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Towards Safer Mobility in Cities and Communities: A Framework to Assist the Design Process of Cycling Warning Systems

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ABSTRACT

Cycling is currently booming as an affordable mean of transportation to replace fossil fuel vehicles. Regardless of multiple projects to increase and promote safe cycling environments, riders safety is a growing concern since it is affected by multiple variables such as circulating vehicles and pedestrians, road and city design and conditions, rider's behavior, bicycle characteristics, among others. Currently, there are already some devices to help bicycle riders to discern threats in their journey and the literature reports a few studies aiming to evaluate users perception regarding such devices effectiveness and usability. However, according to our knowledge, those studies are scattered, focused on evaluating specific solutions and their contributions were not yet described in a holistic perspective. Based on an scoping literature review, presented paper aims to add a contribution to the topic by arranging knowledge from across those fragmented research approaches into a coherent framework. Since this work is part of a project focused on cycling safety solutions based on the use of digital technologies to assist rider preventive behaviour, the review was firstly conducted by assessing research dealing with this still emerging concept of rider self-protection enabled through warning systems, transportable by the cyclist or applicable on a bicycle, independent of the existence of a dedicated and/or exclusive external infrastructure. Additionally, some studies addressing safety measures depending upon other vehicles, city facilities or any other external entities or devices were also assessed, identifying the risk situations they address and user requirements in an alert situation. Aiming to bridge and unify knowledge, an integrative framework was developed. The framework intends to depict the principles of cycling self-safety systems mediated by smart devices, revealing key variables and concepts, clarifying its definitions and foundations, relationships between them, related processes and evaluation/measurement factors. The main contribution of this work is the proposal of a provisional integrative framework to serve as a guide during the process of designing cycling warning systems. Proposed framework is expected to assist the different activities throughout the design process, providing design and evaluation guidelines for selection of unexplored product development opportunities, new concepts development and selection, test and validation of prototypes or even products already in the market.

Keywords: Cycling warning systems, Cycling safety, Accidents prevention, Design process guidelines, Integrative framework

INTRODUCTION

General concern with the environment is a global topic nowadays revolving around pollution generated by fossil fuels, with automotive industry increasingly offering more eco-friendly means of transportation. At the same time, worldwide population is slowly reducing the use of automotive vehicles and travelling smaller distances by bicycle. But because bicycle wasn't seen as a commuting vehicle in several cultures and locations, it was not taken into account in city planning until a few years back. Thus, many cities aren't ready to accommodate cycling traffic and new problems regarding safety are emerging (Pucher and Buehler 2017).

In 2016 was averaged that 1.25 million people die every year from road traffic accidents with four percent of them corresponding to cyclists. Although the absolute number of fatalities is decreasing, the relative proportion of bike fatalities compared with other traffic fatalities is still increasing (Gohl et al., 2016). This increase is due to the global increment in bike usage. For example, according to Pucher and Buehler (2017), France had 1500 bikes in bike sharing services in 2005 and over three million in 2017. This increment in bike circulation proves that cycling is becoming a viable mean of transportation but also reveals the need to increase safety for this type of transportation.

While it is established that cycling safety is an urgent problem to solve, one should recognize the solution must account for the diversity of traffic conditions potentially affecting cycling accidents such as vehicles, pedestrians, the direction of travel, type of location, lighting, road surface, and weather (Costa et al. 2022). Warning systems directed to measure and inform about these factors avoid occurrences by influencing cyclist's reaction as stated by Strohaeker et al. (2022).

Addressing the problem from the product design and development standpoint, present work, which is part of an ongoing MSc. research project, builds on the idea that the process of designing better bicycle warning systems can benefit from a structured framework providing design and evaluation guidelines to select unexplored product development opportunities, new concepts development and selection, test and validation of prototypes or even products already in the market.

STUDY METHODOLOGY

The study followed a scoping literature review approach, which general purpose is "to clarify key concepts/definitions in the literature", "to identify key characteristics or factors related to a concept" and "to identify and analyse knowledge gaps" (Munn et al., 2018, p. 2). Search was performed through SciVerse Scopus database with the following combination of terms: "Cyclist Safety AND Sensing", "Warning Systems AND Cycling", and "Warning Systems AND Bicycle". A total of 1447 studies were retrieved, then screened by criteria listed below.

First criterion is the year of publication, since we wanted to scope the most recent technological studies in the field, without losing significance. According to Kapousizis et al. (2022) publications in this field started to peak

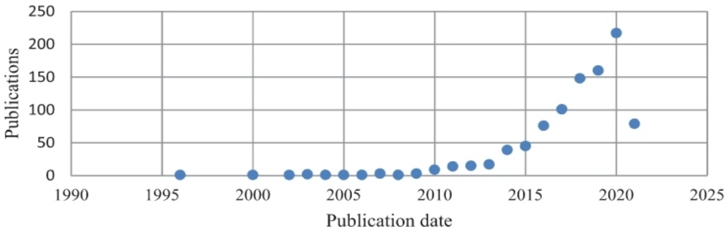

Figure 1: "Distribution of publication through the years" (Kapousizis et al. 2022).

around 2017, (Figure 1), reason why a timeframe between 2017 and 2022 was assumed. Second criterion implies that all analyzed studies needed to be empirical, meaning a warning system concept was described in it, regardless of its development level. Purely theoretical studies, such as literature reviews were excluded. Furthermore, included studies needed to report warning systems for a bicycle that don't take control away from its rider. For example, studies proposing autonomous breaking systems were excluded from the final count. Finally, the third criterion was set to admit studies reporting warning systems able to collect data relevant to traffic or the cyclist, such as a smart bicycle that captures the surrounding vehicles and informs the cyclists as presented by Jeon et al. (2021), excluding papers that measured environmental data.

After screening, a total of 17 studies were considered to analysis. Given the reduced number of results, the timeframe was extended to englobe the years from 2012 to 2016 resulting in five more studies, with a final corpus of 22 studies (Table 1). Although modest, this collection of studies constitutes the scoping phase of the review, aiming the development of the first proposal to the framework. A systematic review, considering a larger corpus through more permissive criteria, will be carried in later in the next phases of study.

Table 1. Corpus of analysis.

Terms	Authors	Count
"Cyclist Safety" AND "Sensing"	(Costa et al. 2018; Bernardes et al. 2019; Nuñez et al. 2018; Matviienko et al. 2022; Jin et al. 2021; von Sawitzky et al. 2022; Han et al. 2022; Dong et al. 2022)	8
"Warning Systems" AND "Cycling"	(van Brummelen et al. 2017; Oczko et al. 2020; Kaparias et al. 2021; Zignoli et al. 2022; Zignoli 2021; Strohaeker et al. 2022; Dozza et al. 2016; Dozza and Fernandez 2014; Blumenstein et al. 2014)	9
"Warning Systems" AND "Bicycle"	(Jeon et al. 2021; von Sawitzky et al. 2020; Panxhi et al. 2017; Wallich 2015; Liebner et al. 2013)	5

DIVERSITY OF CYCLING ACCIDENTS

Resulting from the increasing overall awareness regarding the multifactorial nature of traffic accidents, some projects have been developed to increase the safety of cyclists, by analyzing traffic scenarios and developing systems to monitor the rider's condition, as well as road vehicles.

Road cycling happens in a multitude of scenarios which, according to Gohl et al. (2016) can be divided into the following categories: longitudinal (parallel to the road direction), crossing (at intersection and crosswalks), turning (changing direction at an intersection) and others (involving stationary objects). This categorization of scenarios covers the relevant actions of cycling while excluding actions prohibited by law, like cycling in highways and pavements.

Besides the type of scenarios where cycling accidents can occur, variables such as car doors, irresponsible parking, or lack of space for safe cycling, may create conflicting scenarios, that jeopardize the cyclist's safety. For example, Schimek (2018) states that door openings compose 12%-17% of bicycle-to-car accidents, due to the lack of space in the bicycle lanes. Analyzing each incident considering the multiplicity of possible involved elements, risks to generate overflowing datasets, that still may do not represent all accident possibilities. A more comprehensive classification of accidents elements may be gathered from police reports including motor vehicles, bicycles, pedestrians, fixed objects, falls and others, as suggested by Shinar et al. (2018). Additionally, as pointed by Matviienko et al. (2021) complete information about accidents should consider not only qualitative data coming from cyclists' own reports and third-person descriptions but also objective/quantifiable data, such as from traffic cams, car sensors, bike dynamics, and riders'. Thus, conducted review clearly settles that first, cycling safety has a broad spectrum of variables to tackle and, second, measuring those variables only from a qualitative or quantitative perspective lacks a global understanding of the problem.

Regarding the specific aim to propose a design warning systems framework, by bringing together the contributions from 2 of the analyzed studies, it was possible to propose 2 major groups to describe the majority of cycling accidents: Road Cycling Action and Type of Accident. In the first group we included 3 from the one proposed by Gohl et al. (2016): Longitudinal, Turning, and Crossing. Category Others was excluded to avoid subjectivity. In the second group we listed 6 categories. Five originally proposed by Schimek (2018): Motor Vehicles, Bicycles, Pedestrians, Fixes objects and Falls. Again, category Other was removed (for the same reason already mentioned). A newer category, Cycling Lanes, contemplating road conditions was added to cover a larger number of situations. As a result, proposed framework will focus on 18 possible accidents scenarios.

TECHNOLOGY RELATED TO CYCLING SAFETY

This section aims to map the relation between bicycle warning systems and technologies by identifying which were involve in the concepts reported in the 22 analyzed studies.

Overall, the smartness level of a bicycle warning system will depend on the specific features granted by the technology it incorporates. However, this definition is too broad to comprehend and distinguish all the safety systems in a bicycle (englobing market solutions and emerging technologies). Kapousizis et al. (2022) introduced a system to classify multiple types of bicycle safety systems, in accordance with their smartness degree, through an easily understandable scheme divided into six levels as presented in Figure 2. The system is aimed to clarify the benefits and limitations of each type of technology which those authors synthesize into a table and purposefully indicate that microcontrollers are left out due to the multimodality inherent to them. However, in our perspective, controllers and microcontrollers must not be overlooked given the fact that they are the cognitive force that can increase a system's smartness. They also affect the overall performance of the final product since real-time data and fast data aren't the same as stated by Karvinen and Karvinen (2014).

Looking specifically into bicycle warning systems, we found that the technology behind them it's generally the same that is applied to smart bicycles, although studies englobing bicycle or cycling warning system concepts tend to be at early stages of development. Generally, what those studies propose are new digital solutions for safety by promoting augmented, virtual or mixed reality prototypes to test concepts and methods of information or monitoring such as those presented by Matviienko et al. (2022); Oczko et al. (2020); von Sawitzky et al. (2020); von Sawitzky et al. (2022). The more common approach implements GPS (global positioning system) and IMU (inertial measuring unit) to monitor cycling activity as reviewed by Han et al. (2022); Dong et al. (2022); Bernardes et al. (2019); Costa et al. (2018); Strohaeker et al. (2022); Zignoli (2021); Kaparias et al. (2021). Even this frequent approach is showing recent progresses, as indicated by Zignoli et al. (2022) who concluded that the advancements in GPS technologies, numerical optimization techniques and modeling capabilities broaden the capacity to interpret cycling data. GPS technology can be implemented through smartphones that have enough accuracy to detect the location of the cyclist as stated by Liebner et al. (2013). Besides the previously mentioned technologies, review results show that other technologies are being implemented, such as ultrasonic, laser, radar sensors, gyroscopes, and accelerometers to measure one or more conditions during cycling (Jin et al. 2021; Nuñez et al. 2018; van Brummelen et al. 2017; Panxhi et al. 2017; Blumenstein et al. 2014).

The reviewed projects typically use technology to enhance safety, and the technological components utilized are consistent across all projects, as shown

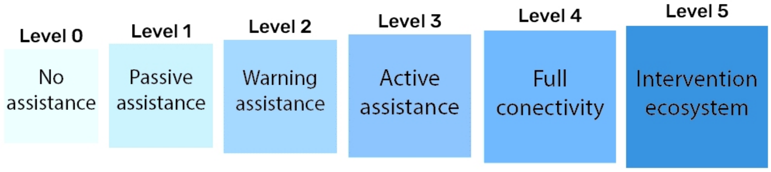

Figure 2: Adapted smartness level of bike categorization (Kapousizis et al. 2022).

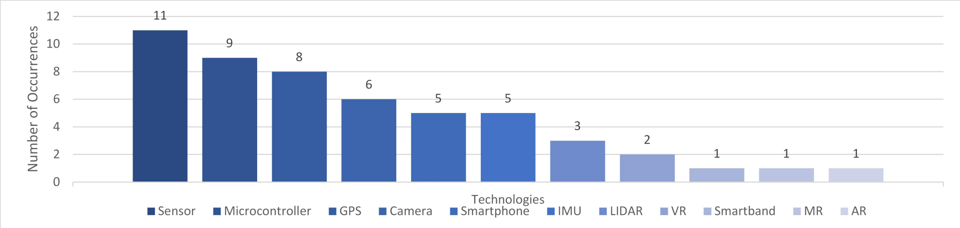

Figure 3: Technologies applied in bicycle warning systems (@authors).

in Figure 3, indicating the flexibility of technology to adapt to different situations or variables. Since the same technology is applicable to multiple projects, the components become a by-product of the purpose given to the technology. Ahead, in Table 3 we present the same technologies, retained from the reviewed studies, to incorporate the framework proposal.

FRAMEWORK PROVISIONAL PROPOSAL

The provisional framework presented in this section is aimed to assist the process of designing cycling warning systems. Previous sections depicted the current knowledge regarding bicycle warning systems, accident scenarios and technologies as these variables are addressed in 22 recently published empirical studies. Eighteen scenarios and eleven different technologies were identified, to be included in our framework.

Additionally, the analysis revealed that the diversity of perspective presented in the studies derives from the importance that each author gives to different high-level requirements. We organized these requirements in an 8-category classification as showed in Table 2: Target Market, Sustainability, Objective, Technology, Scope, Information Type, Usability and Embed Zone.

From these eight high-level requirements categories, Target Market and Sustainability are concepts related to product design and development and are transversal to all project requirements as stated by Ulrich et al. (2020). The remaining categories arise from authors experience and understanding

Table 2. Project high-level requirements.

High-level Requirements	Options List
Target Market	Bike Sharing, Commuting, City Adventure, Fitness…
Sustainability	Ambiental, Social, Economic…
Objective	Monitor, Inform, Both
Technology	Sensor, Microcontroller, GPS, Camera, Smartphone, IMU, LIDAR, Smartband, VR, AR, MR…
Scope	Internal (directed to the cyclists), External (other road users)
Information Type	Visual, Tactile, Auditive
Usability	Effectiveness, Efficiency, Security, Utility, Learnability, Memorability…
Integration	Cyclist or Bicycle

about aspects that drive and limit product design, directed to bicycle warning systems. The Objective variable defines the purpose of the project by indicating if it monitors (cyclist, bicycles, road users, or traffic conditions) or informs (cyclists or other road users) while the Technology one corresponds directly to was discussed in section 3. The Scope refers to the type of monitoring that the project is directed to and is classified as internal (monitoring the cyclist or bicycle) or external (monitoring other road users or traffic conditions). Information Type refers to the sensorial type perceived, meaning visual, tactile, or auditive cues. In terms of Usability, this is the system's capacity to allow the user to perform its functions without difficulty. Integration is directed to the location of application, for example, on the bicycle handlebars or the rider's wrists. The categories presented above are subject to further development and may be changed either in number or in definition. The options list for each category must be dynamic and updated according to the latest knowledge in the area. These options can be further broken down into more specific levels to detail project requirements and/or specifications. Finally, to relate the 8 high-level requirements categories with the 18 scenarios previously mentioned, our provisional framework proposal (Figure 4) draws out a 3-dimensional table where requirement levels are disposed in the same plane, and depth is achieved by stacking similar planes that differ only by the cycling scenario, that way allowing comparison of the variable's context across the board.

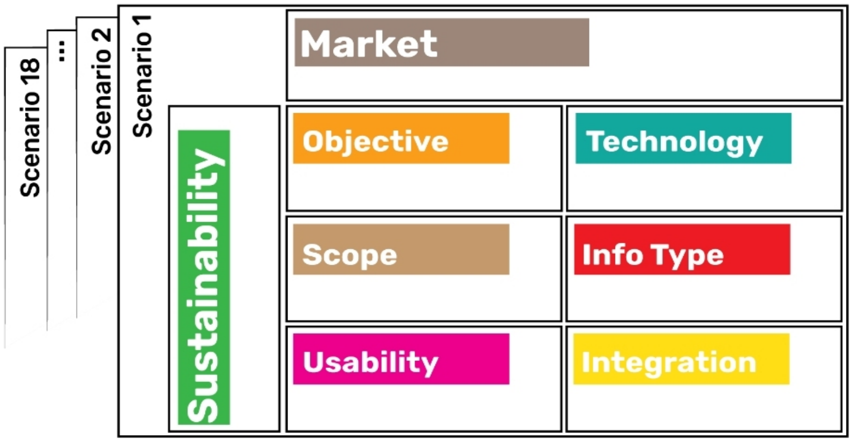

Figure 4: Framework proposal (@authors).

FINAL REMARKS

The use of bicycle as a commuting vehicle is increasing worldwide, mostly due to increasing global concerns about fossil fuels consumption. Meanwhile, most cities infrastructures are not prepared to accommodate cycling traffic. Adding to this the enormous amount of motor vehicles still in circulation and the problem of cycling safety and the multitude of variables gravitating around it becomes evident. Cycling warning systems, either as part of the bicycle or as an accessory, have been proposed as a means of contributing to the safety of cyclists. Looking at this issue from the perspective of product design and development and, considering the diversity and unpredictability of the elements possibly involved in a cycling accident, this paper aims to put forward a provisional proposal for a design framework specifically dedicated to warning systems. The presented framework results from a scoping literature review that examines 22 warning system concepts reported in the literature in recent years and includes a three-dimensional matrix aimed at examining an 8-level requirements taxonomy across 18 different accident scenarios. Next phases of our study will include the validation of the proposal through a 2-stage validation process involving focus groups with bicycle design experts and the collection of feedback from users external to the project and then testing the framework against practical cases.

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