Vehicular Communications-based Speed Advisory System for Electric Bicycles

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*Abstract***— Smart transportation, an important dimension of smart cities, includes both intelligent and "green" transportation solutions. Cycling, as one of the most sustainable form of transportation, is and should be an important component of the smart cities. Electric bicycles, the most popular electric vehicles, subscribe to this type of transportation. They have several advantages when compared to traditional bicycles, but also issues that relate to battery limited capacity and long periods of charging. Consequently energy-efficient solutions for electric bicycles are of very high research interest. Research on vehicular communications-based energy-efficient solutions for electric vehicles is still in early stages. Among electric vehicles, electric bicycles distinguish themselves as a special class as they have different characteristics and road-related requirements. This paper proposes a novel vehicular communications-based speed advisory system for electric bicycles. The solution recommends strategic riding (i.e. the appropriate speed) when bicycles are approaching a signaled intersection to avoid high power consumption scenarios. The proposed approach includes a Fuzzy Logic-based wind-aware speed adaptation policy, as among all the other vehicles, bicycles are mostly affected by the wind. Experimental results based on a real test-bed and extensive simulations-based testing demonstrate that by using the proposed solution significant energy savings are recorded. In addition, an analysis on comfort-related metrics shows that the proposed solution can also contribute to improving the cycling experience.**

Keywords-component; vehicular communications, electric bicycles, energy efficiency, speed advisory, green transportation

I. INTRODUCTION

Smart cities, as a hot research topic for both academia and industry refer to making use of city facilities (buildings, infrastructure, transportation, energy, etc.) in order to improve people's quality of life and creating a sustainable environment. Smart transportation, as a fundamental dimension of smart cities, relates to both intelligent and "green" transportation solutions. Cycling is considered to be one of the most sustainable and green forms of transportation. It can be the answer to many problems of the nowadays' society including large amounts of greenhouse gas emissions, traffic congestion, limited parking, etc.

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Therefore, it is not surprising that cycling occupies an important place among smart transportation initiatives in particular and smart cities initiatives in general. For instance, promoting cycling is listed as main objective by the European Initiative on Smart Cities [1].

Lately, a modern form of cycling which uses electric bicycles has gained popularity. Research reports show that there is and there will be a worldwide increase of electric bicycles in the next years [2], [3]. Electric bicycles have many benefits. Like traditional bicycles, electric bicycles are environmentally friendly and are associated with very low gas emissions when compared to other vehicles. According to a study performed in 34 major cities in China [4], the CO2 emissions of electric bicycles are between 14-27g/pkm (passenger kilometre), about 10 times less when compared to conventional vehicles and 9 times less when compared to electric cars. In a top of 7 greenest vehicles[1] , electric bicycles are situated second with 5-30g CO2e/km depending on the type of fuel used for the electricity, after the traditional bicycles that have also associated CO2 emissions if their production is considered. Electric bicycles improve the traditional riding experience, especially for the people who are not so fit, in hilly terrain or in bad weather conditions (e.g. riding against the wind). In comparison with other green vehicles, electric bicycles have lower energy cost per distance travelled [5] and avoid other additional costs (e.g. parking, insurance, registration, etc.). Consequently, it is not a surprising fact that electric bicycles are the most popular among all electric vehicles and their popularity is increasing.

Electric bicycles have also disadvantages. Some of these are well-known disadvantages of cycling in general: weather conditions are affecting the cyclists the most among the traffic participants, and cyclists and pedestrians are the most vulnerable category in traffic. Moreover, electric bicycles have a weak point related to the same aspect that makes them capable of providing some of the already mentioned advantages to the cyclists: the battery. Because of the battery, electric bicycles are in general heavier than traditional bicycles, a varying extra-weight of 2 to 5kg than usually corresponds to the battery weight being added. Furthermore, the battery has a relative short autonomy, most of the electric bicycles claiming to have an autonomy range falling in the 16km-50km interval (range that is affected in time by the number of charges) and battery charging cycle between 2 and 6 hours [5]. This is a relative long period and makes

[1] http://shrinkthatfootprint.com/7-green-vehicles

performing research to find power-saving solutions for electric bicycles of very high interest. Some efforts have been focused on the battery technologies themselves, namely on building batteries with lower recharging times or on “in-bicycle” solutions, including using controllers that help save energy [6].

Vehicular networking is considered to play a crucial role in supporting the creation of smarter cities. It is based on “smart” inter-vehicle communications and with the infrastructure via so called V2X communications (i.e. V2V – vehicle-to-vehicle and V2I/I2V – vehicle-to-infrastructure/infrastructure-to-vehicle). V2X communications demonstrated their huge potential when designing not only intelligent transportation solutions [7], [8], [9], [10] and traffic management systems [11], but also green transportation solutions [12], [13]. The latter category was mostly focused on V2X communications-based solutions aiming to reduce fuel consumption and gas emissions. With the increased popularity of electric vehicles (EV), the focus has been recently moved on how V2X communications can help electric vehicles save energy.

In this paper, a novel vehicular communications-based Speed Advisory system for Electric biCycles (SAECy) is proposed. The solution exploits the I2V communications, namely the communication between traffic light (i.e. the infrastructure) and bicycle, in order to reduce the energy consumption of the electric bicycle and to improve cycling experience. The solution recommends strategic riding (i.e. the appropriate speed) when bicycles are approaching an intersection to avoid, if possible, stopping and starting due to red traffic light signals, which are high power consumption scenarios. The proposed approach includes a Fuzzy Logic-based speed adaptation policy independent of the traffic light phases which is wind-aware as among all the vehicles, bicycles are the most affected by the wind [14]. This policy provides a better speed adaptation to the wind conditions leading to increased savings in energy. Real life testing shows that an electric bicycle equipped with the proposed speed advisory system achieves significant energy savings as compared to a non-equipped bicycle. Moreover, extensive simulations-based testing demonstrates considerable energy savings obtained by the proposed solution in comparison with both a non-equipped bicycle and other similar approaches proposed in the literature. In addition, in terms of general comfort-related metrics the proposed solution also contributes to improving the cycling experience.

II. RELATED WORK

Vehicular communications are the core of some successful designs of both intelligent and green transportation solutions [12], [13]. Two main classes of green transportation solutions based on vehicular communications can be identified: eco-routing and eco-driving solutions.

A. Vehicular Communications-based Eco-routing Solutions

These approaches subscribe to the major class of vehicle routing solutions. Vehicle routing aims to find the most convenient path from start to destination based on certain criteria. In eco-routing the criteria is less gas emissions, fuel or energy consumption. Vehicle routing problem is well represented in the literature and a large plethora of solutions have been proposed. V2X communications capabilities allowed for advanced dynamic and real-time routing solutions based on more accurate information regarding real-time traffic conditions and events or road characteristics and conditions. Such solutions are proposed in [15], [16], [17] and are dedicated to internal combustion engine-powered vehicles. The authors show how they reduce fuel consumption and gas emissions. The best route decision is taken in [15] based on three factors: travel time of the road, the estimated fuel consumption and road congestion, while in [16] time is not considered in taking the best route decision, only the road characteristics and road congestion. In both approaches, vehicular communications are employed in data collection. The solution proposed in [17] has a different approach and can be said that is an event-driven eco-routing solution. The vehicle is following its regular route until an event warning message (e.g. accident, congested road ahead) is received via vehicular communications. Based on this information the vehicle is re-routed in order to avoid congestion that may determine increased fuel consumption and gas emissions.

Vehicular communications-based eco-routing solutions dedicated to EVs are in early exploration. However, solutions have been proposed for EVs too, such as the one presented in [18]. In this solution, machine learning techniques are employed in the computation of the most energy efficient route that integrates static map information and database information containing previous driving experience: road conditions and characteristics, traffic conditions, and charging stations. The data collection process is done via V2X communications. It is expected that the solutions proposed for internal combustion engine-powered vehicles to be brought and studied in the context of EVs as basically same external factors that influence fuel consumption and gas emissions, also affect the energy consumption in case of EVs.

B. Vehicular Communications-based Eco-driving Solutions

Solutions in this class advise on how to drive in order to reduce fuel consumption, gas emissions or energy consumption. This class includes many solution types. Among these, a representative type comprises solutions exploring the communications between traffic light and vehicles combined or not with V2V communications. Some of these solutions [19], [20] adapt the traffic light phases to the flow of vehicles approaching the intersection. When employing these approaches, the waiting times and the number of vehicles stopped at the intersection are reduced and consequently the fuel consumption and gas emissions also decrease. In both cited approaches the information regarding the density of the vehicles approaching the intersection is gathered via V2V communications and is further transmitted to the traffic light.

However, most approaches adapt the speed of the vehicles to the traffic light phases by exploiting the traffic light – to – vehicle communication (I2V communications) in order to avoid stopping to the signaled intersections or have inadequate speeds and maneuvers that are leading to increased fuel/energy consumption and/or gas emissions. These solutions are also known in the literature as Green Light Optimal Speed

Advisory (GLOSA) solutions. GLOSA approaches are presented in [21], [22], [23], [24], [25], and are dedicated to internal combustion engine-powered vehicles.

In [21] the focus is not on the mechanisms behind the speed advisory system, but on studying the factors influencing the reduction of the fuel consumption and gas emissions when such a GLOSA system is employed. The main results of the study reveal two such important factors: the gear choice and the distance from the traffic light where the message containing the information from the traffic light is received by the vehicles. For fuel consumption and gas emission measurements, the authors employ the Passenger car and Heavy duty Emissions Model (PHEM), developed at the Institute of Internal Combustion Engines and Thermodynamics of Graz University of Technology which is highly used in various R&D projects [26], [27].

In [22], [23], [24] and [25] the focus is on the speed advisory algorithm of GLOSA systems: finding the appropriate speed that will prevent stopping at the intersection if possible and minimize the fuel consumption and gas emissions. The approaches proposed in [23] and [25] do not consider in computing the appropriate speed any fuel consumption or gas emissions model, and employ these models when evaluating the performance of the GLOSA systems proposed only. These solutions consider the vehicle's different maneuvers only (e.g. acceleration/deceleration), and from this point of view, the approach presented in [25] is the most complex in the literature so far, as it considers all possible maneuvers. It also includes complex testing, the performance of GLOSA system being evaluated against penetration rate variations and using an almost realistic scenario. In [22] and [24] the authors do consider a fuel consumption and emission model when computing the appropriate speed, namely the Virginia Tech Microscopic (VT-Micro) model. The goal is to find the optimum speed, especially in [24] where a very complex algorithm is employed for finding this optimum. Specific to [24] when compared to the other presented GLOSA approaches is the fact that V2V communication is also employed in sending the traffic light phasing messages in a multi-hop architecture in addition to I2V (traffic light-to-vehicle communication). In the GLOSA solutions presented, the benefits in terms of fuel savings and gas emissions reduction vary in a range of 8% - 22%, the higher ranges being associated with simple testing scenarios that consider a single intersection. However, the lower range can be even lowered at small penetration rates as shown in [25].

Reference [29] reports a study performed in order to demonstrate that similar GLOSA systems proposed for reducing fuel consumption and gas emissions can be employed for reducing energy consumption of electric cars. The focus is not on computing the appropriate speed, simple policies being implemented in computation, based on the strategies used for internal combustion engine-powered vehicles. Instead, while showing benefits in terms of energy consumption reduction, the authors of the study underline the need for GLOSA systems for EVs to take into consideration EV specific characteristics as compared to internal combustion engine-powered vehicles.

Although electric bicycles subscribe to the EV class, they have different characteristics as compared to electric cars, and different power consumption models. Therefore, dedicated solutions need to be designed for electric bicycles so that this class of vehicles benefit from the communication with the traffic light. The potential of GLOSA applications helping electric bicycles save energy has been studied for the first time in [30] and [31]. The bicycles are able to receive messages from the traffic lights through the cyclist smartphone that can be mounted on the handlebar. The IEEE 802.11p communication interface, the main enabling technology of vehicular communications, is made now available for the smartphones as well [33]. The results of the studies demonstrate that electric bicycles can benefit from GLOSA systems as well, resulting in energy savings. However, in these approaches the studies are performed using a single intersection and important factors influencing bicycles specifically among the other vehicles, such as wind, are neglected.

III. THE SPEED ADVISORY SYSTEM (SAECY)

A. Overview

This section presents the overview of the proposed speed advisory system (Figure 1), the main inputs of the system and its functions. The main function of SAECy is to recommend the cyclist the appropriate speed when approaching a signalled intersection in order to avoid stopping at the traffic light. This is the main function of any GLOSA system designed for vehicles in general. In addition to this main function, a secondary function is included that increases the benefits in terms of energy efficiency. This secondary function is provided by a Fuzzy Logic-based wind-aware speed adaptation policy, is weather dependent only, and does not relate to the traffic light phasing. Its aim is to provide a better adaptation of the bicycle speed to the wind conditions with the purpose of reducing the energy consumption. Among all the vehicles, the bicycles are mostly affected by the wind [14]. This second functionality of the system is providing an extra recommendation to the cyclist: the advised speed is communicated in terms of maximum speed, and the cyclist should not exceed the indicated speed limit in order to increase the energy savings.

SAECy can be deployed on the cyclist smartphone that can be easily mounted on the handlebar. The smartphone is considered to be configured as a vehicle on board unit and has the IEEE 801.11p Wireless Access Vehicular Environment (WAVE) support [33]. This configuration enables the smartphone receive messages from the Road Side Units (RSU) associated to the traffic lights via IEEE 802.11p communication interface. These messages are generated by the *Traffic Light Controller* component that is associated to each traffic light. The Traffic Light Controller is considered to have a SPaT (Signal Phase and Timing) interface, thus able to generate and transmit the standardized SPaT and other associated messages such as GID (Geographical Information Data) messages [34], [35].

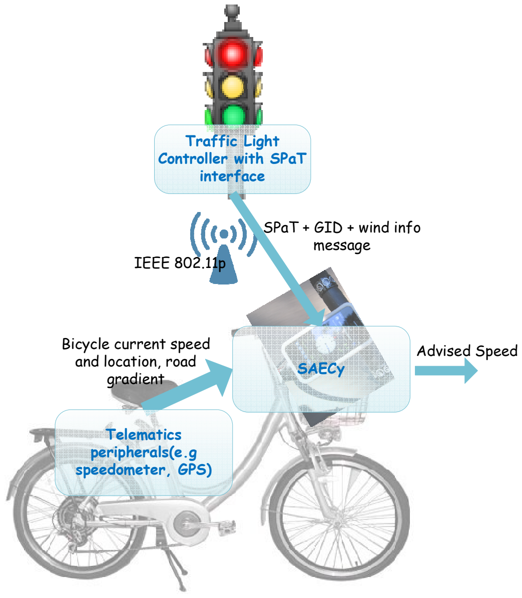

Figure 1. SAECy - Overview

Moreover in vehicular networking, the infrastructure, such as traffic lights, is used to disseminate updated and relevant weather information as they are local-based and can be easily obtained from local weather stations or through V2I communications [36]. In this approach the Traffic Light Controller is also in charge with providing wind information. Traffic Light Controller encapsulates all the information, SPaT, GID and wind information, into a single message.

The main fields of interest from SPaT message are the following ones:

- *timeToChange*, time until the current traffic light colour changes
- *signalState* , indicating the current traffic light phase

These message fields are stated for each lane and possible direction that can be taken at the intersection. The GID message provides the coordinates of the position of the intersection. Thus, the speed advisory system is receiving from Traffic Light Controller via I2V communications the necessary information related to the traffic light phasing and the position of the intersection.

From the *Telematics Peripherals* SAECy is receiving the coordinates of the current position of the bicycle, the current speed, direction and the road gradient. *Telematics Peripherals* can be an external device (e.g. speedometer, cycling computer) or it can be an application on the smartphone (e.g. the integrated GPS). In the first case the communication of the information can be ensured through the IEEE 802.15.1 interface.

B. Architecture

This section presents the architecture of SAECy. Each of the architectural components, illustrated in Figure 2, is detailed next.

1) Data Collector and Processor

This component collects the local information that relates to the bicycle and the network information received via I2V communications. The local information comprises the bicycle current speed and location. The network information is represented by a message that encapsulates SpaT, GID and wind information. The Data Collector and Processor component extracts the following information: *timeToChange*, *signalState*, intersection location coordinates and wind speed and direction (v_w, D_w). Based on the intersection location and the bicycle current location coordinates the component computes the distance till the intersection, d. This parameter together with *timeToChange*, *signalState*, bicycle speed (v_i), direction (D_B), and v_w are fed as input for the Computation and Recommendation Module component.

2) Computation and Recommendation Module

This is the core component of SAECy, its inputs being the aforementioned parameters fed by the Data Collector and Processor, while the output is the advised speed. Computation and Recommendation Module has 4 internal components: Advised Speed Computation component, a Fuzzy Logic System (FLS), Bicycle Power Consumption Model and Bicycle Dynamics Model. Next sub-sections present in detail these 4 components.

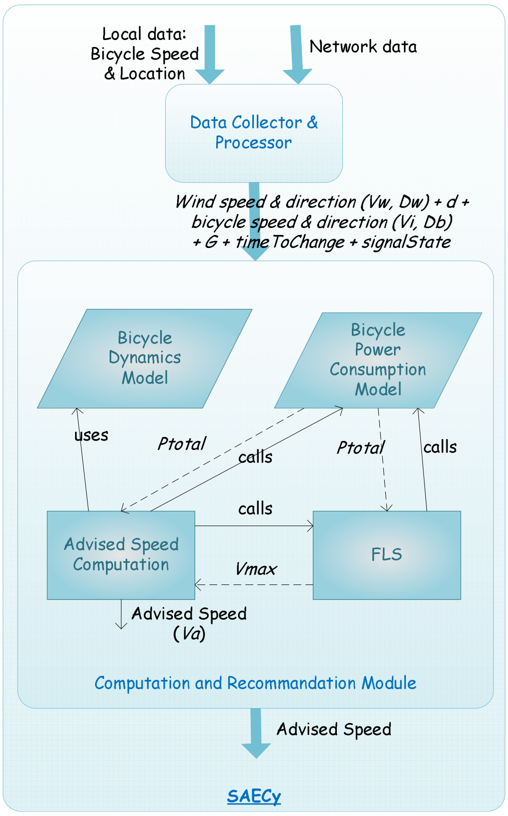

Figure 2. SAECy Architecture

a) Bicycle Power Consumption Model

SAECy uses the power consumption model that was employed in computing the theoretical power consumption of an electric bicycle in [5] and [14]. According to this model the total power consumption (P_{total}, see eq. (1)) is the sum of three terms: the power needed to overcome the air drag (P_{drag}, see eq. (2)), the power needed to overcome the slope (P_{hill}, see eq. (3)) and the power needed to overcome the surface resistance ($P_{friction}$, see eq. (4)). Note that in the computation of the P_{drag}, the wind is considered with its both influencing components: speed (v_w) and direction (D_w).The notations employed in the equations are explained in TABLE I.

$$P_{total} = P_{drag} + P_{hill} + P_{friction} \quad (1)$$

$$P_{drag} = \left[0.5 \cdot C_d \cdot D \cdot A \cdot (v_g + v_w \cdot \cos(D_w - D_B))^2\right] \cdot v_g \quad (2)$$

$$P_{hill} = (g \cdot G \cdot m) \cdot v_g \quad (3)$$

$$P_{friction} = (g \cdot m \cdot R_c) \cdot v_g \quad (4)$$

Most of the parameters used in the power consumption model have typical values in urban environments [5], therefore they can be preset in the system and allowed to be changed through an user interface if whished so. The same user interface can be used to set the *m* value which is dependent on the cyclist and that can be changed when the bicycle is used by another user. The variable parameters are v_g, D_B, D_w, v_w and *G*. v_g is provided by the components triggering the functionality of this model, while the rest of the parameters are provided by the Data Collector and Processor component.

TABLE I. POWER CONSUMPTION MODEL NOTATIONS

Notation	Explanation
C_d	Drag coefficient
D	Air density (kg/m^3)
A	Frontal Area (m^2)
v_g	Ground speed of the bicycle (m/s)
D_B	Bicycle direction (degrees)
v_w	Wind speed (m/s)
D_w	Wind direction (degrees)
g	Gravitational acceleration = 9.81 (m/s^2)
G	Slope grade
m	The overall weight: cyclist + bicycle + additional equipment (kg)
R_c	Rolling coefficient

As any theoretical model, the model employed has limitations: it does not best capture the power loss for executing the following maneuvers: acceleration, deceleration and starting the bicycle. The modifications in acceleration caused by these maneuvers are embedded in the theoretical power model via the speed factor, vg only. However, experimental results presented in section IV have shown that decelerating is not costly at all, on the contrary, the power drops to 0 for a moment when breaking, as illustrated in Figure 4, while the cost imposed by the acceleration is negligible. Regarding the power loss when starting the bicycle, this can be more significant and is further discussed in section IV.

TABLE II. BICYCLE DYNAMICS MODEL NOTATIONS

Notation	Explanation
d	The distance to the intersection
t	The time in which distance d is to be travelled
v_i	Initial speed of the bicycle (current speed of the bicycle before advised speed is recommended)
v_a	The advised speed
t_{ia}	The time passed till the moment the bicycle speed v_i becomes v_a
x_c	The distance the bicycle is assumed to be travelling at a constant speed after reaching the recommended speed necessary to cross the intersection without stopping
t_c	The time distance x_c is travelled
a	Acceleration or deceleration required so that v_i becomes v_a

b) Bicycle Dynamics Model

Equations of motion (5) and (6) – for uniformly accelerated/decelerated motion –, and (7) – for constant motion – were used to model the bicycle dynamics [32]. For hilly terrain these equations are adapted by considering in addition the gravitational acceleration.

$$v_a = v_i \pm a \cdot t_{ia} \quad (5)$$

$$v_a^2 = v_i^2 \pm 2 \cdot a \cdot (d - x_c) \quad (6)$$

$$x_c = t_c \cdot v_a \quad (7)$$

$$t_c + t_{ia} = t \quad (8)$$

The equations were adapted to our solution (see TABLE II. for more detailed explanations) and further computations were made. From equations (5), (6), (7) and (8) the value of v_a is deducted in equation (9).

$$v_a = \begin{cases} \frac{2 \cdot d}{t} - v_i, \text{ if } t_c = 0 \\ v_i + a \cdot t - \sqrt{|a \cdot (a \cdot t^2 + 2 \cdot t \cdot v_i - 2 \cdot d)|}, \text{ if } t_c \neq 0 \text{ and it is accelerated motion} \\ v_i - a \cdot t + \sqrt{|a \cdot (a \cdot t^2 - 2 \cdot t \cdot v_i + 2 \cdot d)|}, \text{ if } t_c \neq 0 \text{ and it is deccelerated motion} \end{cases} \quad (9)$$

c) FLS and Advised Speed Computation Components

FLS is a Fuzzy Logic system that implements the Fuzzy Logic-based wind-aware speed adaptation policy. Its functionality is triggered by the Advised Speed Computation component. The FLS has a single input and a single output and makes use of the Bicycle Power Consumption Model. The design of the FLS is focused on reduced computation complexity following design principles from [37]. It follows a zero-order Sugeno model known for its efficiency, reduced complexity and suitability for real-time systems [38]. The structure of the system is classic for a FLS. The full description of this structure is presented in the section C2), as it is intrinsically connected to its functionality which is described in this section.

Advised Speed Computation component is the core of the Computation and Recommendation module. It has as inputs all the inputs of the Computation and Recommendation module, while the output is the advised speed (v_a). The component makes use of the other components of the module as it can be seen from Figure 2 and it implements the main logic behind the computation of the advised speed, namely the SAECy algorithm that is described in the next section.

C. SAECy Algorithm Description

The algorithm employed in the computation of the advised speed is presented in two stages. As described in SAECy overview (section IIIA.), SAECy's complete functionality is provided by: a Green Light Optimal Speed Advisory function, the main function of any GLOSA system designed for vehicles in general, and a Fuzzy Logic-based wind-aware speed adaptation policy. In the first stage, the algorithm describes only the Green Light Optimal Speed Advisory function (Algorithm 1), which can work standalone. In this case, the FLS architectural block is not employed not being needed, whereas the rest of SAECy's architecture remains relevant. In the second stage, the Fuzzy Logic-based wind-aware speed adaptation policy is added to this function and included in the description of the algorithm (Algorithm 3). The latter represents the complete SAECy algorithm and encompasses all the functionality of the proposed speed advisory system.

1) Green Light Optimal Speed Advisory Function

The computation of the advised speed is described in details in Algorithm 1. It includes an initialization phase (ln. 1-6) that assigns the initial values to some of the parameters and the main procedure.

After the initialization phase, as long as the cyclist has not crossed the intersection yet, the speed of the bicycle is monitored continuously. Action is taken in two situations. First, if *signalState = "red" && timeToChange* < *t* (ln. 23), a new, decreased speed is recommended. Second, if *signalState = "green" && timeToChange < t && timeToChange* ≥ d/v_{max} (ln. 26), a new, increased speed is recommended. The parameters *t* and *d* are explained in TABLE II. , while the parameter v_{max} represents the maximum speed that can be recommended by the speed advisory system as this is the maximum speed that can be supported by the bicycle. Next paragraphs include further explanations in relation to this important parameter that conditions the computation of the advised speed (ln. 26). The advised speed is computed based on the Bicycle Dynamics Model (eq. (9)).

Note that this algorithm, although it does not include the Fuzzy Logic wind-aware speed adaptation policy, it does consider the wind speed, too. The algorithm is designed to take into account the characteristics of the bicycles in general as compared to other vehicles, and as it was underlined before, the bicycles are the only class of vehicles highly affected by the wind. In most of the GLOSA systems designed for vehicles in general, the maximum speed considered in computation, v_{max} is equal to what in our algorithm is represented by *maxSpeed*, which is the maximum speed or the speed limit of the vehicles. In the case of the vehicles in general this is given by the road rules and regulations. In the case of the bicycles, we chose as *maxSpeed* a safety value of 25km/h (6.95m/s). However, v_{max} is not always equal to this *maxSpeed* as in the case of the other vehicles and this is due to the special characteristics of the bicycles in general and electric bicycles in particular. First, the wind factor is highly affecting the power consumption and second, every electric bicycle has a power limit that can be sustained while riding. This power limit is associated to the *maxPower* parameter in our algorithm. Thus, v_{max} is computed based on the Bicycle Power Consumption Model considering all these factors (ln. 15 - 19). If v_{max} is not computed by taking into consideration these special characteristics of the bicycles, the advised speed recommended in the case: *signalState* = "green" && *timeToChange* < *t* && *timeToChange* ≥ *d/vmax* (the advised speed would be a new increased speed) could be too high in order to be sustained by the bicycles. Therefore, the Green Light Optimal Speed Advisory functionality could be affected in a certain degree. Such a use case is detailed in the results section, IV.B.4), and can be observed in Figure 19.

Algorithm 1: Green Light Optimal Speed Advisory Function

1 **INITIALIZATION PHASE:**
2 **BEGIN**
3 *maxSpeed* = 6.95 //*the maximum speed set for bicycle*
4 v_{max} = *maxSpeed*
5 $v_w = 0$
6 **END**
7
8 **GREEN LIGHT OPTIMAL SPEED ADVISORY**
9 **PROCEDURE:**
10 -triggered when a message is received from a traffic light and then
11 triggered in the monitoring cycle while the bicycle has not crossed
12 the intersection yet
13 **BEGIN**
14 **update** v_w
15 **compute** P_{total} //*eq. (1), where* v_{max} *replaces* v_g *in eq. (2), (3), (4)*
16 **while** (P_{total} > *maxPower*)
17 $v_{max} = maxSpeed - 1$
18 **compute** P_{total}
19 **endwhile**
20 **get** the distance till intersection, *d*
21 **get** the current speed of the bicycle, v_i
22 $t = d/ v_i$
23 **if** (*signalState* = "red" && *timeToChange* < *t*)
24 **compute** v_a**:** *eq. (9) for decelerated motion*
25 **endif**
26 **if** (*signalState* = "green" && *timeToChange* < *t* &&
27 *timeToChange* ≥ d/v_{max})
28 **compute** v_a**:** *eq. (9) for accelerated motion*
29 **endif**
30 //*the computed advised speed,* v_a, *is recommended to the rider*
31 **END**

2) Fuzzy Logic-based Wind-aware Speed Adaptation Policy

This policy is implemented as it was previously mentioned by the FLS component of the Computation and Recommendation Module. The FLS has a single input, the wind speed – v_w – , and a single output, v_{max}.

The structure of the FLS, includes a *Fuzzifier*, an *Inference Engine*, a *Defuzzifier* and a *Knowledge Rule Base* and is typical for a FLS.

Algorithm 2: Computing the membership function parameters

maxSpeed = 6.95 //*the maximum speed set for bicycle*
v_{max} = *maxSpeed*
$v_w = 0$
$v_w = v_w + windUnit$
$v_{windmax} = 10$
$i = 1$
while ($v_w < v_{windmax}$)
    compute P_{total} //*eq. (1), where* v_{max} *replaces* v_g *in eq. (2), (3), (4)*
    while ($P_{total} < maxPower$)
        $v_w = v_w + wind\_step$
    endwhile
    $v_{wi} = v_w$
    $v_{max} = maxSpeed - 1$
    i++
endwhile

Algorithm 3: Green Light Optimal Speed Advisory Function + Fuzzy Logic-based Wind-aware Speed Adaptation Policy

INITIALIZATION PHASE:
BEGIN
    maxSpeed = 6.95 //*the maximum speed set for bicycle*
    v_{max} = *maxSpeed*
    if (wind_info available from a weather server)
        init v_w
        call FLS => v_{max}
        $v_a = v_{max}$
        //*advise the cyclist to ride at a maximum speed of* v_a
    else
        $v_w = 0$
    endif
END

GREEN LIGHT OPTIMAL SPEED ADVISORY PROCEDURE:
-triggered when a message is received from a traffic light and then triggered in the monitoring cycle while the bicycle has not crossed the intersection yet
BEGIN
    update v_w
    call FLS => v_{max}
    get the distance till intersection, *d*
    get the current speed of the bicycle, v_i
    $t = d/ v_i$
    if (*signalState* = "red" && *timeToChange* < *t*)
        compute v_a**:** *eq. (9) for decelerated motion*
    endif
    if (*signalState* = "green" && *timeToChange* < *t* && *timeToChange* ≥ d/v_{max})
        compute v_a**:** *eq. (9) for accelerated motion*
    endif
    //*the computed advised speed,* v_a*, is recommended to the rider*
END

FINAL PHASE:
-intersection is crossed
BEGIN
    //*advise the cyclist to ride at a maximum speed of* v_a
END

Fuzzifier takes the crisp value as inputs and gives as output the corresponding Fuzzy degree of membership based on the defined membership functions.

Inference Engine maps the input fuzzified value to the output based on the "IF-THEN" rules contained in the ***Knowledge Rule Base***. The *Knowledge Rule Base* is the one that also contains the membership functions.

The membership function of v_w is trapezoidal and it is described in eq. (10) and (11). Trapezoidal function was used for the input parameter due to its suitability for real-time systems as it has reduced computation complexity [37].

$$\mu_{trapezoidal} = \begin{cases} \frac{x-a}{b-a}, & a \le x \le b \\ 1, & b \le x \le c \\ \frac{d-x}{d-c}, & c \le x \le d \\ 0, & otherwise \end{cases} \quad (10)$$

$\mu(v_w) = \{(a, b, c, d) |\ a, b, c, d$ *are the coefficients for the corresponding fuzzy*$\} = \{(0, 0.2v_{w1}, 0.8v_{w1}, v_{w1}), (0.8v_{w1}, 0.2v_{w2}, 0.8v_{w2}, v_{w2}), \ldots, (0.8\, v_{wi}, 0.2v_{windmax}, \infty)\}$ (11)

The membership function is parameterized and its parameters are computed in real-time based on the bicycle power consumption model. Thus, $v_{wi,}$ parameters are dynamically computed following a very simple and fast iterative procedure described in Algorithm 2. This process takes place at system initialization, when the power consumption model is set.

Being a zero-order Sugeno FLS, the IF-THEN rules have as consequents crisp values. This is the reason why the output was not associated with a membership function. The crisp values taken by the output v_{max} are described in eq. (12) and they are designed to correspond to each of the input's Fuzzy set described in eq. (11). Consequently these crisp values were parameterized, too. An example of an "IF-THEN" rule is given in eq. (13).

$\{|v_{w1}| - windUnit, |v_{w2}| - windUnit, \ldots, |v_{windmaax}| - windUnit\}$ (12),

where $|v_{wi}|$ represents the value of the v_{w1} rounded to the speed measurement unit used by the speed advisory system to present the recommendations to the cyclist, while *windUnit* represents one single unit of the same measurement. The choice of these outputs has been made mainly for practical purposes.

IF v_w *is Low* ***THEN*** v_{max} is v_{w1} *- windUnit* (13)

where *Low* is the Fuzzy set described by $(0, 0.2v_{w1}, 0.8v_{w1}, v_{w1})$ in eq. (11).

Defuzzifier's role in a FLS is to give the crisp value of the output applying different defuzzification methods on the output of the *Inference Engine*. In this case, the *Defuzzifier* uses the weighted average defuzzification method that is specific to the Sugeno fuzzy models. However, being a single-input single-output controller, the defuzzifier can be bypassed as the value of the output is given in crisp value directly by the *Inference Engine.*

The algorithm describing the full functionality of SAECy, the Green Light Optimal Speed Advisory function and the wind-aware speed adaptation policy is presented in Algorithm 3. Note that in this case, the solution will make two different recommendations depending on the context: a recommendation of the advised speed before intersections, where the cyclist is recommended to ride at a certain speed (the advised speed – ln. 33), and a second recommendation done whenever the wind information is made available that will recommend the cyclist a speed limit (now the advised speed is communicated as a maximum speed – ln. 39). The Green Light Optimal Speed Advisory procedure is the same as presented in section 1), with a single modification, the v_{max} is now computed by the FLS (ln. 7, ln. 22).

IV. Performance Evaluation

The proposed speed advisory solution, SAECy, is assessed both through experiments using a real-life test-bed and via simulations, using realistic scenarios. For validation purposes, the scenarios used for the experimental testing are also implemented in the simulation environment used for the simulation-based assessment. Comparable results are obtained, thus leading to the validation of our simulation model. However, in order to perform extensive testing, more complex scenarios are also tested via simulation.

Figure 3. Experimental Test-Bed

A. *Experimental Testing. Simulation Model Validation*

1) *Experimental Test-Bed Description*

This section presents the experimental test-bed, as captured in Figure 3, consisting of an electric bicycle enhanced with additional equipment. The main components of the electric bicycle are: a battery and an electric motor. The additional equipment consists of a meter for measuring the power consumption, a speedometer, a GPS device and a video recorder for monitoring the power meter. Moreover, the test-bed also includes the cyclist smartphone that is supposed to support V2X communications capabilities and has deployed SAECy.

The battery of the electric bicycle is a Lihium Ion battery with the following characteristics: 10Ah capacity, nominal voltage of 36V, charging time ~ 6h, full charge capacity ~ 300Wh and weight of 5kg. The claimed battery range is of about 36-40km (20 miles), but in real life testing the range was measured to be around 25-30km, offering an autonomy in the 1h – 1h 20 mins range.

The electric motor, mounted on the front wheel, has a wired connection with the battery and the pedal so that the motor is engaged by applying pressure to the pedal. The bicycle subscribes to the category of electric bicycles with assistance at start [39].

A Garmin Edge 500 [2] bike computer incorporates the functionalities of both speedometer and GPS-based location device. Garmin Edge 500 features a high-sensitivity GPS receiver that allows for accurate positioning and also for an accurate output of instantaneous speed. The power meter was connected according to the requirements to the battery and the electric motor. The outputs of the power meter are instantaneous power, voltage, current and the total power consumption per hour (i.e. energy consumption in Wh). A video recorder is used to monitor both the functionality of the meter and the instantaneous power output. The recorded values were then used in the result analysis. This method was preferred, as the serial output-based logging designed in the absentia of a built-in recording functionality is still very sensitive to the motion.

Other variables that affect the power consumption are shortly described next. The tire pressure, important parameter for a better rolling, was correspondingly adapted to the city roads scenario and to the weight of the cyclist (80kg), its value being 100psi. The total weight of the bicycle with all the equipment was 25 kg. Moreover, the wind speed during the tests was negligible, v_w = 0m/s, (it was checked using an electronic anemometer) and the tests were performed on a relative straight road with normal roughness, in excellent weather conditions.

2) *Scenarios Description*

The testing scenarios considered an electric bicycle that is approaching a signaled intersection. If the current speed is maintained, the cyclist will not be able to cross the intersection without stopping, being enforced to stop at the traffic light. There are two possible scenarios in which the proposed solution takes action when a bicycle is approaching an intersection and these are the testing scenarios considered.

In the first scenario (Scenario 1), when the distance between bicycle and traffic light is equal to a predefined distance *d*, the color of the traffic light is *green*. The time till traffic light changes (*timeToChange*) to *red* is 70s and the duration of *red* is 50s. This scenario corresponds to the condition expressed in the speed advisory computation algorithms (Algorithm 1 and Algorithm 3) as: *signalState = green && timeToChange < t*.

[2]Garmin Systems: https://buy.garmin.com/en-US/US/into-sports/cycling/edge-500/prod36728.html

In the second scenario (Scenario 2), when the distance between bicycle and traffic light is equal to the predefined distance *d,* the color of the traffic light is *red*. The time till traffic light changes (*timeToChange*) to *green* is 50s and the duration of *green* is 70s. In the tests performed, the role of the traffic light is taken by a timer. This scenario corresponds to the condition expressed in the speed advisory computation algorithms (Algorithm 1 and Algorithm 3) as: *signalState = red && timeToChange < t.*

Note that as the tests have been performed in no-wind conditions, the Fuzzy Logic-based speed adaptation policy is not triggered, thus the results obtained for Scenario 1 and Scenario 2 correspond to Algorithm 1.

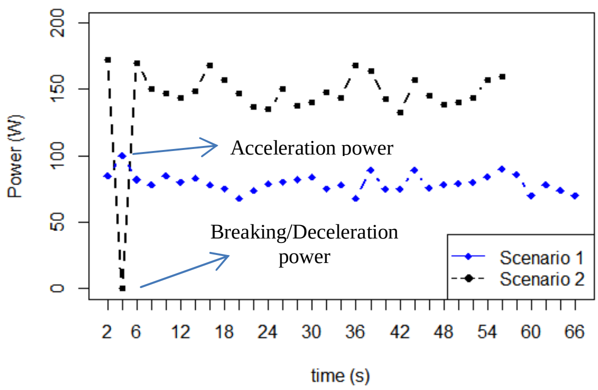

Figure 4. Power consumption for bicycle equipped with speed advisory system – test-bed results

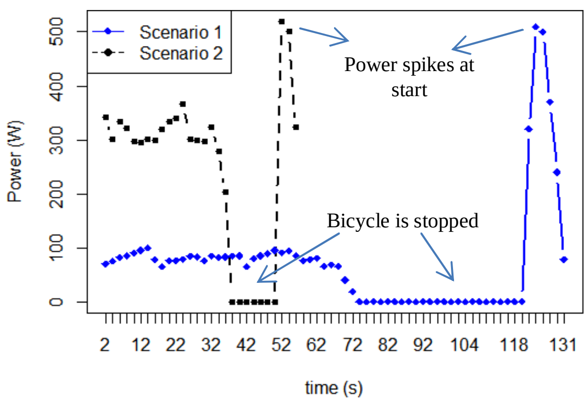

Figure 5. Power consumption for non-equipped bicycle – test-bed results

Power consumption is recorded for each of the two above scenarios in two cases: in the first case the bicycle is equipped with the speed advisory system (Figure 4), while in the second case the bicycle is not equipped (Figure 5). In the first case for each testing scenario, the rider makes use of the speed advisory system and consequently avoids stopping at the traffic light. It is assumed that the information regarding traffic light phasing and positioning is received via V2X communications when the distance between bicycle and traffic light is equal to *d*. The value of *d* is set in the test scenarios to 200m, typical value for transmission ranges in 802.11p. The rider ensures that the current speed when receiving the recommended speed is 10km/h for Scenario1, respectively 20km/h for Scenario 2. Power consumption is monitored on the distance *d*.

In the second case for each testing scenario, the electric bicycle is not equipped with the speed advisory system. The electric bicycle is in motion having the corresponding speed for each of the two scenarios: 10km/h for Scenario 1 and 20km/h for Scenario 2. This time, the rider does not receive any information while traveling the same distance (*d*) towards the traffic light and keeps the speed constant. When it gets at the traffic light, the rider stops. Power consumption is monitored for the same distance *d*.

3) *Results Analysis. Experimental vs Simulation Results*

In both testing scenarios, significant benefits in terms of power consumption were obtained when using the proposed speed advisory system. In the first testing scenario, Scenario 1, the proposed solution reduces the energy consumption with 46% when compared to the classic case of a non-equipped bicycle, while in Scenario 2 the energy consumption is reduced with 44%. These results were obtained using the previously described test-bed.

It can be seen in Figure 5 that the electric bicycle used in the test-bed is included in the category of electric bicycles with assistance at start as power spikes are noticeable when starting the bicycle. The power consumption model used in the implementation of the speed advisory system does not consider these power spikes as it is a generic model suitable for all types of bicycles. However, these power spikes have no influence in deciding the recommended speed as they appear only when starting the bicycle and our main goal is to avoid when possible stopping at the traffic light.

Same scenarios were implemented in the simulation model that is next described in section B1). However, in order to correspond to the real tests performed with the test-bed, the communication modelling between traffic light and bicycle is removed from the simulation model for these 2 scenarios, being considered that the bicycle receives the message from the traffic light exactly at distance *d* = 200m from traffic light. Moreover, the starting power spikes were introduced in computation in the simulation model in order to obtain a fair comparison between the test-bed results and simulation results. Comparable results were obtained, benefits of 45% for Scenario 1, respectively 41% for Scenario 2.

TABLE III. RESULTS SUMMARY EXPERIMENTAL VS SIMULATION TESTING

Testing environment		**Energy consumption reduction – equipped bicycles vs non-equipped bicycles**	
		Scenario 1	Scenario 2
Electric Bicycle with assistance at start	**Test-bed**	46%	44%
	Simulation	45%	41%
Electric Bicycle without assistance at start	**Test-bed**	24%	32%
	Simulation	19%	28%

Assuming that the electric bicycle used in the test-bed would be without assistance at start, the power spikes from start were removed, and the simulation model was left unaltered (without the power spikes previously introduced based on the experimental results). Again comparable results were obtained in terms of energy consumption reduction for the two testing environments, test-bed and simulation as it can be seen in TABLE III. that summarizes all the results related to the Scenario 1 and Scenario 2.

B. *Simulation-based Testing*

1) *Simulation Model*

The simulations are performed using iTETRIS[3] simulation platform designed in the context of a European FP7 project. The platform couples the traffic simulation capabilities of SUMO[4] and the network communication capabilities of ns3[5].

The values of the parameters used in the simulation model were chosen to correspond to the realistic conditions:

- D = 1.247 kg/m^3, A = 0.7 m^2, R_c = 0.004, C_d = 1 (typical values [5]).
- m = 105 kg (cyclist 80kg, bicycle 25kg – as used in the test-bed based testing)
- v_w was varied between 0 to 10m/s.
- *maxSpeed* = 6.95m/s
- *maxPower* = 400W (corresponding to the test-bed, but also this is the maximum instantaneous power while riding provided by most of the electric bicycles [5])
- IEEE 802.11p was used to model the communication between the infrastructure (traffic light) and the smartphone attached to the bicycle. The transmission range considered was 250m, within the range employed in other similar works [21]. Each Traffic Light Controller broadcasts information messages every second, typical frequency value chosen also in [21], [25]. The message size varies depending on the number of possible vehicle movements at the intersection, but is similar to those used in the literature [25], with the exception of 3 additional bytes used to carry wind information. In the simulations performed, the message size was between 31 bytes to 48 bytes.

2) *Scenarios Description*

This section presents the scenarios used to evaluate the performance of the speed advisory system. Basically, there are three testing scenarios, each represented by a different route with a different topology and different numbers of traffic lights on the way with the phases between 55 and 85s. These are real routes established on real map data, the map of Dublin, Ireland. The destination of each of the routes is Dublin City University (DCU, coordinates: -6.26263, 53.38507) as it can be seen on the maps (Figure 6, Figure 7).

First route (Route 1) starts at [-6.26263, 53.38507], has a simple, quite straight topology and has 6 traffic lights on the way (Figure 6). This is a simple scenario as the traffic lights from a straight route tend to be synchronized, thus for a relative constant speed the number of stops at traffic lights are relatively reduced.

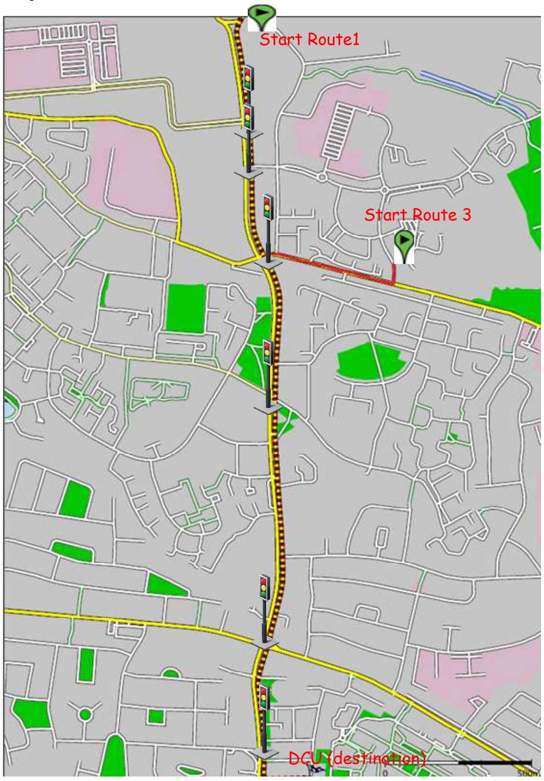

Figure 6. Route 1 and Route 3

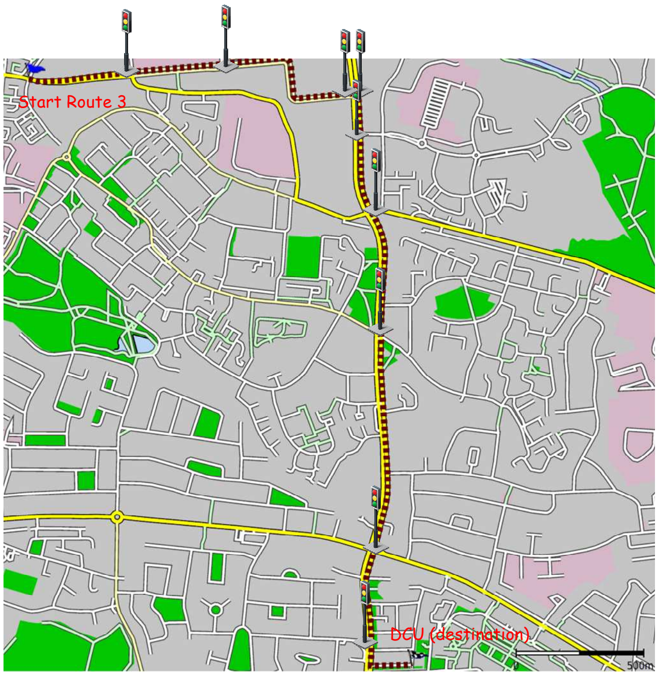

Figure 7. Route 2

Second route (Route 2) starts at [-6.28407, 53.40603] and

[3] iTETRIS website: www.ict-itetris.eu

[4] SUMO website: www.sumo-sim.org

[5] NS3 official website: www.nsnam.org/

has the most complex topology among the three routes, including more turns and having 9 traffic lights on the way (Figure 7).

Third route (Route 3) starts at [-6.25725, 53.40098] and has only 4 traffic lights on the way (Figure 6). Route 1 and Route 3 were chosen to be able to measure the benefits of the solution proposed for routes having less traffic lights and also for routes with simple topologies.

3) Comparison-based Performance Assessment

Two versions of SAECy are considered for performance assessment. The first version, SA1, implements the proposed approach having only the Green Light Optimal Speed Advisory function only (Algorithm 1), while the second, SA2, has the Fuzzy Logic-based wind-aware speed adaptation policy added to the Green Light Optimal Speed Advisory function (Algorithm 3).

In the simulation model it is also implemented a classic approach of a GLOSA system (C-GLOSA) proposed in [22]. The C-GLOSA approach was such implemented in order to correspond to the bicycle dynamics.

All these approaches are compared among themselves and also against the baseline which is represented by the common case when the bicycles are not equipped with any type of speed advisory system (noSA).

4) Results and Analysis

The proposed speed advisory system is evaluated in terms of energy consumption reduction and two comfort-related metrics: *number of stops* and *waiting times* at traffic lights cumulated over each route. In addition, the impact of the speed advisory system on the total travel time is analyzed, known as a highly important metric for assessing the quality of a travel [40], [41]. These metrics are studied against the variation of the wind speed from 0 to 10m/s.

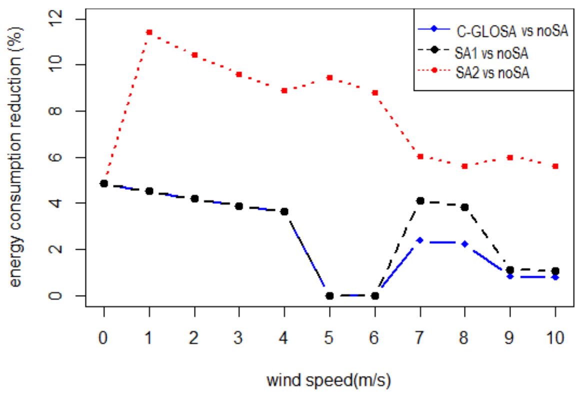

Figure 8. EC reduction – Route 1 (bicycle without assistance at start)

For the energy consumption reduction metric, two sets of results were obtained for each of the three routes. In the first set of results, the power consumption model was left unaltered, as it is described in section III B. This model corresponds to an electric bicycle without assistance at start.

For the second set of results, we considered that the bicycle is with assistance at start and as the parameters used in computation are compliant to the conditions in which the tests with the test-bed were performed, we introduced in computation the power spikes experimentally determined. The other metrics are not affected by this modification in the power consumption model, thus they are the same for the bicycle with or without assistance at start.

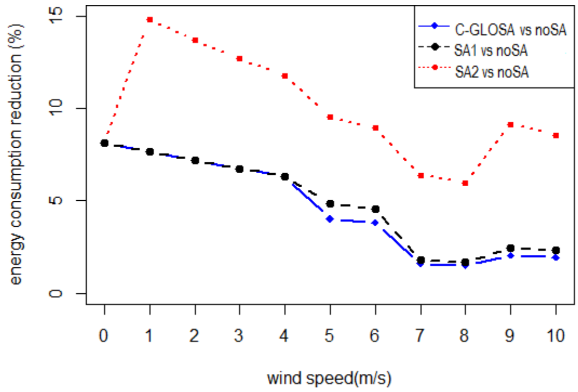

Figure 9. EC reduction – Route 2 (bicycle without assistance at start)

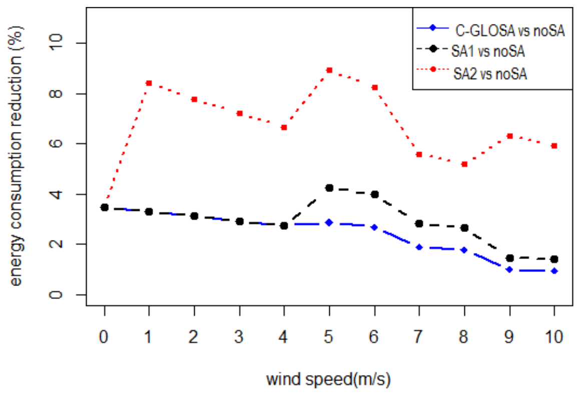

Figure 10. EC reduction – Route 3 (bicycle without assistance at start)

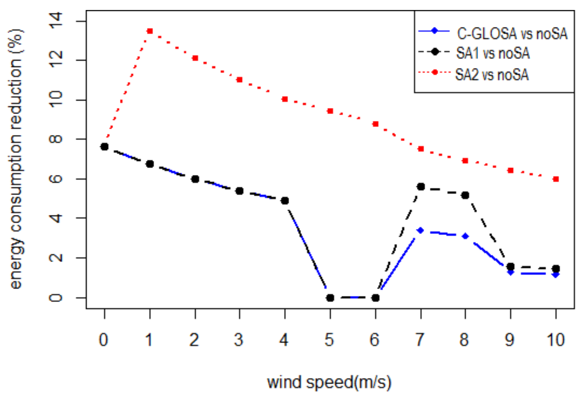

Figure 11. EC reduction – Route 1 (bicycle with assistance at start)

Energy consumption reduction metric evaluates the percentage of energy savings of the three approaches C-GLOSA, SA1 and SA2 against the baseline noSA allowing then for a comparison between them. Following a general analysis on the results of this metric (Figures 8-13) it can be said that SA2 clearly outperforms the other two approaches, C-GLOSA and SA1, for all the routes, and the energy consumption reduction is more significant in the case of the bicycles with assistance at start. SA1 approach is also outperforming C-GLOSA. Another observation that can be made is that the energy savings are more significant for Route 2, as this has the largest number of traffic lights and a more complex topology. A higher number of traffic lights and a more complex topology of the route determined an increased number of stops at the traffic lights along the way as it can be seen in Figure 14 as compared to the other routes, Route 1 and Route 3. Thus, for Route 2, the energy consumption reduction for the bicycles without assistance at start can reach to 15% for SA2 and 9% for SA1, while for bicycles with assistance at start the energy consumption reduction reaches 18% for SA2 and 13% for SA1.

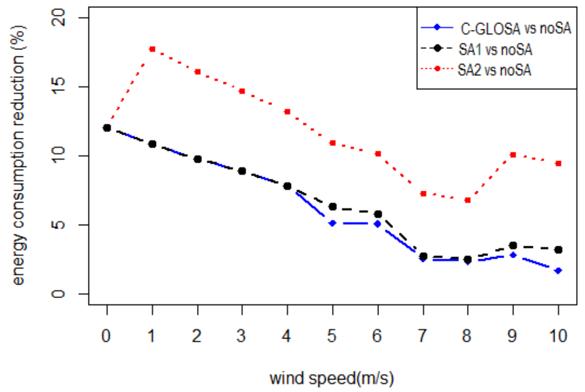

Figure 12. EC reduction – Route 2 (bicycle with assistance at start)

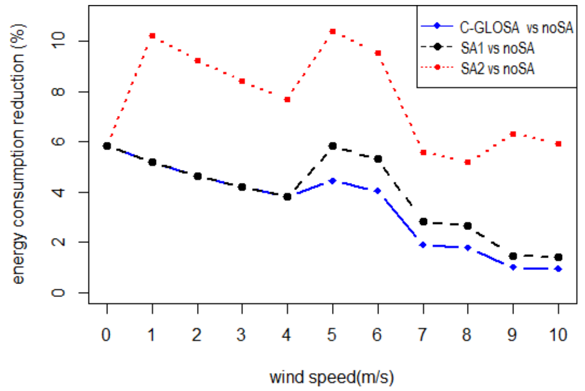

Figure 13. EC reduction – Route 3 (bicycle with assistance at start)

It can be seen that there are some fluctuations in the plots that are associated with energy consumption reductions. There are two reasons for these fluctuations. First reason is illustrated by the first fluctuation in the SA2 vs. noSA curve corresponding to the change in wind speed from 0m/s to 1m/s (Figure 8 – 13) and represents the increase in the energy consumption reduction due to bicycle's speed adaptation to the wind speed. The second reason of fluctuation is associated with the increase/decrease of the energy consumption reduction due to the numbers of stops avoided (e.g. the fluctuation of SA2 vs. noSA or SA1 vs. noSA curves in Figure 10). The number of stops to be avoided (Figure 14) varies due to the fact that the average speed of the bicycle is also varying with the wind speed imposed by power limitations. This is also the reason behind the waiting time curves variation (Figure 16 – 18).

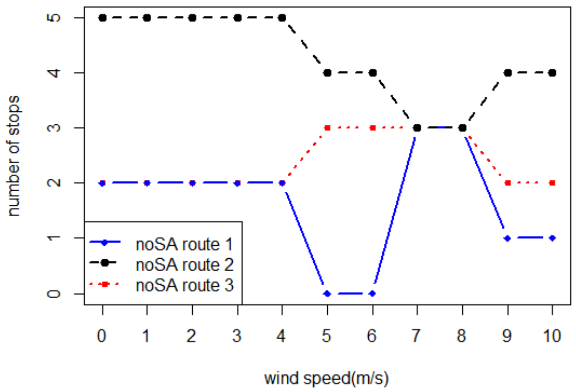

Figure 14. Number of stops for the non-equipped bicycle for the three routes

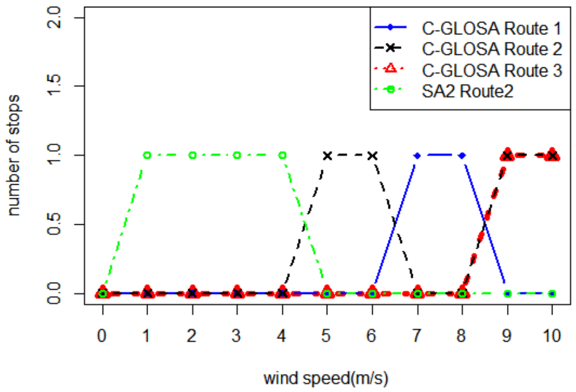

Figure 15. Number of stops for the equipped bicycle for the three routes

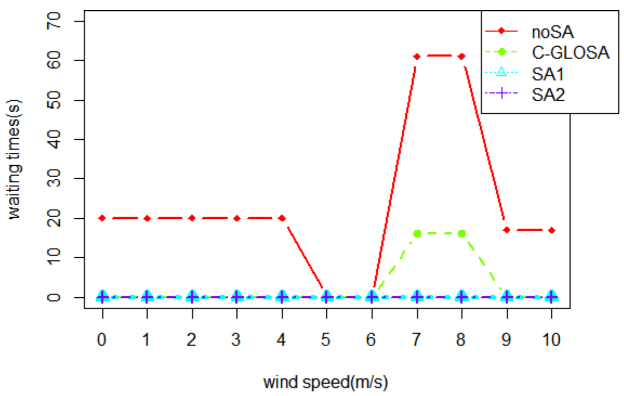

Figure 16. Waiting times – Route 1

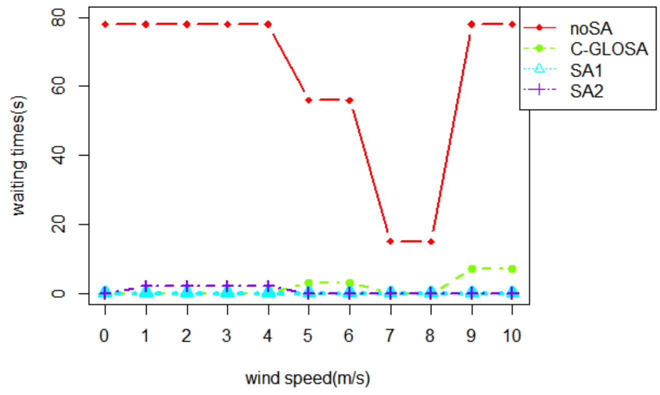

Figure 17. Waiting times – Route 2

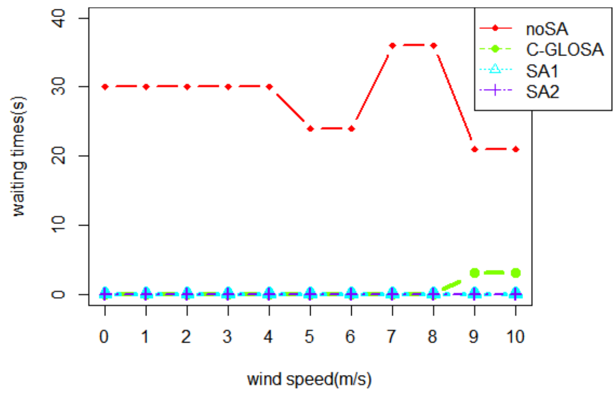

Figure 18. Waiting times – Route 3

Regarding the number of stops and waiting times, the proposed speed advisory system implemented in both forms SA1 and SA2 reduces these to 0, respectively 0s with one exception. This exception is caused by the fact that 2 traffic lights on the Route 2 are much closed to each other and there is not enough time to adapt the speed to avoid stopping at the second traffic light. However, the waiting time is very much limited to 3 s only (Figure 17). This situation can happen for any type of green light optimal speed advisory system such as the classic approach represented by C-GLOSA. It can be seen that C-GLOSA fails in a bigger proportion in reducing completely the number of stops at the traffic lights (Figure 15) and this is not caused by the positioning of the traffic lights. The failure is due to the fact that the advised speed to avoid stopping at the traffic light does not take into consideration the wind speed and recommends speeds that are not adapted to this important factor for the bicycles. Consequently, these speeds cannot be sustained by the bicycles and the bicycles end up stopping at the traffic light and also more power is consumed and waiting times are introduced (Figure 16-18).

The impact of the speed advisory systems on the total travel time is proven not to be substantial in most cases, as it can be seen from TABLE IV., TABLE V. and TABLE VI. However, in few cases, SA2 causes some delays at some wind speeds which is acceptable as it recommends a decreased speed than the one that can be sustained by the bicycle in order to decrease the energy consumption. Some of the largest delays in the total travel time imposed by SA2 are for instance 132s for Route 2 (TABLE V.), and 87s for Route 3 (TABLE VI.) when the wind speed is 9-10m/s. This means that SA2 adds approximately 2 minutes to a total travel time of 21 minutes in the first case, and 1.5 minutes to a total travel time of approximately 14 minutes in the second case, respectively.

TABLE IV. TOTAL TRAVEL TIME – ROUTE 1

Wind speed (m/s)	Total travel time (s)			
	noSA	**C-GLOSA**	**SA1**	**SA2**
0	469	467	467	467
1	469	467	467	474
2	469	467	467	474
3	469	467	467	474
4	469	467	467	474
5	505	505	505	572
6	505	505	505	572
7	664	664	663	669
8	664	664	663	669
9	722	720	722	788
10	722	720	722	788

TABLE V. TOTAL TRAVEL TIME – ROUTE 2

Wind speed (m/s)	Total travel time (s)			
	noSA	**C-GLOSA**	**SA1**	**SA2**
0	851	850	850	850
1	851	850	850	848
2	851	850	850	848
3	851	850	850	848
4	851	850	850	848
5	945	940	938	1011
6	945	940	938	1011
7	1020	1022	1022	1105
8	1020	1022	1022	1105
9	1278	1278	1278	1410
10	1278	1278	1278	1410

TABLE VI. TOTAL TRAVEL TIME – ROUTE 3

Wind speed (m/s)	Total travel time (s)			
	noSA	**C-GLOSA**	**SA1**	**SA2**
0	554	553	553	553
1	554	553	553	569
2	554	553	553	569
3	554	553	553	569
4	554	553	553	569
5	654	653	653	669
6	654	653	653	669
7	754	754	753	776
8	754	754	753	776
9	857	857	856	944
10	857	857	856	944

At the end of this section, a set of results is presented for all three routes that show the power consumption vs. time and in which the modifications in terms of bicycle speed vs. time, number of stops, waiting times and total travel times can be clearly noticed. All the cases discussed were considered: rider with no advisory system, rider with C-GLOSA, rider with the proposed speed advisory system having GLOSA function only (SA1) and rider with the proposed speed advisory system having the complete functionality (SA2). These results are displayed in Figure 19 – 21 and are meant to provide a better understanding on the previously presented results and a better comparison between the non-equipped bicycles and the bicycles equipped with the different speed advisory solutions.

The wind speed considered was 7m/s. This speed was chosen due to the fact that it reflects two special cases. The first special case is in the context of route 1 and reflects the use case of C-GLOSA that does not take into account the wind factor and consequently recommends *maxSpeed* = 6.95m/s which is impossible to be maintained due to bicycle's power limitations. Consequently, stopping at the traffic light is not avoided (Figure 19 – portion of C-GLOSA curve, after time step 79, where power equals 0). Moreover the energy consumption also increases on the portion of road where the unreachable recommended speed is forced (Figure 19 – portion of C-GLOSA curve, around time step 37, where power reaches 400W).

The second case is in the context of route 2, where the SA2 causes some delay to the total travel time, however due to the average lower power consumption over time, the energy consumption is still reduced. It can be seen in all the figures corresponding to all three routes (Figure 19 – 21) that the Fuzzy Logic-based weather aware speed adaptation policy implemented in SA2 results in an energy consumption decrease on average, leading to a higher energy savings.. This energy saving is more significant than that of SA1 or C-GLOSA which focus on avoiding stopping at the intersection only. The stops at the intersection for the non-equipped bicycle (noSA) can be easily identified in the graphs when the power consumption is 0. It can also be seen how the speed advisory systems avoid the stops by recommending for instance lower speeds. The lower speeds are marked by lower power consumption (e.g. Figure 21, the SA2 curve around time step 317 has the power value around 100W).

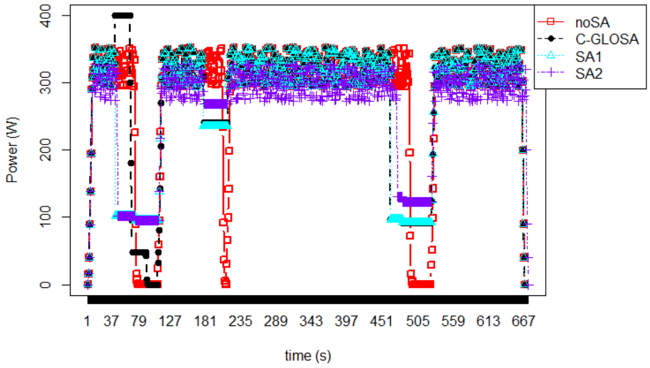

Figure 19. Power vs time – Route 1

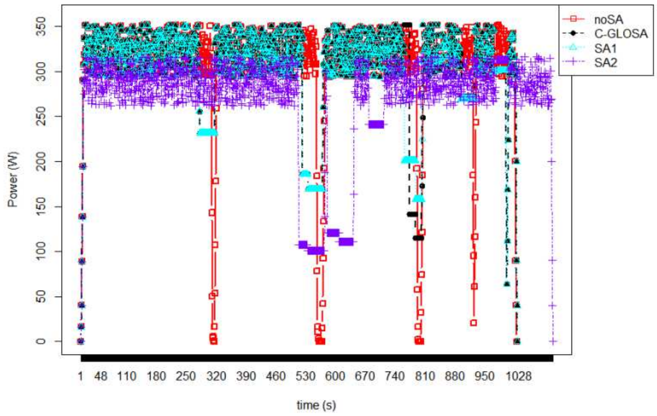

Figure 20. Power vs time – Route 2

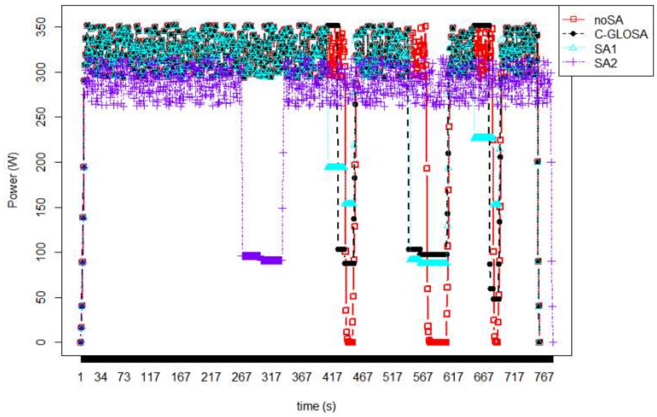

Figure 21. Power vs time – Route 3

V. CONCLUSIONS

This paper has proposed SAECy, a novel vehicular communications-based speed advisory system dedicated to electric bicycles. The solution subscribes to the class of GLOSA systems based on the traffic light to vehicle communications (I2V communications). The proposed solution recommends strategic riding (i.e. the appropriate speed) when bicycles are approaching an intersection to avoid high power consumption scenarios. Moreover, the approach also includes an innovative Fuzzy Logic-based wind-aware speed adaptation policy as among all the other vehicles, bicycles are mostly affected by the wind. Testing results have shown how this speed adaptation policy increases the energy savings of the electric bicycles.

Experimental results based on a real test-bed have shown that the proposed speed advisory system is leading to energy savings of up to 46% vs. the baseline (non-equipped bicycles) for the electric bicycles with assistance at start and up to 32% vs. the baseline for the electric bicycles without assistance at start. The test-bed was also used to validate the simulation model further employed for extensive testing on more complex scenarios. Simulations performed on the same scenarios used for the test-bed lead to comparable results. Due to logistics constraints, these scenarios include a single traffic light and they follow the energy consumption on a relative short distance.

Therefore more extensive testing was required to be performed using the validated simulation model. Considerable more complex scenarios were analyzed, on long distances, with different number of traffic lights and different topology. The solution was also compared against a classic GLOSA system proposed in the literature. Energy savings of up to 18% vs. the baseline have been obtained for the bicycles with assistance at start and up to 15% vs. the baseline for the bicycles without assistance at start. As compared to the classic GLOSA solution, our speed advisory system can increase the energy savings with up to 7%. In addition, an analysis on comfort-related metrics has shown that the proposed solution can also contribute to improving the cycling experience.

In the context of improving mobility modelling and simulations, the creation of micro-simulation models for bicycles and cyclists and their integration with the existing vehicular traffic is a work in progress. Based on this work, new steps can then be taken in the context of the proposed solution. Future works include the study of the proposed solution for multiple bicycles using cycling lanes, considering different factors such as: penetration rate of the technology, compliance rate and other characteristics that can be modelled in the context of the cyclist behaviour based on the future micro-simulation models for the cyclists. Further on, the proposed solution can be studied for the bicycles using the same lanes as other types of vehicles.

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