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RESEARCH ARTICLE

Evaluation of Cycling Safety and Comfort in Bad Weather and Surface Conditions Using an Instrumented Bicycle

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ABSTRACT Understanding how vulnerable road users (cyclists and pedestrians) behave enables the construction of better roadways with adapted geometric and surface design which leads to improve cycling safety and comfort. This study examines the behavior of cyclists using an instrumented city bicycle that allows collecting exact data about bicycle dynamics, trajectory, and speed, as well as essential information to study the behavior of the cyclists, their reaction to the different features of the road surface and geometric design, and their interaction with other road users such as pedestrians, vehicles and other cyclists. 22 cyclists participated in an experiment following a predetermined route in Stockholm, Sweden. The route consisted of a circuit with different types of cycling facilities in order to study the different interactions (cyclist-car and cyclist-pedestrian), the circuit was divided into 3 zones: the first is mixed traffic, the second is a separate cycling lane and the third is shared pedestrian-cycling path. The results show significant data to evaluate cycling safety and comfort in snowy weather conditions and the perception-reaction behavior of cyclists; accordingly, the infrastructure-related risks were evaluated from subjective and objective points of view. In this paper, we propose a new concept to evaluate cycling behavior. This concept allows us to evaluate cyclists' behavior through the calculation of Behavioral Risk Indicator (BRI) based on different risk factors owing to weather, road and traffic conditions, interaction with other road users and reaction to infrastructure drawbacks. The applications of the proposed concept allow us to evaluate the risks caused by multiple traffic factors and infrastructural drawbacks and study cyclist–bicycle–road interactions and their influences on cycling safety. In addition, the concept provides a new foundation for establishing cycling safety measures that could be applied to improve the infrastructure and reduce traffic accidents in order to attract more people to ride bicycles.

INDEX TERMS Bicycle instrumentation, experimentation, cycling safety and comfort, road characteristics, cycling risk indicator.

I. INTRODUCTION

Road traffic crashes represent the eighth leading cause of death worldwide, with more than 1.35 million fatalities each year and up to 50 million injuries [1]. More than half of

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all road traffic fatalities are among vulnerable road users (pedestrians, cyclists, and motorcyclists); in fact, several countries reported an increased number of fatalities among cyclists in recent years, probably reflecting the increased popularity of this mode of travel [2]; cycling fatalities represents 4% of traffic fatalities with more than 50 000 deaths per year [3]. A study by [4] shows that the risk for a cyclist to be killed in a traffic accident is 3 times higher than for a car driver when considering the time spent in transportation. Cycling also poses a risk to other road users, in 2016, three pedestrians were killed in crashes with cyclists in the United Kingdom [5].

In the European Union, more than 2000 cyclists are killed annually, which represents 6% of all traffic fatalities [6]. In Sweden, 17 cyclists were killed in 2019 (8% of all traffic fatalities), in 2018, 921 persons suffered Maximum Abbreviated Injury Scale (MAIS) in-which 40% were cyclists [7]. In Norway, the risk of injury, expressed as fatalities per kilometer, for cyclists is about 7.5 times higher than for car drivers [8], [9]. In the Netherlands, bicycles cause around 5.5 times as many fatal injuries per kilometer as cars do [10]. A study in Portland (US) reported that nearly one in five cyclists experienced an event leading to injury, regardless of gender, age, body mass index (BMI), or cycling skill level [11]; injuries were mainly caused by 'slipping' (35%) or 'collision with a car' (19%). In 2015, in Japan, among 4117 traffic fatalities, 572 (13.9%) cyclists were killed [12] where the most frequent cause of death was head injuries [13]. In France, despite the fact that cycling represents 2.7% of all commuting trips, cyclists represent 5% of accidents mortality; in 2017, 173 cyclists were killed in road accidents (which represents an increase of 6.8% compared to 2016), 68 % of them were over 50 years old and 44% were over 65 years [14]; this value has never been reached since 2006 (181 were killed). 93% of people killed or hospitalized in accidents involving a cyclist were cyclists; 12% of them were killed or hospitalized during self accidents and 3% in accidents with another cyclist. According to a survey in 2005, only 14.5% of cyclists in France wear helmets, despite the fact that helmets can help to reduce the severity of accidents [15].

Looking at the causes of cycling accidents, the literature shows that the 'Imprudence' of the cyclist was the cause of the accident in 26% of reported cases, and 'Distraction' was responsible for 11% of accidents [16]. In Belgium, a study showed that men have more accidents than women as they cycle more frequently for a longer time and larger distances. (83%) of the investigated accidents that occurred during a trip to or from work, 53% of the accidents took place during the morning peak hours and 17% during the evening peak hours [16]; the morning peak hours are the most dangerous moment of the day to cycle to work [17], this could be explained by the aggressive behavior of both motorists and cyclists during the busy morning commute which increases the likelihood of having an accident [17]. Another study shows that a typical collision involving cyclists being hit by turning motorized vehicles occurred due to the cyclist's presence in the blind spot of the driver [18]. Cycling accidents may also occur due to the combined effect of low visibility near intersections and the cyclists' behavior in terms of their velocity [19]. The safest areas tend to be where people cycle the most and where cycling infrastructure is most developed [10]; this is known as the "safety in numbers" effect, and applies to both cyclists and pedestrians: The greater the number of cyclists, the more they are expected and observed, and so the risk decreases [19]. According to the literature review, bicycle instrumentation could be used for different purposes and contexts such as: determining the trajectory classes for cyclists, collecting naturalistic cycling data, studying the bicycle's dynamics, and defining cyclists' behaviors. For example, a bicycle was instrumented with gyroscope, accelerometer, absolute encoder, and hall effect sensors to determine the trajectory of cyclists in London [20]. In [21] and [22] the researchers used an instrumented bicycle to validate a multi-body model. The bicycle was equipped with five sensors i.e. an inertial measurement unit (IMU), an inclinometer, and incremental rotary encoders. In [23] the researchers used a bicycle equipped with GPS, video camera, accelerometer, compass, and gyroscope to discover and characterize conflict points between cyclists and other road users.

In Gothenburg (Sweden) a bicycle was equipped to collect naturalistic cycling data, the instrumentation consists of two cameras (one facing forward and the other facing the cyclist's face), a GPS, two inertial measurement units (IMU), two pressure brake sensors, a speed sensor, and a push-button (to allow the cyclist to report any risks) [24]. The outcomes reveal that cycling near crossings increases the danger, particularly when there is sight blockage (e.g., buildings and hedges), whereas poor maintenance and road surface condition raised the risk by ten times [25], [26]. Reference [27] have studied the effect of the appearance of cyclists on drivers' overtaking proximity, it was found that overtaking distance decreases when vehicles pass a male cyclist, a cyclist wearing a helmet, or a cyclist cycling away from the road's edge. Whereas in [28], the results show that the passing distance decreased when motorcycles overtake a cyclist compared to cars and small trucks. Cyclists appeared unstable when a bus (longer passing time) passed them. Another study by [29] shows that vehicle drivers do not provide a comfortable passing distance to cyclists in the adjacent cycling lane.

To shed light on the safety of vulnerable users, this study analyzes how the infrastructure affects the behavior of weak users and in particular how their interaction takes place. An on-site test was conducted in Stockholm with 22 cyclists, using an instrumented bicycle to trace the kinematic parameters during the route. This paper presents an innovative approach that deals with an objective evaluation of behavior related to the use of sensors, and a subjective one that is extrapolated by questionnaires answered by each participant. The paper is structured as follows: the second part is devoted to the experimenting procedure; the third part describes the experimentation conducted using the instrumented bicycle and discusses the results of all participants; the fourth part is dedicated to the analysis of the eye-tracker videos and the behavior of cyclists and their interaction with the road infrastructure and other road users; the fifth part shows the analysis of the questionnaire answered by the participants regarding their evaluation of cycling safety and comfort, and finally the conclusion.

II. EXPERIMENT PROCEDURE

A. PARTICIPANTS

22 cyclists were involved in the study, 14 male (Mean age = 37.9, SD = ±13.4) and 8 female(Mean age = 32.4, SD = ±14.1). They were recruited by sending emails to the students and employees of the Royal Institute of Technology in Stockholm (KTH) and the Research Institutes of Sweden (RISE) and posting on the social media groups of Stockholm. Participants represented a homogeneous sample, which had an average cycling experience of 30.9 years (SD: ±15.9) for males and 26 years (SD: ±15.8) for females, an average cycling frequency of 4.9 trips/week (SD:±2.3) for males and of 3.1 trips/week (SD: ±2.2) for female and an average cycling distance of 43.9 km/week (SD:30.5) for males and 34.4 km/week (SD: 25.5) for females. 64% of the users are familiar with the experiment route (57% of males, 75% of females).

B. EXPERIMENT ROUTE

The route (3.6 km) was located in the north of Stockholm, it begins and ends at the Integrated Transport Research Lab (ITRL). The circuit is divided into three zones considering the different use of the road and the geometric design (Fig.1):

1) zone 1 consists of a mixed-traffic street with a 30 km/h speed limit without a separate cycling lane;
2) zone 2 includes an on-street separate cycling lane without a physical barrier for most of it and a shared bicycle-bus lane for the rest;
3) zone 3 consists of a shared pedestrian-cyclist way passing between trees and parking lots that separate the path from passing traffic.

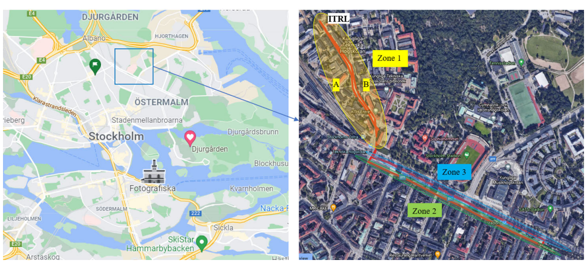

FIGURE 1. The predetermined route of the experiment in Stockholm (not to scale).

C. PROCEDURE

In the beginning, the participants signed a standard consent form including brief details about the experiment, the data collected, and the following analysis. After the adjustment of the sensors, they were asked to wear a helmet and a reflective vest (optional) and to follow the predetermined cycling path using GPS map displayed on a mobile mounted on the handlebar. The test was composed of two sessions: 1. in the first session, the temperature was −3 to −11 degrees, and the road surface was a mix between snow sludge and ice along the experiment route; 2. in the second session, the temperature was 3 to 9 degrees, and the surface was wet in some places and dry in others with accumulated snow sludge at some spots like intersections. During the test, each participant passed through eleven traffic lights, four of them intersected major roads (main crossings), whereas the rest intersected secondary roads. After the cycling task finished, the participant completed a questionnaire related to personal general information such as age, gender, weight, and cycling experience; and their evaluation of the experiment route regarding safety and comfort.

D. INSTRUMENTATION

The participants had to use two definite instruments: an instrumented bicycle and a mobile eye tracker. The special glasses called Tobii Pro-Glasses 2 is a Mobile Eye-Tracker created to record the gaze of the participant during the experiment, a visual angle of 82° horizontal and 52° vertical, a microphone to record the ambient sounds, and protective lenses.

A city bicycle with winter tires and a single-speed transmission system was used in this experiment (Fig. 2), the following sensors and devices were installed on the front and rear parts of the bicycle: 1. Hall Effect Sensor to count the number of rotations per minute (RPM) for the front wheel to calculate its angular velocity. 2. A triaxial accelerometer. 3. Garmin Edge 130 plus includes a positioning system and internal memory to save data from other Garmin sensors. 4. A potentiometer to measure the steering angle. 5. Inertial Measurement Unit (IMU) unit and a GPS. 6. A laser scanner. 7. Power source. 8. A speed sensor. 9. Power meter pedals. 10. Cadence sensor.

III. RESULTS AND DISCUSSION

In order to study the different factors influencing cycling safety, a specific data analysis has been carried out. In fact, the cyclist's behavior was studied in both an objective view, evaluating the results of the instruments used, and a subjective one, by analyzing the questionnaire given to the participants.

A. KINEMATIC OUTPUTS ANALYSIS

The use of Garmin system allowed us to quantify the behavior of cyclists in terms of speed, power, and cadence. All these factors have been 'normalized', i.e. zero values were eliminated (when the cyclist was stationary). Fig.3 shows the average normalized speed for all participants for the complete experimental route, and separately for each zone in both snowy and dry surface conditions. Comparing cycling in both conditions, it is noticed that the speed decreases by 15%

FIGURE 2. **Schematic of the instrumented bicycle, more details about the different sensors following the correspondent numbers below.**

(from 15.73 km/h in dry conditions to 12.45 km/h in snowy conditions). This speed reduction could be explained by the cyclists' cautiousness to avoid slipping and other weather-related risks. The average speed when cycling on a dry surface matches the universal average cycling speed, which is 16 km/h [30].

The highest average speed for all participants was recorded in zone 2 with 13 km/h on snow and 17 km/h on dry surface conditions, this could be explained by the existence of a separate cycling lane on a flat-straight street. In zone 3, where the geometry is similar to zone 1 but surface and traffic conditions are different, the average speed decreased to 12 km/h in snowy and 15 km/h in dry surface conditions; this could be due to the increase of conflict when sharing cycling path with pedestrians; this complies with the results found in the literature [31]. On the other hand, the effect of slopes on cycling speed appears when comparing zone 1A (snow: 12.4 km/h, dry: 17.2 km/h) where the slopes are mostly downhill, and zone 1B (snow: 11.6 km/h, dry: 14.4 km/h) where the slopes are mostly uphill. The average maximum speed for all participants was recorded in zone 2 with 20.2 km/h on snowy and 24.4 km/h on dry surfaces, whereas the maximum individual speed is 26.2 km/h on snowy and 29.9 km/h on dry surfaces. Moreover, in zone 3, the legislation suggests a speed limit of 10 km/h for the cycle-pedestrian shared path [32]; this limit was not respected by cyclists, particularly when the surface is dry. The average normalized speed on the snowy surface for male participants is 13.8 km/h and 10.8km/h for females, the maximum speed recorded was around 17.5 km/h for a 46-year-old male, while the minimum speed of 7.2 km/h was recorded for 58 years old female.

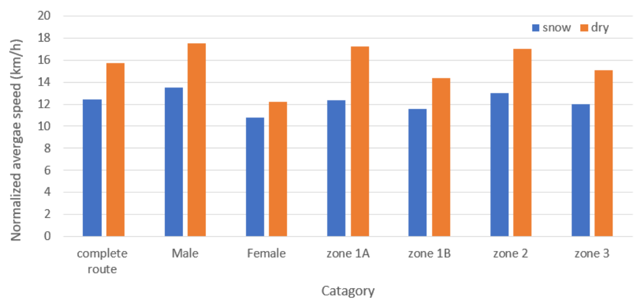

FIGURE 3. **The mean normalized speed using Garmin speed sensor, the data categorized according to gender and different zones of the experimental route.**

Fig.4 shows a difference between cycling on dry or snowy surface conditions; comparing the data for each zone, it can be seen that the average normalized power for zone 1b is the highest in both dry and snowy conditions; this is explained by the uphill slope at the beginning of the zone, on contrary, the power consumed in zone 1A is the lowest since the slope was mostly downhill. In some cases, the consumed power does not reflect the correspondent speed, for example, in zone 2 where the highest average and maximum speed were recorded.

Fig. 5 shows the average cadence in different zones and surface conditions. The average cadence for the complete route on the snowy surface is 50 RPM, whereas it rises to 60 RPM in dry conditions, as users gain confidence in driving due to increased wheel-road grip. The cadence recorded in zone 2 which records the lowest value, shows an opposite trend to the speed, which records the highest average compared to other zones, this shows that the increase in speed is

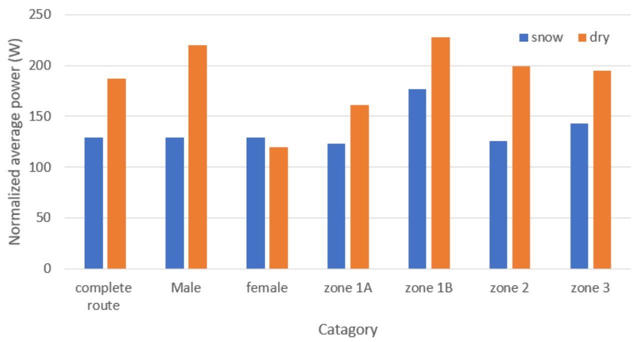

FIGURE 4. The mean normalized power extracted from the pedaling power meter from Garmin.

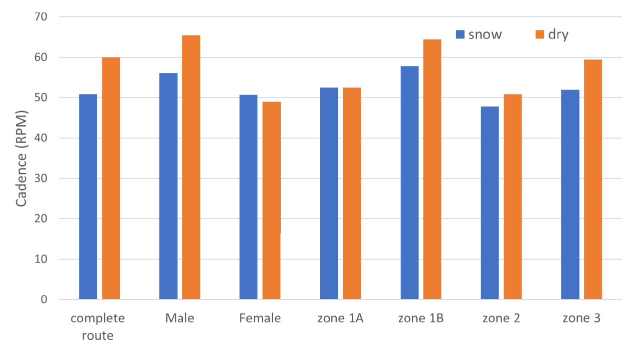

FIGURE 5. Cadence extracted from the cadence sensor of Garmin.

not necessary due to the cadence rate. Zone 1B recorded the highest cadence and power and the lowest speed; this could be explained because of the slipperiness between the wheel and the road surface and the negative impact of the uphill slope.

B. ANALYSIS OF PERCEPTION-REACTION LOOP USING THE EYE-TRACKER VIDEOS

19 videos were recorded using the mobile eye-tracker, 16 of them on snowy surface conditions and 3 on dry surface conditions. These videos were analyzed in detail to study cyclists' behavior and their interaction with different features of the infrastructure and with other road users. The results show that when cyclists approach the two-way cycling path in zone 1 and 3, 62% of the participants cycled on the right side, whereas in 33% of the cases, they cycled to the middle or left side of the path, opposing cyclists possibly approaching from the opposite side. This could be explained by the lack of vision of the markings and the separating line due to the snow accumulation, in one case the cyclist had to use the left lane to avoid collision with pedestrians walking on the cycling path. It is also noticed that in 5% of the cases, the cyclists did not use the cycling path, due to the lack of attention to the traffic vertical signs and the absence of on-street marking that leads to it.

Analyzing the interaction with cars, the results show that in zone 1, when cycling on-street without a dedicated cycling area, 50% of the participants cycled in the middle of the street, unless when a car was approaching from behind, they slide to the right allowing it to pass; 31% cycled on the right side of the street and 19% cycled behind cars without passing them. This risky cycling behavior is explained by the lack of space on the right side because of the snow accumulation. On the other hand, the video analysis shows that in 3 cases there was a risk of collision with parked cars leaving their spots, where the cyclist braked heavily and stopped shortly before the car. In zone 2, there were 3 risks of collision because of the heavy traffic and cars blocking the cycling lane.

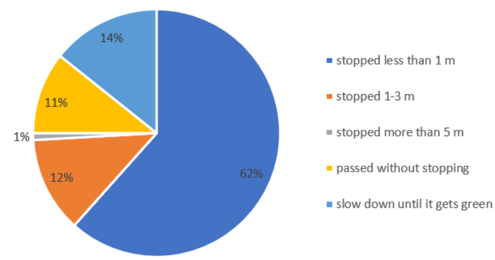

FIGURE 6. The reaction of cyclists when encountering red traffic lights.

When encountering a red traffic light, the results show that in 14% of the cases, the cyclists slowed down until waiting for the signal to turn green, while in 11% of the cases they broke the traffic light without slowing down. In the case of stopping, the majority (62%) stopped at less than 1 m from the traffic light (Fig. 6). On the U-turn between zone 2 and 3, where the zebra crossing is painted and a traffic signal is absent, the results show that 61% of the participants looked back to check the traffic and then turned left and crossed the street, whereas in 11.1% of them crossed with looking back (Fig.7), this behavior may put them in danger, as depending on hearing is not sufficient, especially with the spread of electric cars which have silent motors.

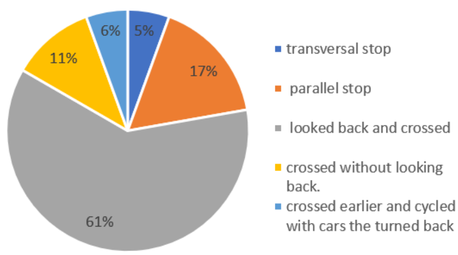

FIGURE 7. U-turn crossing behavior between zone 2 and 3 with the absence of traffic light.

Studying the interaction of cyclists with pedestrians crossing the street shows that in only 4% of the cases the cyclists stopped when realizing the pedestrians were waiting to cross. In 44% of the cases, the cyclists continued cycling in front of pedestrians, after they started crossing the street, whereas in the rest of the cases (52%) the cyclists slowed down allowing pedestrians to cross, then accelerate again when the crossing is clear. The videos analysis shows that in zone 1, there was a risk of collision with pedestrians in 7 cases, mainly because the cyclist did not stop. In zone 2 there was a collision risk with one pedestrian for the same reason. In other cases, some cyclists crossed the street between pedestrians at the traffic light, which caused discomfort for both sides. In zone 3, where the cycling path is shared with pedestrians, 28% of the cyclists passed the pedestrians from the left, 67% switched between passing from right or left, and 5% passed always from the right side. When the cyclists crossed the streets going through the cycle-pedestrians zone, in 28% of the cases they did not give attention to the crossing traffic and contained cycling normally, whereas in the rest of the cases they checked for oncoming traffic before crossing.

When interacting with buses in zone 2, in 43% of the cases, cyclists passed the bus from the left while giving attention to their left and checking for passing cars, whereas in 43% of the cases, they stayed behind the bus, and in 14% of the cases they passed the bus from the right side when they got enough space from empty parking spots. One cyclist said he would rather not cycle on a bus lane since he can not hear the bus sound.

C. SUBJECTIVE EVALUATION OF CYCLING SAFETY AND COMFORT

After the end of the experiment, the participants filled out a questionnaire in regard to their cycling experience and their evaluation of cycling safety and comfort during the experiment. They were handled a map showing the different zones of the experiment in order to help them to answer the questionnaire properly. Table 1 summarizes the general data collected by the participants and some of their responses about the risks facing them when cycling in cold weather and snowy surface condition.

It is noticed that the cyclists, who were using winter tires before the experiment, felt a higher grip, especially on ice patches. The cyclists who use them for the first time confirmed this and reported they felt a better grip and were more stable (7 out of 11 agreed on that). However, some participants felt that they consumed more effort compared to regular tires. One participant commented: 'The winter tires were better than regular ones on the ice and hard-packed snow, but no difference on looser snow; however, the friction on the dry road is higher compared to regular tires.' In regards to the effect of wind on cycling comfort, 6 participants experienced a negative impact of the wind, not only due to the effort increase but also the discomfort felt when the cold wind blows on their faces and eyes.

Fig.8 shows the response of all the participants regarding their evaluation of safety for each zone along the experiment route. The results show that 13 participants (59%) chose the 3rd zone as the safest. They explained their choice by the absence of passing vehicles; the wide separation to the carriageway; the flatness of the road; and even though the surface was covered with snow, it was hard and covered with gravel which reduce slipperiness. These outcomes are consistent with the literature that confirms that safety is associated with protected and separated bike facilities [33]. Contrary to the fact that most participants chose zone 3 as the safest, 5 of them (23%) ranked it as the least safe due to the existence of pedestrians, and the lack of traffic lights at some intersections. 12 participants (55%) chose zone 2 to be the least safe, this is mainly because of its stance on the carriageway without a physical barrier with passing traffic; the constraint to cycle on the carriageway as the cycling lane was covered by snow and ice (as seen in the recorded videos; the snow was evacuated from the carriageway and accumulated on the cycling lane); and the sharing the lane with buses, which were not loud enough to be detected; one of the participants commented 'The bike lane was very icy and I had the feeling I could fall quite unexpectedly, and cars overtake me at a quite high speed.' On the other hand, zone 1 (A+B) was ranked the safest 7 times (32%) and the second safe 16 times (73%), this significance is explained by better surface conditions (less snow and ice); and low and slow traffic. On contrary, the participants who chose it as the least safe explained their feeling by the steep slopes towards the end of the zone and the absence of a separate cycling lane.

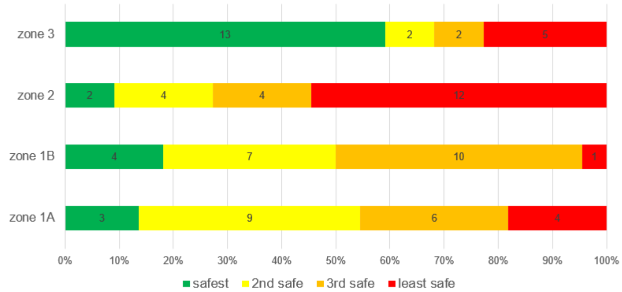

FIGURE 8. The evaluation of the participants of the safety for the different zone of the experiment route, the numbers on the bars represents the number of the participants who voted for the mentioned zone.

Considering cycling comfort, 17 participants (77%) chose zone 1B as the most power-demanding among the three zones; they explained this mainly because it is located on an uphill street with steep slopes, however, 3 of them mentioned it was because it locates towards the end of the experiment route where they got exhausted. On contrary, the 3 who chose zone 1A said they consumed more power because it was downhill. 20 participants said that cycling on snow sludge is the hardest, whereas 2 said it is harder to cycle on ice (Fig. 9).

Fig. 10 shows the evaluation of the participant of comfort when cycling on different surfaces and different traffic sections; it is noticed that 9 of them (50%) chose zone 2 as the most comfortable and 9 (41%) as the second most comfortable. The reasons behind that according to them are the scariness of snow sludge, the smooth and flat surface, and the separate cycling lane. Zone 3 was chosen to be the least comfortable by 9 participants due to the unevenness of the surface caused by small stones spread on top to reduce slipping, the accumulation of snow-sludge mixed with dirt coming from the unpaved surface, and the existence of pedestrians. 8 (36%) chose zone 1B to be the least comfortable due to the steep slopes and the snow accumulation.

TABLE 1. Descriptive characteristics of the study group (means ± SD or N %).

Characteristic	Male	Female	Total
N	14 (64%)	8 (36%)	22
Age (yrs)	37.9 (±13.4)	32.4 (±14.1)	35.9 (±13.3)
Wight (kg)	78.8 (±9.0)	62.5 (±12.5)	72.9 (±12.6)
Cycling experience (yrs)	30.9 (±15.9)	26 (±15.8)	29.1 (±15.3)
Cycling frequency (trips/week)	4.9 (±2.3)	3.1 (±2.2)	4.2 (±2.3)
Cycling distance (km/week)	43.9 (±30.5)	34.4 (±25.5)	40.5 (±27.9)
Cycling on snowy/icy surface	10 (71%)	7 (87%)	17 (77%)
Usage of winter tires	7 (50%)	3 (37.5%)	10 (45.4%)
familiarity with the experiment route	8 (57%)	6 (75%)	14 (64%)
foot slippery when stopping	3 (21%)	3 (37.5%)	6 (27%)
feeling less safe when cycling in cold weather	7 (50%)	2 (25%)	9 (41%)
the comfort of eye-tracker (positive)	8 (57%)	3 (37.5%)	11 (50%)
increasing effort because of the wind	5 (35.7%)	1 (12.5%)	6 (27.3%)

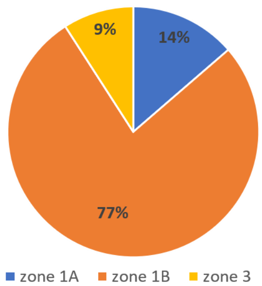

FIGURE 9. The response of the participants about where they consumed more power comparing between zones.

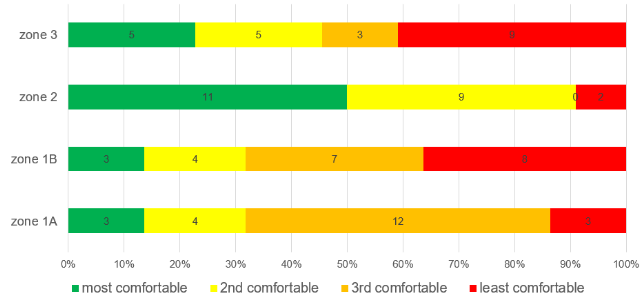

FIGURE 10. The response of the participants about where they felt more comfortable comparing between zones.

Regarding the participants' perception of cycling on a snowy surface, the results show that all participants increased their effort and reduced their speed to avoid slipping, besides, they experienced steering difficulty when cycling on snow sludge and ice, with the possibility to get stuck in dips and grooves left by previous bikers, walkers, and prams. 6 participants experienced foot-slip upon stopping especially at the red lights, 3 of them anticipated this to happen and slowed down before stopping. Considering the weather conditions, 9 participants evaluate the test as less safe for the cold situation besides the discomfort due to wearing special clothes and thick gloves which limits body movements and impairs visibility.

D. EVALUATION OF INFRASTRUCTURE RELATED RISKS AND ASSOCIATED CYCLIST' BEHAVIOR

After the analysis of the different outputs of the sensors (details published in [34]), the eye-tracker videos, and the post-experiment questionnaire, the effects of road surface characteristics and geometric design on the behavior of cyclists and their interaction with other road users were studied. In the following points, we present different evaluated risks, caused by the geometric misdesign or lack of maintenance of the road surface, the associated behavior of cyclists, and the type of accident related to these risks. A comprehensive summary is shown in Appendix A.

1) The decreased low adhesion, due to the icy/snowy surface condition, may lead to the sliding of the bicycle's wheels or foot slipping when the cyclist stops. The analysis of the videos and the questionnaire show that 6 participants experienced foot slippery when stopping and all of them experienced wheel slippery because of the ice and snow accumulation. In order to reduce the impact of low road adhesion, cyclists need to increase attention, reduce their speed, use winter tires for their bicycles, and wear appropriate winter shoes to improve contact when stepping on a slippery surface.
2) By analyzing the output signals of the IMU, the tri-axial accelerometer, and the laser scanner, it is possible to correlate vertical acceleration, lateral acceleration, and yaw rate to the calculated road profile. The analysis of the signals shows that the unevenness of the road, caused by the misimplementation or damage of the road surface, leads to an increase in the vertical acceleration, this increase of the vertical acceleration -besides affecting cycling comfort [35], [36]- leads to an increase in the lateral acceleration and roll rate. This lateral instability of the bicycle may subsequently lead to rollover or lane departure. The analysis of the eye-tracker videos revealed the reaction of cyclists when encountering road surface defects such as cracks and potholes; the cyclists react in three different ways: the first is avoiding the defects in the road surface which leads to lane departure, the second is reducing their speed to minimize the impact on their stability and comfort, and the third is continuing cycling at the

same speed when they do not notice the defect or have limited time to react; this behavior may put them in risk of rollover. In order to avoid the risks associated with road surface damage, cyclists are advised to repeatedly check the road surface to detect any defects at an early stage to take the right decision whether by avoiding them without conflicting with other vehicles or slowing down in case they are unavoidable. This finding is correlated to the outcomes of [37] which shows that potholes were the most significant pavement distress for perceived comfort and safety; the eye-tracker data analysis showed that unevenness of the road surface drew the greatest fixations for the longest period, potentially raising a safety risk. Another research shows that building better surfaces will improve safety feeling and encourage more people to ride bicycles [35].

3) The increase of conflict points with pedestrians at intersections and on the shared pedestrians-cycling path increases the possibility of collision with them, especially when exceeding the speed limit when sharing the cycling path with pedestrians. In order to reduce this conflict, it is recommended to separate cyclists' crossings from pedestrians' by adding a distance of 1 or 2 m between them; moreover, it is safer and more comfortable to build special infrastructure for cycling independently from walking areas and separate them with barriers or clearance zone.
4) The existing vertical and horizontal traffic signs and road markings did not properly direct the cyclists to follow the cycling lanes, the analysis of the eye-tracker videos and the subsequent questionnaire show that some cyclists failed to follow the bicycle lane in zone 1 as they did not detect it due to the absence of appropriate signs and unfamiliarity with the experimental route, this increased the conflict with vehicles, as cyclists were forced to cycle on-street, which may lead to a collision with other vehicles. In order to better direct cyclists, it is recommended to increase the number of traffic signs and place them within the field of view of the cyclist; to paint directional arrows on the pavement; use a different pavement color for cycling lanes, and channelize the intersection to separate the different types of traffic. Previous research showed that the reduction in conflicts leads to remarkable safety improvement after conducting smart channeling [38], [39].
5) The low radius of curvature, due to inappropriate design and limited space, leads to an increase in lateral acceleration and roll rate as noticed when analyzing the date of IMU, the potentiometer, and GPS signals, for example, we can notice the increase in steering angle on sharp curves and its impact on roll rate and lateral acceleration. In order to better understand cyclists' turning behavior, the intersection between zone 1 and 2 was analyzed for all participants where they had to turn left on a low-radius-of-curvature curve (angle of curvature less than 90). By analyzing the steering angle signal, it was found that at the maximum steering angle, the lateral acceleration and roll rate severely increased for all participants. It is also noticed that some participants did not follow the cycling path in order to increase the radius of curvature and reduce the steering angle, for example, one participant steered the handlebar at an angle of 23 but he left the cycling lane which led to a dramatic increase of in lateral acceleration (18 m/s^2). The increased lateral acceleration and roll rate are indications of rollover risk, as found in [40] where the analysis shows that lateral stability decreases when maneuvering a bicycle handlebar in either right or left directions. However, some cyclists did not follow the cycling lane in order to increase their turning radius and maintain their speed, this lane departure may lead to a collision with other vehicles passing by. To solve this issue, the radius of curvature should be designed to accommodate the cyclists' needs, or a physical barrier should be added to force cyclists to follow the cycling path and reduce their speed.
6) The absence of any physical barrier between cycling lanes and other modes of traffic leads to an increase in conflict points and may cause a collision, in addition, other road users may invade the cycling space and decrease the feeling of safety as mentioned by some participants who experienced a risky situation because of cars parking or driving on the cycling lane. A study implemented in Toronto, Canada shows the impact of protected cycle tracks. The results showed a decreased risk of collision for cyclists following its construction, besides the added benefit of increasing the number of cyclists using cycling facilities in these areas [41].
7) Sharing cycling facilities with pedestrians increases the risk to collide with them and reduces their comfort and safety feeling. On the other hand, cyclists have to reduce their speed to adapt to the pedestrians and maneuver amongst them as their walking behavior is unpredictable.
8) Cycling on a shared bus-bicycle lane reduces the safety feeling of cyclists, especially when buses are electric, they become less predictable as they have silent motors. The conflict occurs when the bus stops. The cyclist has to decide to pass or stop waiting for the bus to move again. The passing decision is harder as the passing time increases, and loss of attention may lead to a collision with other passing vehicles when invading the carriageway. In order to reduce this risk it is recommended to add a separate passage for cyclists behind the bus stop to avoid conflict with pedestrians and stopping buses; in addition to smooth passing for cyclists.
9) The increase of longitudinal slopes leads to increased speed when cycling downhill, and decreased speed and

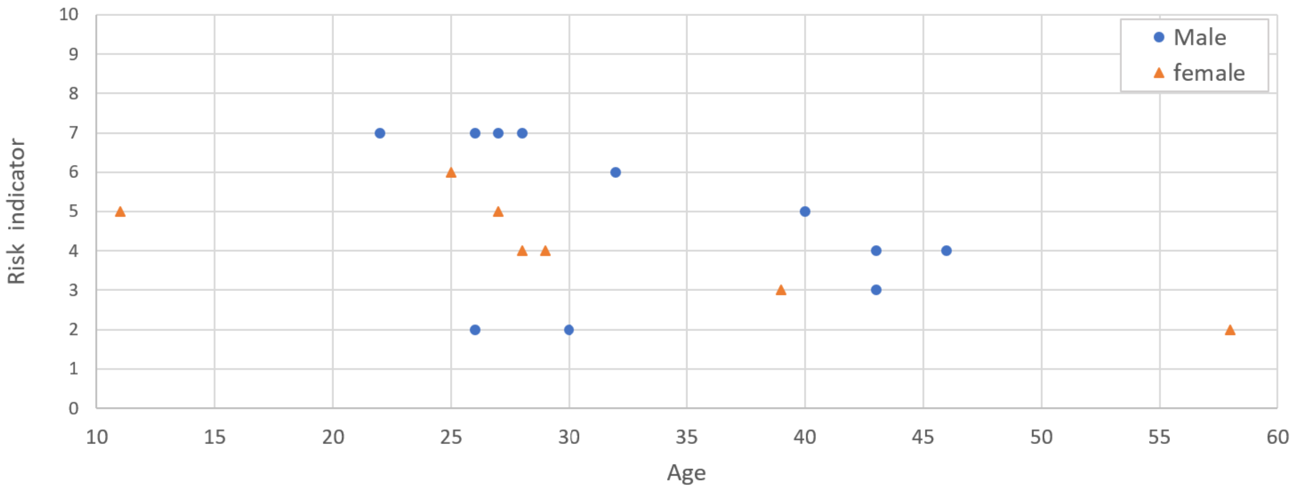

FIGURE 11. The behavioral risk indicator for the cyclists who participated in the Stockholm experiment; where 0 represents the safest and 10 represents the riskiest possible behavior.

increased power when cycling uphill. In order to mitigate the effect of high slopes, road designers should consider, when designing cycling paths, the physical abilities of cyclists when cycling uphill and the required stopping distance in case of breaking downhill.

10) Breaking red traffic lights by cyclists without keeping attention may lead to collisions, especially on intersections with reduced sight distance, due to existing buildings limiting the sight of cyclists and the drivers approaching from the transversal street.
11) Cycling in narrow spaces between cars or other road furniture increases the chance of collision and limits cyclists' field of view. The analysis of the eye-tracker videos shows that some cyclists were cycling very close to cars, especially in parking lots, and sometimes they had to heavily break to avoid collisions with cars leaving the parking zone. In order to avoid this it is recommended to construct cycling paths away from parking lots or add physical barriers between cycling paths and on-street parked cars.
12) Lack of attention when crossing the street: it was noticed in zone 3 when cyclists cross multiple streets that they do not look around and seem they only depend on their hearing, even though hearing is very important to detect passing vehicles, looking around still necessary especially with the emerge of elect-silent vehicles.

The combination of infrastructure parameters drawbacks and the associated cyclists' behavior, which are listed in Appendix B, were used to calculate RI by applying (1):

$$RI = \frac{\sum B.S}{n} \tag{1}$$

where B represents the errant behavior of the cyclist when interacting with the infrastructure or other road users, S is the severity of the possible accident, and n is the number of parameters under investigation. The different parameters used to calculate the safety indicator are attached in Appendix B. The risk indicator (BRI) ranges between 0 and 10 (0 the safest and 10 the riskiest); the cyclist's behavior is considered 'Risky' if the behavioral risk indicator (BRI) is above 5, whereas it is considered 'Safe' if BRI is equal or less than 5.

The analysis of the cyclists' safety profiles (Fig. 11) shows that 30% of the participants have risky behavior, their ages range between 22 and 32 years, 45% of males and 17% of females have risky behavior.

IV. CONCLUSION

This paper shows an important study of cycling safety in extreme weather and surface conditions, considering the design and maintenance of the infrastructure and the behavior of cyclists. The evaluation of cycling safety and comfort in snowy conditions was investigated through a case study in the city of Stockholm, where an instrumented bicycle was used to conduct an experiment involving 22 cyclists. The experimentation results for all participants, the subsequent questionnaire, and the eye-tracker videos were analyzed. The findings indicated some of the dangers that cyclists face, particularly in risky weather conditions; in many cases, the accumulation of snow drove riders to leave their cycling paths putting them at risk of collision, for example, in zone 2 where the cyclists were forced cycle closer to passing vehicles. It was also found that cyclists' risky behavior may put them and other road users in danger; examples include breaking red lights, passing pedestrians from the right side, and crossing streets without paying enough attention. The subjective evaluation of cycling safety shows that the participants felt safer in zone 2, where there is a separate cycling lane, even though a physical barrier between the cycling lane and other vehicles is missed.

A direct impact of road surface characteristics and infrastructure geometric design was observed on cyclists' behavior.

TABLE 2. The evaluation of risks related to the interaction between cyclists and road infrastructure.

no.	Infrastructure parameter drawback	Cause	Associeted behavior	Type of accident			
				lane departure	collision	rollover	sliding/slipping
1	low road adhesion	accumulation of snow and ice	speeding, foot slipping when standing	X			X
2	unevenness of road profile	damage of road or mis-design of the pavement	increase of vertical acceleration which affects stability and comfort	X		X	
3	increase in conflict points at interesections	poor geometric design	crossing in front or between pedestrains without slowing	X	X		
4	poor road marking and signs	lack of maintenace	not following cycling path	X			
5	low radius of curvature	poor geometric design	speeding on sharp curves which increase of steering angle and	X			
6	absence of physical barrier between cycling	limited space	cycling near other vehicles		X		
7	walking and cycling shared path	mis-use of the space	passing pedestrian from right		X		
8	bus/cycle shared lane	limited space	passing buses without attention		X		
9	high slopes	ignoring cycling needs in design	speeding downhill, consume more power uphill		X	X	X
			Cyclist misbehavior (irrelated to infrastructure)				
10			non-using winter tires				X
11			cyling in narrow spaces		X		
12			lack of attention crossing the street		X		
13			breaking red light		X		

TABLE 3. Risk indicator calculation for all participants.

no.	gender	Age	unusing winter tires	foot slipping when stepping	cyling in narrow spaces	crossing in front or between pedestrains	lack of attention when crossing	breaking red light	speeding on sharp curves	unfollow cycling lane	passing buses without attention	passing pedestrians from right
1	Male	65	X	X								
2	Female	43	X									
3	Male	42										
4	Male	62		X								
5	Male	43				X	X	X		X		
6	Male	27	X	X	X	X	X	X				X
7	Male	22	X			X	X	X	X	X		X
8	Female	27			X	X	X	X				X
9	Male	26		X		X	X	X		X	X	X
10	Female	25	X			X	X	X		X		X
11	Male	43				X	X	X				
12	Female	58				X	X					
13	Male	26	X									X
14	Female	11			X	X	X				X	X
15	Female	28	X			X	X					X
16	Male	27	X	X		X	X		X	X		X
17	Female	28	X			X	X					X
18	Male	32	X	X		X	X		X	X		
19	Male	46			X	X	X		X			X
20	Male	40	X		X	X	X			X		
21	Female	39	X			X	X					
22	Male	30	X				X					

The reaction of cyclists to the drawbacks of the infrastructure was evaluated to calculate the Behavioral Risk Indicator (BRI) for each cyclist and classify the behavior as risky or safe. This indicator could be used more broadly in testing cycling infrastructure adequacy and its impact on cyclists' behavior. Based on the analysis of the behavioral risk indicator (BRI) for the experimental route in Stockholm, different measures are recommended to improve cyclists' behavior and reduce the probability of accidents including:

- Maintaining the road surface to make it more even and smooth for cyclists, in fact, a well-maintained cycling facility encourages more people to cycle, as it is essential for the safety, accessibility, and riding comfort of cyclists.
- Removing the accumulated snow from the cycling lane will improve road adhesion provide more space for cyclists, and reduce the risk of sliding or slipping.
- Installing a physical barrier between cycling lanes and carriageways reduces the conflict, and the risk of collision with other vehicles, besides improving the feeling of safety which encourages people to cycle more.
- Separate cycling and pedestrian paths, which may improve comfort and reduce the risk of collision with pedestrians.
- Improving the communication between the road designer and cyclists through the proper installation of vertical and horizontal signs will help to give the right directions to cyclists, warn them of possible risks, and advise them to take the right actions.

In the future, the output signals and the behavior of cyclists will be compared to the outputs of PICS-L bicycle simulator after the reproduction of the same environment and scenario in virtual reality. This comparison will further be used to study the behavioral, physical, and subjective validity of the simulator. The validity of the simulator will allow for conducting more experiments to test different scenarios and measures to improve cycling safety in a secure environment inside the lab before applying them on-street.

APPENDIX A
ACCIDENT RISKS

See Table 2.

APPENDIX B

See Table 3.

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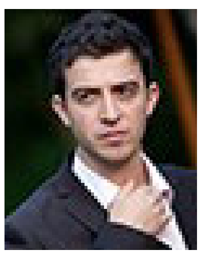

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