrid displays that complement haptic-based warnings with accurate visual

or auditory warnings.

IV. CONCLUSIONS

In this paper we have presented a cooperative cycling cyber-physical system. The proposed system integrates a Cooperative Adaptive Cruise Control (CACC), bicycle-to-bicycle communications, and a novel human-bicycle interface. The work is motivated by the need to improve safety and comfort for groups of cyclists circulating on crowded urban bicycle paths and cycle highways. From empirical studies conducted with our working prototypes, we conclude that the participants' responses to our system's signals were sufficient to preserve a cohesive group of cyclists although few acceleration adjustment responses were true positives.

Additionally, we have provided extensive simulations that integrate the human error factor collected from the empirical studies. The simulations also implement different filters that allow us to prevent cyclists from overreacting to system's stimuli, in a way that the filter does not compromise the platoon's coordination. Furthermore, we have shown the performance evolution of the platoon when participants improve their training. In general, the proposed system is able to achieve a desired spacing policy even for large platoon sizes (up to 10 participants) but it requires specific levels of training to avoid misinterpretation of the system's signals.

Coordinated platoons of cyclists can be extremely useful to maximize the positive impact of "green waves" for cyclists in smart cities and can be extended to other kinds of two-wheeled vehicles such as e-bicycles, mopeds and self-balancing vehicles.

REFERENCES

- [1] R. Kamphof and S. Voom, "A Strategic Knowledge and Research Agenda on Sustainable Urban Mobility," European Metropolitan Network Institute, The Hague, Netherlands, Tech. Rep., 2016. [Online]. Available: http://www.eukn.eu/fileadmin/Files/EUKN_Documents/EMI_Sustainable_Urban_Mobility.pdf
- [2] K. C. Heesch and G. Turrell, "Key influences on cycling for transport," *Journal of the Australasian College of Road Safety*, vol. 25, no. 4, pp. 43–46, 2014.
- [3] 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.
- [4] I. Heins and K. Wazlak, "The Cycling Boom in Berlin: A Challenge for Public Transport," *Public Transport International*, vol. 59, no. 4, 2010.
- [5] W. Jeon and R. Rajamani, "Rear vehicle tracking on a bicycle using active sensor orientation control," *IEEE Transactions on Intelligent Transportation Systems*, vol. 19, no. 8, pp. 2638–2649, Aug 2018.
- [6] U. Hernandez-Jayo, I. De-la Iglesia, and J. Perez, "V-alert: description and validation of a vulnerable road user alert system in the framework of a smart city," *Sensors*, vol. 15, no. 8, pp. 18480–18505, 2015.

- [7] S. Smaldone, C. Tonde, V. K. Ananthanarayanan, A. Elgammal, and L. Ifode, "The cyber-physical bike: A step towards safer green transportation," in *Proceedings of the 12th Workshop on Mobile Computing Systems and Applications*. ACM, 2011, pp. 56–61.
- [8] V. Campagnolo, "Electronically controlled speed change device for bicycles," 1999, uS Patent 5,865,454.
- [9] C. Outram, C. Ratti, and A. Biderman, "The copenhagen wheel," *A project by the MIT Senseable City Lab*, <http://senseable.mit.edu/copenhagenwheel/index.html>, 2009.
- [10] H. Steltenpohl and A. Bouwer, "Vibrobelt: Tactile Navigation Support for Cyclists," in *Proc. of 2013 international conference on Intelligent user interfaces (IUI)*. ACM, 2013, pp. 417–426.
- [11] S. B. Eisenman, E. Miluzzo, N. D. Lane, R. A. Peterson, G.-S. Ahn, and A. T. Campbell, "Bikenet: A mobile sensing system for cyclist experience mapping," *ACM Transactions on Sensor Networks (TOSN)*, vol. 6, no. 1, p. 6, 2009.
- [12] O. M. Abu-Sharkh and Z. Dabain, "Greenbikenet: An intelligent mobile application with green wireless networking for cycling in smart cities," *Mob. Netw. Appl.*, vol. 21, no. 2, pp. 352–366, Apr. 2016.
- [13] I. Tal, B. Ciubotaru, and G. M. Muntean, "Vehicular-communications-based speed advisory system for electric bicycles," *IEEE Transactions on Vehicular Technology*, vol. 65, no. 6, pp. 4129–4143, June 2016.
- [14] D. Bial, T. Appelmann, E. Rukzio, and A. Schmidt, *Improving Cyclists Training with Tactile Feedback on Feet*. Berlin, Heidelberg: Springer Berlin Heidelberg, 2012, pp. 41–50.
- [15] C. Bertram, M. H. Evans, M. Javaid, T. Stafford, and T. Prescott, *Sensory Augmentation with Distal Touch: The Tactile Helmet Project*. Berlin, Heidelberg: Springer Berlin Heidelberg, 2013, pp. 24–35.
- [16] S. Cespedes, J. Salamanca, J. C. Sacanamboy, and C. Rivera, "Poster: Smart networked bicycles with platoon cooperation," in *2014 IEEE Vehicular Networking Conference (VNC)*, dec 2014, pp. 199–200.
- [17] S. Cespedes, J. Salamanca, A. Yañez, C. Rivera, and J. C. Sacanamboy, "Platoon-based Cyclists Cooperative System," in *IEEE Vehicular Networking Conference*, Kyoto, Japan, 2015.
- [18] J. Salamanca, S. Céspedes, D. Vinasco, and A. Yañez, "Demo: A prototype for a platoon-based cyclist cooperative system," in *2016 IEEE Vehicular Networking Conference (VNC)*, 2016, pp. 1–2.
- [19] X. Lin, P. Wells, and B. K. Sovacool, "Benign mobility? electric bicycles, sustainable transport consumption behaviour and socio-technical transitions in nanjing, china," *Transportation Research Part A: Policy and Practice*, vol. 103, pp. 223 – 234, 2017.
- [20] M. Mendes, G. Duarte, and P. Baptista, "Introducing specific power to bicycles and motorcycles: Application to electric mobility," *Transportation Research Part C: Emerging Technologies*, vol. 51, pp. 120 – 135, 2015.
- [21] F. Behrendt, "Why cycling matters for electric mobility: towards diverse, active and sustainable e-mobilities," *Mobilities*, vol. 13, no. 1, pp. 64–80, 2018.
- [22] Mobycon, Fietsberaad, Ligtermoet & Partners, "Cycling in the Netherlands," Ministry of Transport, Public Works and Water Management. Directorate-General for Passenger Transport, The Netherlands, Tech. Rep., 2009. [Online]. Available: <http://www.fietsberaad.nl/index.cfm?lang=en&repository=Cycling+in+the+Netherlands>
- [23] M. Yamakita and A. Utano, "Automatic control of bicycles with a balancer," in *Proceedings, 2005 IEEE/ASME International Conference on Advanced Intelligent Mechatronics*, 2005, pp. 1245–1250.
- [24] C. Portilla, F. Valencia, J. Espinosa, A. Nuñez, and B. De Schutter, "Including bicycling in a multimodal urban street intersection: a mode-based predictive control approach," *Transportation Research Part C: Emerging Technologies*, vol. 70, pp. 27–41, september 2016.
- [25] hearable.world 2017, "The Hearable Universe 2017 Categorisation and Availability Infographic," 2016. [Online]. Available: <http://hearable.world/the-hearable-universe-2017>
- [26] H. Dambeck, "Too Many Bikes? Challenges in Europe's Cycling Boom," 2015. [Online]. Available: <http://www.spiegel.de/international/zeitgeist/bike-boom-popularity-of-cycling-leads-to-overcrowding-a-915598.html>
- [27] R. Rajamani and H. Tan, "Demonstration of integrated longitudinal and lateral control for the operation of automated vehicles in platoons," *IEEE Trans. Control Syst. Technol.*, vol. 8, no. 4, pp. 695–708, jul 2000.
- [28] R. Rajamani, *Vehicle dynamics and control*. Springer Science & Business Media, 2011.
- [29] G. A. Bekey, G. O. Burnham, and J. Seo, "Control theoretic models of human drivers in car following," *Human Factors*, vol. 19, no. 4, pp. 399–413, 1977.
- [30] T. Robinson, E. Chan, and E. Coelingh, "Operating platoons on public motorways: An introduction to the sartre platooning programme," in *17th world congress on intelligent transport systems*, vol. 1, 2010, p. 12.
- [31] C. Bergenhem, Q. Huang, A. Benmimoun, and T. Robinson, "Challenges of platooning on public motorways," in *17th world congress on intelligent transport systems*, 2010, pp. 1–12.
- [32] I. G. Jin and G. Orosz, "Dynamics of connected vehicle systems with delayed acceleration feedback," *Transportation Research Part C: Emerging Technologies*, vol. 46, pp. 46–64, 2014.
- [33] K. Tang, S. Dong, F. Wang, Y. Ni, and J. Sun, "Behavior of riders of electric bicycles at onset of green and yellow at signalized intersections in china," *Transportation Research Record*, vol. 2317, no. 1, pp. 85–96, 2012.
- [34] L. Lindholm, "Cycling in Copenhagen - the easy way," 2014. [Online]. Available: <http://denmark.dk/en/green-living/bicycle-culture/cycling-in-copenhagen---the-easy-way/>
- [35] C. R  th, "New App Helps Cities Prioritize Cyclists," 2016. [Online]. Available: <https://www.siemens.com/innovation/en/home/pictures-of-the-future/mobility-and-motors/urban-mobility-new-smartphone-app-for-cyclists.html>



Sandra C  spedes (IEEE M'12-SM'17) received her B.Sc.(2003) and Specialization (2007) degrees in Telematics Engineering, and Management of Information Systems, from Universidad Icesi, Colombia, and a Ph.D. (2012) in Electrical and Computer Engineering from the University of Waterloo, Canada. She is an Assistant Professor with the Department of Electrical Engineering, Universidad de Chile, Santiago, Chile and an Adjunct Professor at Universidad Icesi, Cali, Colombia. She serves as an Associate Editor for the journal IET Communications. Her research focuses on the topics of vehicular communications systems, cyber-physical systems, smart grid communications, and routing and protocols design for the Internet of Things.



Juan Salamanca holds a Doctoral degree from the IIT Institute of Design in Chicago, USA, a Master degree in Design Direction from Domus Academy in Milan, Italy, and a BA in Industrial Design at Pontificia Universidad Javeriana in Bogota, Colombia. He is currently Assistant Professor at the School of Art and Design of the University of Illinois at Urbana-Champaign, USA. His current research work is two faceted. One strand inquires for the participation of socially apt smart artifacts in socio-material interaction. The other explores the design of visual and tangible data for the achievement of unplanned collective goals such as urban commuting.



Alexis Y  nez studied Electrical Engineering at the Department of Electrical Engineering, Universidad de Chile, Santiago, Chile. He has worked on projects related with vehicular communications systems, as well as developing devices with the Internet of Things and the implementation of community networks. Currently, he is a M.Sc. student at the same department and a part-time instructor at Universidad Santo Tom  s, Santiago, Chile. His research interests include context-aware systems and machine learning applied to vehicular ad-hoc networks.



Daniel Vinasco studied Systems Engineering and Informatics at Universidad Icesi (2007), Cali, Colombia. A long time electronics enthusiast, he has a great affinity with microcontrollers, in special, with custom applications and developments under Arduino and Mbed platforms. He works with the private sector and universities on fast prototyping and hardware developments.