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CYCLISTS' PHYSIOLOGICAL STRESS AND NETWORK PLANNING AND EVALUATION

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I would like to dedicate this dissertation to my mother, Enith Nuñez for her encouragement and unconditional love.

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"*Life is like riding a bicycle.*

To keep your balance you must keep moving."

Albert Einstein

RESUMO

NUÑEZ, J. Y. M. **Estresse fisiológico dos ciclistas e planejamento e avaliação de redes cicloviárias.** 2018. Tese (Doutorado) - Escola de Engenharia de São Carlos da Universidade de São Paulo, 2018.

Os planejadores de transporte precisam avaliar as condições de estresse dos usuários em infraestruturas cicloviárias, uma vez que situações de alto estresse podem desencorajar o uso deste modo de transporte sustentável. Poucas pesquisas têm questionado se existe alguma relação entre esses fatores ambientais e a resposta emocional em termos de medidas objetivas do estresse. O objetivo deste trabalho é explorar a incorporação de sensores inteligentes no planejamento e avaliação da infraestrutura cicloviária. Essa nova abordagem é focada na perspectiva de monitorar parâmetros intrínsecos ao usuário, como as emoções. Nesta perspectiva, os indicadores dos níveis de estresse são feitos a partir da medição direta de respostas fisiológicas em ciclistas ao longo do percurso. Essa abordagem aproveita os recursos tecnológicos para extrair informações dos usuários e permitir o uso dessas informações de forma integrada para melhorar a infraestrutura dos ciclistas. Os dados foram coletados por meio de sensores de estresse, de ruído e acelerômetros incorporados a um *smartphone* e GPS. Inicialmente é apresentado o problema e como o projeto e avaliação das ciclovias tem sido abordada na literatura. A abordagem proposta permitiu identificar as contribuições mais relevantes e as lacunas de pesquisa, tais como, a falta de pesquisas baseadas em critérios de objetivos e a falta de pesquisas que envolvam o desenho e a avaliação de cenários de infraestrutura compartilhados com veículos automotores. Em seguida foi proposto um método objetivo de avaliação de infraestruturas cicloviárias, combinando a avaliação ambiental com medições de aceleração vertical, a fim de melhorar a coleta de dados e outros procedimentos necessários para avaliar os principais componentes das infraestruturas cicloviárias. Na sequência uma ferramenta para caracterizar o estresse de tráfego de ciclovias, denominada *Level of Traffic Stress* (LTS), foi validada com medidas fisiológicas no contexto urbano de uma cidade brasileira de porte médio. Observou-se que não há correlação e há pouca concordância entre esses parâmetros. Ressalta-se ainda que, mesmo ao incorporar informações de velocidade de tráfego à ferramenta LTS, não foi significativamente relacionado com estresse medido sob a perspectiva do ciclista. Por fim, foi investigada a influência do ruído, vibração, presencia ou ausência de ciclovias e período do dia no estresse experimentado pelos ciclistas. Uma análise dos valores de p e dos intervalos de confiança das razões de chances mostraram, com um nível de confiança de 95%, que apenas o período do dia influenciou o estresse. Neste caso, as chances de ter estresse aumentaram em 24% na hora pico da tarde em comparação com a hora pico da manhã. Este estudo mostrou a viabilidade da avaliação do estresse em ciclistas por meio de um método de medida objetiva além da rápida identificação dos níveis críticos de estresse.

Palavras-chave: Planejamento de Transporte Cicloviário, Sensoriamento, Estresse, Ruído, Vibração, Infraestrutura cicloviária. Data mining

ABSTRACT

NUÑEZ, J. Y. M. **Cyclists´ physiological stress and network planning and evaluation** 2018. Thesis (PhD) - Escola de Engenharia de São Carlos da Universidade de São Paulo, 2018.

Transportation planners need to assess users' stress conditions on cycling infrastructures given that highly stressful situations can discourage the use of this sustainable transport mode. Not many studies have addressed the relationships between these environmental factors and users' emotional responses in terms of objective measures of stress. The aim of this study is to explore a new approach for planning and evaluating cycling infrastructure, based on smart sensors. This new approach focuses on the perspective of monitoring parameters intrinsic to the user, such as emotions. In this perspective, the indicators of stress levels are made from directly measuring cyclists' physiological responses throughout the journey. This approach makes use of technological resources to extract information from users through sensors and imparts this information in an integrated way to improve infrastructures for cyclists. The data were collected using stress and noise sensors, accelerometers embedded in a smartphone and a GPS. Initially, the problem is posed and we discuss how the design and evaluation of cycle paths has been addressed in the literature. The proposed approach identifies the most relevant contributions and research gaps, such as the lack of research based on objective criteria and research that involves designing and evaluating infrastructure scenarios shared with motor vehicles. In the sequence, an objective method for assessing bicycle infrastructures combining environmental assessment with vertical acceleration measurements was proposed in order to improving data collection and other procedures required for assessing the main components of cycling infrastructures. Subsequently, a tool to characterize traffic stress of cycling routes, called the Level of Traffic Stress (LTS), was validated with physiological measures in the urban context of a medium-sized Brazilian city. It was observed that there is no correlation and little agreement between the parameters. It is also emphasized that even when incorporating information about the traffic speed to the LTS tool, it was not significantly related to stress from the perspective of the cyclist. In the final analysis the influence of noise, vibration, cycle paths and period of day on stress experienced by cyclists was investigated. An analysis of the p-values and odds ratio confidence intervals shows, with a 95% confidence level, that only the period of the day influenced stress, as confirmed by the data. In this case, the chances of having stress increased by 24% in the afternoon rush hour compared to the morning rush hour. This study showed the feasibility of stress assessment in cyclists using an objective measurement method, as well as quick identification of critical levels of stress.

Keywords: Cycling Transportation Planning, Sensoring, Stress, Noise, Vibration, Bicycle infrastructure, Data mining.

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INTRODUCTION

Traffic congestion, noise and air pollution are common problems nowadays in urban areas. As these growing problems are all closely associated with motorized transport modes, cycling is becoming an attractive alternative for urban transportation. However, the success of cycling as a viable transport mode depends on the conditions of the infrastructure, given that safety and comfort are essential to attract new users (Dill and Carr 2003; Pucher and Buehler 2007). In addition, proper maintenance of cycling infrastructures is equally important for the different parties involved in public financial resource urban planning and management.

Planning and managing the extensive infrastructure network for cyclists is a challenge. However, current technological advances in information systems, smartphones and smart sensors have opened up new possibilities for monitoring these infrastructures in real time. Using information provided by sensors can relate geo-referenced measurements of certain conditions (vibration, noise and environmental conditions) throughout the journey with the emotions perceived by cyclists (Zeile, 2016). Thus, it is possible to incorporate these measurements in the planning and evaluation of cycling transport systems.

Some of these sensors in smartphones and embedded systems can be used for data collection from transport system users. An example of a smartphone application for cycling systems is CycleTracks. Different versions of this app were used in other cities in the USA (SFCTA, 2017). These apps were used in bicycle travel demand studies to identify, for example, user preferences. Other smartphone applications, such as Strava and Endomondo, have been developed to provide information about performance, calories burned, etc., during cycling trips.

In general, using smartphones to support data collection for cycling studies has so far focused mainly on cyclists´ physical performance, demand and flow data. Consequently, the potential of several other sensors, also available for smartphones, has not yet been fully investigated to assess the conditions of cycling infrastructures.

However, using smartphone accelerometers and action cameras to collect information about cycling infrastructures is not so common. One exception is a study conducted by Vieira et al. (2016), in which smartphone GPS data were combined with information obtained from an action camera (to evaluate the general conditions of the cycle path) and a cardio signal acquisition belt to evaluate cyclists' stress levels. In this case, however, the video images only provide general information about the path, without any detailed analysis of the pavement conditions (types of surface, types of distress, severity levels and extension) or a comprehensive assessment of the surroundings around the cycle path.

Poor pavement conditions and roughness caused by large cracks, bumps, potholes and loose gravel could cause undesirable vibrations and put cyclists at risk of falling. In addition, cyclists´ comfort is directly associated with the vibrations caused by pavement surface irregularities. According to Griffin (1990), human perception depends on vibration magnitude, frequency and duration. Exposure to strong and long-lasting vibrations may cause health problems (Gemne and Taylor, 1983; NIOSH 1997; Griffin and Bovenzi, 2002). On the other hand, a smooth surface also means less energy is consumed by the cyclists (Vanwalleghem et al., 2012). Considering that accelerometers are now common devices in smartphones, measurements obtained from them could be used in a simple way and in a large quantity to evaluate the quality of cycle ways and cycle paths in terms of pavement condition.

In addition to cycling infrastructure conditions, cyclists can experience various situations during a trip that can trigger moments of stress. This stress, which is commonly associated to negative perceptions, is considered the main barrier to using bicycles as a transport mode (Heesch et al., 2011; Joshi et al., 2001; O'Connor and Brown, 2010; Rissel et al., 2013; Kaplan and Prato, 2016) and in some cases is considered one of the most serious physical and mental health implications of commuting (Legrain et al., 2015).

Indeed, measures and indexes of quality and comfort, as well as stress during a trip have already been proposed in the literature (Mekuria et al., 2012; Wang et al., 2016). One of the first attempts is the index proposed by Sorton and Walsh, 1994. This author proposed an index with five categories as a function of volume, speed of motorized vehicles and effective curb width variables. The bicycle level of service concept was introduced later (Landis et al., 1997; Epperson, 1994; Davis, 1987; Dixon, 1996; Jensen, 2007) and subsequently adjusted by the Highway Capacity Manual (TRB, 2010). However, some authors have pointed out some shortcomings and limitations of the HCM method: poor availability of data; complicated formulas and the fact that the levels of service these models refer to have no meaning either to roadway managers or to the general public (Mekuria et al., 2012).

To overcome these limitations, Mekuria et al. (2012) proposed a method called the Level of Traffic Stress (LTS) that includes 4 categories of classification, based on characteristics of the road infrastructure (number of vehicle lanes, speed limit, bike line width). However, in spite of being a practical method it is still based on external characteristics to the cyclist. Furthermore, most of these methods were calibrated with surveys conducted with people in specific places. According to Caviedes et al. (2017), surveys do not always reflect the psychological and physiological responses and eventually can have bias due to the subjectivity of the metrics.

There are only a few recent attempts in the literature to objectively assess stress in bicycle transport based on measurements obtained directly from cyclists. These possibilities have been explored by some researchers (Zeile et al., 2016; Caviedes et al., 2017; Liu and Figliozzi, 2016; Vieira et al., 2016). From this perspective, negative emotions such as fear and anger may be related to stressful events (Zeile et al., 2015). Such stress can be measured by physiological changes in body temperature, heart rate and skin conductance (Ulrich-Lai and Herman, 2009; Bergner, 2010; Kreibig, 2010). These physiological changes can be generated by stressors such as noise, surface roughness and dangerous situations (Evans and Wener, 2006; Chen et al., 2017; Kaplan and Prato, 2016; Joshi et al., 2010).

Noise is a common stressor in urban environments and can trigger health issues (Szalma and Hancock, 2011). Some of the most common conditions due to noise are: decreased cognitive performance and reduced constant attention (Hockey and Hamilton, 1970); inhibition of episodic memory (Boman, 2005); hearing loss (Barbosa and Cardoso, 2005); as well as increased risks of high blood pressure and cardiovascular disease (Babisch, 2011; Babisch, et al. 2005; Bluhm et al., 2007). Research has shown that natural sounds can be pleasurable but artificial sounds, such as noise from motorized vehicles can be uncomfortable (Brown and Muhar, 2004; Lavandier and Defréville, 2006; Nilsson and Berglund, 2006; Venkatappa and Vinutha Shankar, 2012). Noise from vehicular traffic can cause psychological stress problems (Michaud et al., 2008; Öhrström, 2004; Öhrström et al., 2006; Stansfeld et al., 2000). It is important to consider that although other means of transport where users are in a protected environment (e.g., vehicles) are subjected to a certain degree of environmental noise and stressful situations experienced by cyclists may be influenced more directly by environmental noise.

As reported in the literature, stress experienced by cyclists has been previously studied subjectively (through surveys) and according to factors external to cyclists, such as the flow and speed of motorized vehicles and infrastructure characteristics. In addition, few studies have questioned whether there is any relationship between these environmental factors and the emotional response in terms of objective measures of stress (Fitch et al., 2017).

Based on the above, a method to evaluate the characteristics of a bicycle infrastructure and the real experience of a cyclist´s stress using smart sensors is addressed in this study. This study contributes to the planning and monitoring of bicycle routes by using objective measures of stress and infrastructure conditions. In addition, this research also contributes to the investigation of how some environmental factors can trigger cyclists´ stress such as noise, vibration, presence or absence of infrastructure and the period of day.

Specific objectives

The main objectives of this research are:

- to develop and conduct a critical systematic literature review to design an assessment cycling transportation infrastructure.
- to develop a practical method for quality assessment of bicycle infrastructures combining environmental attributes with vertical acceleration measurements.
- to validate a tool to characterize traffic stress of cycling routes using physiological measures.
- to investigate the relationships between stress and some environmental factors such as noise, vibration, presence or absence of infrastructure and the time of day.

Thesis outline

This thesis consists of five chapters.

Chapter I presents the exploration of data mining resources to develop a procedure in the systematic literature review. The proposed method essentially involves an algorithm to search for studies in databases, followed by cluster analysis to classify the selected studies. The design and assessment of cycling transportation systems was the topic chosen for the application.

Chapter II focuses on developing a method to assess bicycle infrastructures, combining environmental quality with vertical acceleration measurements.

Chapter III presents the validation of a tool to characterize traffic stress of cycling routes using physiological measures.

Chapter IV investigates the relationship between stress responses and environmental factors considered stressors, such as noise, vibration, presence and absence of cycling infrastructure and the period of day.

Chapter V presents the summary, conclusions and suggested future work.

CHAPTER I

SYSTEMATIC LITERATURE REVIEW USING DATA MINING RESOURCES: AN APPLICATION TO DESIGN AND ASSESS CYCLING TRANSPORTATION SYSTEMS

This chapter provides a comprehensive critical review of studies regarding the design and assessment of cycling transportation systems. This approach aims at exploring data mining resources to develop a procedure for systematic literature reviews. The proposed method essentially involves an algorithm for searching studies in databases, followed by a cluster analysis for classifying the selected studies. The conducted review was able to show, for example, that most of the studies considered dealt with a segregated cycling infrastructure, and just a few were dedicated to the infrastructures shared with motorized vehicles. In general terms, the proposed approach helps to identify the most relevant contributions to a certain research topic with the advantage of creating a replicable procedure of the literature review. In addition, the proposed analyses were able to find the highlights and the research gaps in the literature, which makes the procedure a promising alternative for applications in other research areas.

Objectives

The aim of this chapter is to adapt data mining resources in search and classification procedures of results to make it more effective to implement systematic review procedures in order to answer two questions: 1) Is it feasible to use data mining techniques for systematic literature reviews in the area of transportation? 2) In the specific case of the application developed here, which focuses on identifying studies regarding the design and evaluation of cycling transportation systems, can the data mining techniques provide useful and consistent results? To achieve this goal, the proposal presented here make uses of a code developed for selecting and prioritizing the order in which the papers might be read.

Database identification and records to be analyzed

The process begins by selecting an online database that contains a considerable volume of relevant publications in the researched area, such as the integrated Transport

Research International Documentation (TRID) database, which provides access to more than one million transport search records around the world. This database combines records from the Transportation Research Information Services (TRIS), TRB (Transportation Research Board) and International Transport Research Documentation (ITRD) databases. Moreover, this database includes references related to specific topics, such as public health regarding transportation.

The searching procedure in the database begins by using the most comprehensive keywords, aiming to cover the highest number of searches in the literature. These searches should then be indexed and classified according to the selection criteria mentioned in a selection and extraction protocol for relevant papers.

Codification and paper selection

A code created in program R, which can identify the occurrence of keywords in the title and abstract, was developed. This algorithm is intended for coding and ordering the papers downloaded from the database. First, a couple of vectors with the keywords are created. Vector M contains the keywords of the more general search and vector N contains the most specific keywords of the topic searched. An iterative structure combines these keywords to read the data information from the files in XML format. Each file is read using the *htmlTreeParse* function of the R XML package. This package can extract the attributes of interest from the files, such as the title, abstract, keywords, authors, year of publication, etc.

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For each record of the search file and the attributes ABSTRACT and TITLE of each XML file element, a keyword search is performed using the grep function, which returns its position in the abstract/title vector. This process returns the encoding of each paper where was founded the keyword searched. Afterwards, the table function is used to construct a contingency table for each record and the frequency of occurrence of the keywords. After the papers have been selected, those that were duplicated are excluded. Then, a vector is generated with the names of the papers that will be effectively read. Subsequently, the included records are sorted by the highest frequency of occurrence of the keywords to prioritize their reading.

Eligibility criteria

After selecting and prioritizing papers for reading, a new classification should be carried out with new eligibility criteria. This classification is done using the requirements of the research conducted, discarding, for example, references of projects in progress, projects which have not yet produced results, or references whose reading indicates a focus of interest different from what is researched. Subsequently, the papers selected should be read in full one by one, highlighting the common characteristics and variables.

Classification of papers by cluster analysis

Based on the previous reading and classification, a new database is created that contains the relevant information of each search, which will be the fundamental input for analyzing the systematic literature review. In order to aggregate the paper within the relevant characteristics previously defined, a hierarchical clustering analysis was performed. This method starts by assuming that each paper represents a single group (or cluster). The results of this hierarchical procedure can then be plotted as a dendrogram diagram. In this diagram, each paper is clustered using a hierarchical tree-shaped construct. The algorithm combines clusters successively by the distance or dissimilarity between two points until obtaining a single cluster containing all the data (Keirstead, 2011).

This process was followed using the *daisy* package, which automatically calculates the dissimilarity matrix of ordinal or nominal variables. It should be noted that most clustering algorithms assume numeric variables as inputs. However, in the case of literature reviews, the attributes are typically represented by categorical variables so that the dissimilarity matrix must be calculated first. Afterwards, partitioned clustering must be done in the database, dividing the data into a fixed number of clusters according to the number of clusters resulting from the hierarchical clustering.

In order to perform the partitioned clustering in the R program, the *pam* (*Partitioning Around Medoids*) function of the *cluster* library was used with the number of clusters obtained from the hierarchy. The *pam* function creates an object that contains other useful elements: an element called *medoid*, which describes the properties of the cluster centers, and an element called clustering, which tells which group each point has been allocated. These elements were used to generate a summary of the results using the ggplot function of the R. *ggplot2* package (Keirstead, 2011).

Results of the paper selection from the systematic literature review

Following the same sequence of procedures discussed in the previous item, the first presented results identify the database and the records to be analyzed. For the particular case of the application presented here (code available with free access, in the GitHub repository at https://github.com/jymn/Systematic-Literature-Review-tools-in-R), the following words were considered in the first search in the TRID database: bike, bikeway, bike path, cycling, bicycling, biking, bicycle, cycleway, cycle path and bicyclists. The search was completed totaling 25,481 records, grouped into 40 XML files. The words bicycle and bicyclists were the ones that obtained a greater amount of search results, followed by the words cycling, bicycling and bike. However, due to a large number of results obtained, new searches were performed, combining the more general words chosen in the first stage (bike, bikeway, cycle path, cycling, biking, bicycle, cycleway, cycle path, bicyclists) with the specific keywords: planning, infrastructure, design, project and urban. This search procedure reduces the number of selected publications in a controlled way and follows this scheme: Bike ..... Bicycle and Planning and Project / Design / Infrastructure / Urban.

Figure 1 shows the paper selection protocol mentioned at the end of item 2.1. This review was performed using the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyzes) routine (Moher et al., 2014). Two hundred and eighty papers were obtained and 211 of those appeared repeated. From the remaining 69 for reading, 33 were projects in progress or papers whose contents related to cycling infrastructure is limited and were excluded. In total, 36 papers were selected and coded for inclusion in the review, according to item 2.2.

Summary of the most relevant information of each search

From the specific point of view of the developed application, reading the selected papers enabled us to identify groups of relevant aspects and common criteria, summarized in Tables 1, 2, 3, 4 and 5. Another interesting feature was the spatial comprehensiveness of the studies (Urban, Suburban or both).

Classification of papers by cluster analysis

From the hierarchical clustering, four clusters were identified for the application example to be used to perform the partitioned clustering. Thus, the data was divided into four clusters containing the characteristics of design and evaluation of cycle infrastructure. These results plotted in a graph describe the relationship between the method and type of infrastructure to the membership of each group, as shown in Figures 2, 3, and 4.

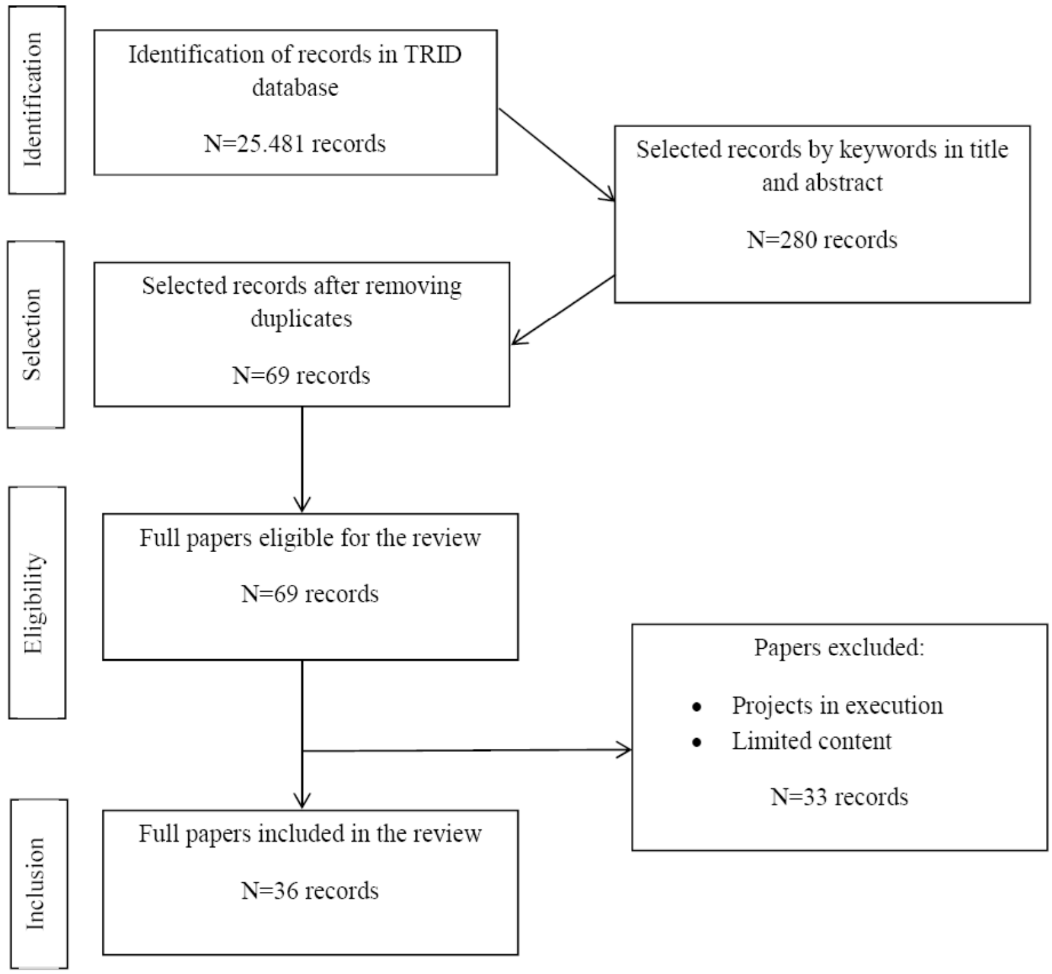


Figure 1. Protocol for paper selection from the systematic literature review

Table 1. Methods for the designing and evaluating bike paths in the reviewed literature.

Method	Description
VN (*Vienna Network*)	Method for assessing cycle systems in Vienna, Austria.
HCM (*Highway Capacity Manual*) method	Bicycle Level of Service method, proposed by the Highway Capacity Manual from the United States of America (USA).
DBLOS (*Danish Bicycle Level of Service*)	Danish method for assessing bicycle levels of service.
BEQI (*Bicycle Environmental Quality Index*)	Index developed in California, USA - provides an infrastructure quality rating on a scale of 1 to 100 and includes infrastructure design variables for segregated cycle paths.
UK *Guidelines*	UK Roadway Design Guides.
Q	Questionnaries.
I	Field information (traffic information, population, demand, etc.)
DOT	US State Departments of Transportation
AUSTROADS	Manuals and reports from the Association of Australian and New Zealand Road Transport and Traffic Authorities.
AASHTO	Documents from the *American Association of State Highway and Transportation Officials* in the USA.
SP	Surveys conducted with bicycle infrastructure users (Stated Preference Survey).
FG	Surveys based on focal groups

Table 2. Infrastructure types considered in the revised literature according to separation and sharing characteristics

Separation	Shared	DESCRIÇÃO
Segregated	*Exclusive*	With some sort of physical separation or marks, without sharing other users (vehicles or pedestrians).
Segregated	*With pedestrians*	With physical separation or not, but shared with pedestrians.
Not segregated	*With motorized vehicles*	No separation and shared with motorized vehicles.

Tabela 3. Indicators for cycle infrastructure design and evaluation selected in the literature reviewed

Indicator	Description
Motor vehicle flow characteristics in the adjacent road	Motor vehicle flow and speed.
Cyclist flow characteristics	Cyclist flow and speed measures
Comfort and facilities	Type and pavement condition, lighting, trees, bicycle parking, drainage, signaling, weather.
Geometry, conflicts and intersections	Frequency of intersections, width of bicycle lanes, width of adjacent lanes, separators, conflicts with pedestrians and other modes, vehicle parking, slope, obstructions (poles, vegetation and others), curves and visibility.
Connectivity and accessibility	Network coverage, connections to the main trip generators and commercial areas, easy access to any location, easy to access and move between other modes, location of the bike path, adjacent land use.
Road safety	Safety related to accidents resulting from traffic and conflicts with other modes.
Public Health	Changes in health related to transportation.

Tabela 4. Levels of study considered in the bicycle infrastructure design or evaluation

Level	Description
Network	Considers the cycleway network of a city.
Segments	Based only on cycling infrastructure links

Tabela 5. Criteria for the bicycle infrastructure design or evaluation selected in the revised literature

Criteria	Description
Objective	Uses clearly defined dimensions and measures
Subjective	Includes information based on surveys, focus groups and field information (traffic, demand, population, etc.).

CLASSIFICATION ACCORDING TO THE LEVEL OF THE STUDY (NETWORK OR SEGMENTS)

Figure 2 shows the analysis of the classification according to the level of the study (Network or Segments, according to Table 4), where there is a predominance of studies at the network level focusing on items of comfort and facilities (Brezina et al., 2012; Nuworsoo et al., 2012; Burke et al., 2009; Ebrahimabadi, 2012; Kimbauer and Baetz, 2014; Bisson et al., 2011; Lin and Yu, 2013; de Leeuw and de Kruijf, 2015; Van den Dool, et al., 2014; Rissel et al., 2013; Surendra, 2015). At the network level, we can observe a concentration of research on cycling infrastructures using surveys and field information in segregated infrastructures (Burke et al., 2009; Pilko et al., 2014; Ebrahimabadi, 2012; Kimbauer and Baetz, 2014; Bisson et al., 2011; Martinek, 2011; Greaves et al., 2015; Evenson et al., 2011; Monsere et al., 2014; Rissel et al., 2013). Research at a segment level also focuses on segregated infrastructures (Parks et al., 2013; Goodno et al., 2013; Miller and Ohlms, 2014; Piccinini et al., 2014; Raith et al., 2011; Jones et al., 2007).

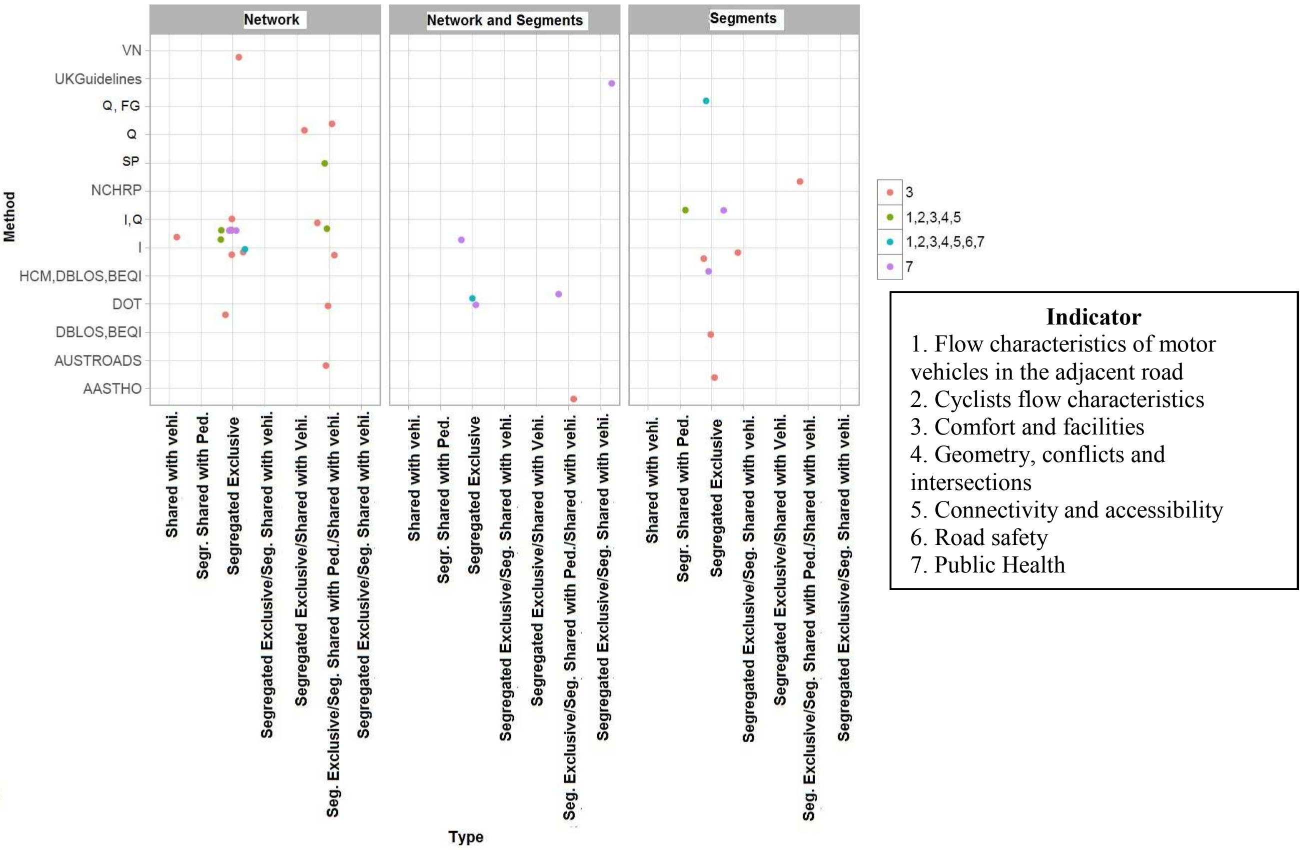


Figure 2. Classification of research according to the level of the study (Network/Segment).

Methods: *Vienna Network* (VN), Method of *Highway Capacity Manual* (HCM), *Danish Bicycle Level of Service* (DBLOS), *Bicycle Environmental Quality Index* (BEQI), United Kingdom design guidelines (*UKGuidelines*), Questionnaires (Q), Field Information (I), US State Departments of Transportation (DOT), Manuals and reports from the *Association of Australian and New Zealand Road Transport and Traffic Authorities* (AUSTROADS), *American Association of State Highway and Transportation Officials*

(AASHTO), Research based on stated preference (SP) and Research based on focal groups (FG).

CLASSIFICATION IN RELATION TO THE CRITERION FOUND IN THE RESEARCH (OBJECTIVE OR SUBJECTIVE)

Figure 3 presents the classification analyses in relation to the criterion found in the surveys (Objective or Subjective, according to Table 5). Most of the research selected (Brezina et al., 2012; Nuworsoo et al., 2012, 2013; Burke et al., 2009; Magalotti, 2013; Pilko et al., 2014; Ebrahimabadi, 2012; Bisson et al., 2011; Martinek, 2011; Greaves et al., 2015; AASTHO, 2010; de Leeuw and de Kruijf, 2015; James, 2015; van den Dool et al., 2014; Philp et al., 2015; Sallis et al., 2013; Evenson et al., 2011; Beukes and Vanderschuren, 2012; Monsere et al., 2014; Clarke, 2008; Goodman and Christopher, 2015; Rissel et al., 2013) was found in the subjective criterion group. Figure 3 also indicates that these studies were mainly focused on the type of segregated infrastructure (Brezina et al., 2012; Burke et al., 2009; Magalotti, 2013; Pilko et al., 2014; Ebrahimabadi, 2012; Bisson et al., 2011; Martinek, 2011; Greaves et al., 2015; Evenson et al., 2011; Monsere et al., 2014; Goodman and Christopher, 2015; Rissel et al., 2013). Within the group of subjective criteria, a number of surveys also focus on the type of infrastructure Totally segregated / Separated. Shared with pedestrians / Shared with vehicles. (Nuworsoo et al., 2012; Nuworsoo et al., 2013; de Leeuw and de Kruijf, 2015; Philp et al., 2015; Beukes and Vanderschuren, 2012; Clarke, 2008).

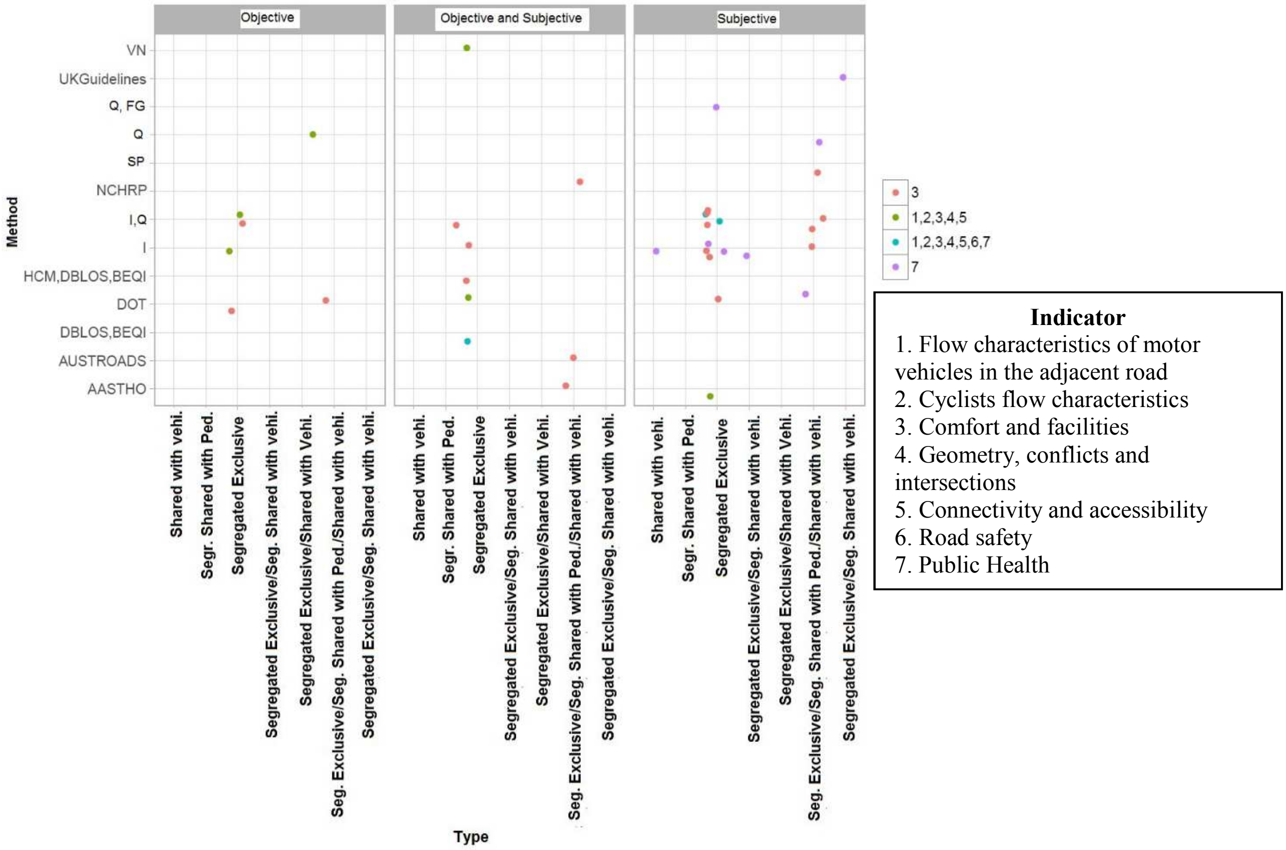


Figure 3. Classification of research according to the characteristic criterion (Objective / Subjective).

Methods: Vienna Network (VN), Method of Highway Capacity Manual (HCM), Danish Bicycle Level of Service (DBLOS), Bicycle Environmental Quality Index (BEQI), United Kingdom design guidelines (UKGuidelines), Questionnaires (Q), Field Information (I), US State Departments of Transportation (DOT), Manuals and reports from the Association of Australian and New Zealand Road Transport and Traffic Authorities (AUSTROADS), American Association of State Highway and Transportation Officials (AASHTO), Research based on stated preference (SP) and Research based on focal groups (FG).

CLASSIFICATION ACCORDING TO THE SPATIAL SCOPE OF THE STUDIES (URBAN, SUBURBAN OR BOTH)

Figure 4 shows the classification according to the spatial extent of the studies (Urban, Suburban or both). In this figure, a significant number of urban studies can be observed (Kuzmyak et al., 2014; Parks et al., 2013; Goodno et al., 2013; Nuworsoo et al., 2012; Piccinini et al., 2014; Burke et al., 2009; Tefe and Langen, 2007; Pilko et al., 2014; Ebrahimabadi, 2012; Kimbauer and Baetz, 2014; Bisson et al., 2011; Lin and Yu, 2013;

Gerlach, 2012; Raith et al., 2011; Sturrock and Brinckerhoff, 2006; James, 2015; Evenson et al., 2011; Beukes and Vanderschuren, 2012; Surendra, 2015; Monsere et al., 2014; Clarke, 2008; Goodman and Christopher, 2015; Rissel et al., 2013. Furthermore, in the urban context, a significant number of studies focusing on the items of comfort and amenities can be observed (Parks et al., 2013; Goodno et al., 2013; Nuworsoo et al., 2012; Piccinini et al., 2014; Burke et al., 2009; Ebrahimabadi, 2012; Kimbauer and Baetz, 2014; Bisson et al., 2011; Lin and Yu, 2013; Sturrock and Brinckerhoff, 2006; Surendra, 2015; Goodman and Christopher, 2015; Rissel et al., 2013), as well as numerous studies on the type of infrastructure segregated (Parks et al., 2013; Goodno et al., 2013; Piccinini et al., 2014; Burke et al., 2009; Pilko et al., 2014; Ebrahimabadi, 2012; Kimbauer and Baetz, 2014; Bisson et al., 2011; Gerlach, 2012; Raith et al., 2011; Evenson et al., 2011; Surendra, 2015; Monsere et al., 2014; Goodman and Christopher, 2015; Rissel et al., 2013). Figure 4 shows a smaller number of studies that cover the Urban and Suburban simultaneously (Brezina et al., 2012; Magalotti, 2013; Martinek, 2011; Greaves et al., 2015; AASTHO, 2010; de Leeuw and de Kruijf, 2015; van den Dool et al., 2014; Philp et al., 2015; Sallis et al., 2013; Olson et al., 2016). In addition, few papers fall into the suburban context uniquely (Nuworsoo et al., 2013; Miller and Ohlms, 2014; Jones et al., 2007).

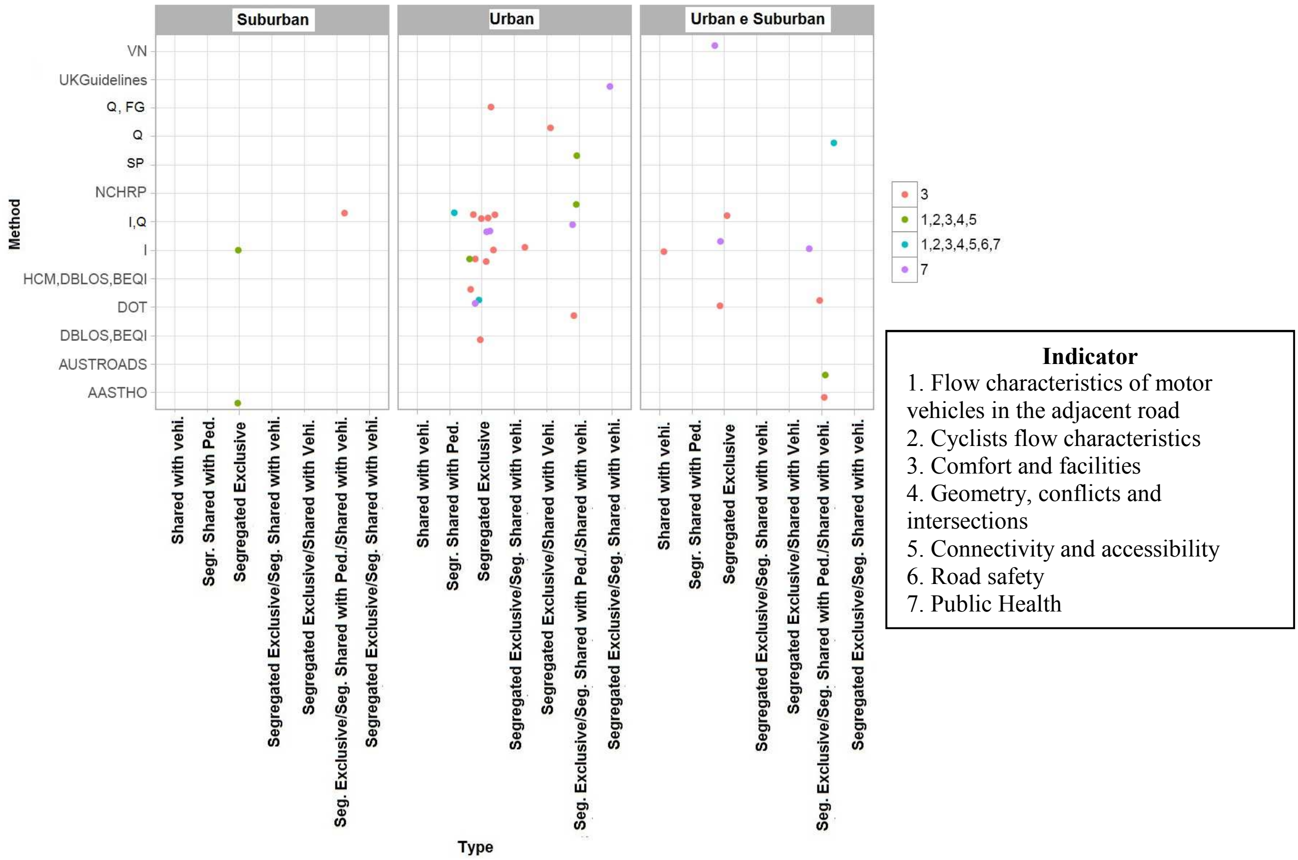


Figure 4. Classification of research according to the spatial context of the studies (Urban/Suburban).

Methods: *Vienna Network* (VN), Method of *Highway Capacity Manual* (HCM), *Danish Bicycle Level of Service* (DBLOS), *Bicycle Environmental Quality Index* (BEQI), United Kingdom design guidelines (*UKGuidelines*), Questionnaires (Q), Field Information (I), US State Departments of Transportation (DOT), Manuals and reports from the *Association of Australian and New Zealand Road Transport and Traffic Authorities* (AUSTROADS), *American Association of State Highway and Transportation Officials* (AASHTO), Research based on stated preference (SP) and Research based on focal groups (FG).

CHAPTER II

COMBINING ENVIRONMENTAL QUALITY ASSESSMENT OF BICYCLE INFRASTRUCTURES WITH VERTICAL ACCELERATION MEASUREMENTS

Pavements in poor conditions can cause risks of accidents and discomfort to cyclists. Currently, management systems for cycling infrastructures rely on visual inspections and users' subjective assessments of the rolling conditions. They do not include objective measurements of vibrations, environmental comfort or any other variable of the physical environment around the infrastructure. This chapter presents an alternative method for inventories and assesses the pavement conditions on cycle paths in terms of pavement conditions. The method introduced here was developed to improve data collection and other procedures required for assessing important components of cycling infrastructures particularly focusing on the pavement surface.

Objective

The aim of this chapter is to develop a method for classifying cycle paths in terms of roughness and general conditions of the pavement surface. In general, using smartphones to support data collection for cycling studies has so far focused mainly on the physical performance of cyclists, demand and flow data (e.g. speed). As a consequence, the potential of several other sensors also available for smartphones, such as the one used in this study, have not yet been fully investigated to assess the conditions of cycling infrastructures.

The objective of this study is to complement the BEQI method by evaluating the condition of the cycling infrastructure using video recordings, GPS and accelerometers embedded in smartphones. Based on analysing and observing the characteristics of the infrastructure from the video recordings, a database can be created. This database can be later complemented with the georeferenced data of vertical acceleration to obtain a complete evaluation of the conditions of cycleways. This development from BEQI aims to add information to an objective and detailed evaluation of the quality of the surface on which cyclists ride.

Background

This section aims to review and summarize the literature related to methods for assessing cycling infrastructures, using smartphones and Global Position Systems to evaluate bicycle infrastructures and assess vibrations on cycleways. The focus is heavily on the pavement quality.

METHODS FOR ASSESSING CYCLING INFRASTRUCTURES

Based on a literature review conducted for this study, we found the following methods for cycling infrastructure design and evaluation as the most common to assess the quality of service of cycleways: the level of service approach for bicycles of the Highway Capacity Manual developed for the United States (TRB 2010); the Danish Bicycle Level of Service - DBLOS (Goodno et al. 2013) and the Bicycle Environmental Quality Index - BEQI, developed in California, USA (SFDPH, 2009; 2014). The particularity of these methods is that they have been calibrated from survey models and include the condition of the pavement surface as a factor based only on subjective evaluations. The BEQI method assesses the characteristics of cycling infrastructure based upon the visual assessment of street segments by a trained observer. This index assesses the bicycle environment on roadways and qualifies the conditions of the cycleways.

We also found technical manuals, such as the UK guidelines for cycling projects (James, 2015), documents from State Departments of Transportation (DOT) in the United States (Olson et al. 2016; Magalotti 2013), manuals and reports from transport authorities in Australia (AUSTROAD) (van den Dool et al. 2014) and documents drawn up by the American Association of State Highway and Transportation Officials (AASTHO 2012) and requirements for high quality cycling infrastructure design in Vienna, Austria (Brezina et al. 2012). These manuals provide recommendations about how the cycleways should be designed. However, they do not propose a way to carry out an inventory and evaluation of the different components and pavement conditions of cycleways. In addition, none of them have included vertical acceleration measurements along the route in their pavement condition indicators. These methods lack detailed information of the pavement conditions such as types of surface and distress on pavement surfaces.

SMARTPHONES AND GLOBAL POSITION SYSTEMS USED TO PLAN AND EVALUATE CYCLEWAYS

Using Global Positioning Systems (GPS) is currently almost a mandatory condition in data collection procedures for inventories and evaluating transport infrastructures. Some authors have used GPS for demand studies, for example (Harvey et al. 2008; Menghini et al. 2010; Hood et al. 2011; Broach et al. 2012; Casello and Usyukov 2014; Jackson et al. 2014; Segadilha and Sanches 2014). GPS receivers were also combined with dedicated accelerometers to evaluate pavement conditions (Benbow et al. 2006; Yamanaka and Namerikawa 2007; Olieman et al. 2012; Macdermid et al. 2014; Bíl et al. 2015; Takahashi et al. 2015; Ambrož 2016; Joo et al. 2015; Joo and Oh 2013; Calvey et al. 2015). A smartphone app GPS was used by Strauss et al. (2017) to investigate the relationship between reported cyclist road injuries and the safety in cycle paths. Nowadays, with the development of electronic devices such as smartphones, using embedded sensors with georeferencing has made it easier to incorporate measures of these devices into the inventory and evaluation methods of cycleways.

Smartphone apps are already an alternative for collecting data from transport system users due to GPS records embedded into these devices. An example of a smartphone application for cycling systems is CycleTracks. Other versions of this app were used in other cities in the USA (SFCTA 2017). These apps were used in bicycle travel demand studies to identify, for example, user preferences. Other smartphone applications, such as Strava and Endomondo, have been developed to provide information about performance, calories burned, etc., during cycling trips.

However, using smartphone accelerometers and action cameras to collect information about cycling infrastructures is not so common. One exception is a study conducted by Vieira et al. (2016), in which smartphone GPS data were combined with information obtained from an action camera (to evaluate the general path conditions) and a cardio signal acquisition belt to evaluate cyclists' stress levels. In this case, however, the video images provide only general information about the cycleway, without any detailed analysis of the pavement conditions (types of surface, types of distress, severity levels and extension) or a comprehensive assessment of the cycle path surroundings.

VERTICAL ACCELERATION AND VIBRATION ON CYCLEWAYS

Roughness caused by large cracks, bumps, potholes and loose gravel could cause undesirable vibrations and put cyclists at risk of falling. In addition, cyclists´ comfort is directly associated with the vibrations caused by pavement surface irregularities. According to Griffin (1990), human perception depends on vibration magnitude, frequency and duration. Exposure to strong and long-lasting vibrations may cause health problems (Gemne and Taylor 1983; NIOSH 1997; Griffin and Bovenzi 2002). On the other hand, a smooth surface also means less energy is consumed by the cyclists (Vanwalleghem et al. 2012).

The ranges of vibrations and frequencies that affect the comfort and health of human beings have been discussed by various authors, such as Giubilato et al. (2014), Matsumoto and Griffin (1998) and Miwa (1975). Other authors have analyzed the direct effect of wavelengths on the perception of the quality of the trip (Ron 1994; Cairney and King 2003; Benbow et al. 2006; Barbudo et al. 2015; Thigpen et al. 2015). According to Benbow et al. (2006), user perception studies show that the profile wavelengths that cause users most discomfort are those in the range of 1-5 meters. Wavelengths between 5 and 10 meters have some impact on comfort perception, and values larger than 10 meters have no effect on user perception.

Accelerometers can be used to determine the characteristics of the vibrations on cycleways (Wigan and Cairney 1985; Torbic et al. 2003; Hastings et al. 2004; Levy and Smith 2005; Champoux et al. 2007; Yamanaka and Namerikawa 2007; Du et al. 2009; Giubilato and Petrone 2012; Hölzel et al. 2012; Olieman et al. 2012; Vanwalleghem et al. 2012; Arpinar-Avsar et al. 2013; Duvall et al. 2014 - case of pathways used by wheelchairs; Macdermid et al. 2014; Parkin and Sainte Cluque 2014; Ayachi et al. 2015; Bíl et al. 2015; Chou et al. 2015; Li et al. 2015; Takahashi et al. 2015; Ambrož 2016). These investigations have shown the importance of measuring vibrations to evaluate the quality of the cycleways and the close relationship with user comfort. Considering that accelerometers are now common devices in smartphones, measurements obtained from them could be used in a simple and intense way to evaluate the quality of cycleways.

Developed Method

The method introduced here was developed for improving data collection and other procedures required for assessing the main components of cycling infrastructures. The approach is based on the Bicycle Environment Quality Index (BEQI), which is a consolidated and relatively recent method developed for evaluating the general conditions of cycling infrastructures (SFDPH 2014). The original method adopts a concept of deductible values (borrowed from roadway pavement management systems) on a 1-100 scale, in which 100 is the best condition. It also takes into account the general conditions of the environment around the cycle paths. Our approach adopts the following procedures: i) inventory data collection, ii) vibration measurements, and iii) infrastructure assessment.

INVENTORY DATA COLLECTION

The data collection procedures were all conducted directly using a bicycle (Table 1 and Figure1). A video camera was adapted to the bicycle frame to help identify the different elements distributed along the cycle paths. A smartphone was fixed to the bicycle frame, under the saddle, to register vertical acceleration values and the associated vibrations along the way. All the information was georeferenced by the GPS data obtained from the smartphone. In order to synchronize the GPS and the accelerometer during the data acquisition, a program was specifically developed in R software. The input data used by the program are found in .csv and .gpx format files. The program automatically extracts the characteristics, classifies them and builds databases that can be directly exported to GIS software or directly visualized using mapping routines of R.

Table 1. Main characteristics of the bicycle used for data collection.

Material Frame	**Aluminum**
Size Frame	Small
Wheel Size	27.5 in
Tire pressure	40 psi
Suspension Fork	Blocked for tests
Total bicycle mass	12.5 kg

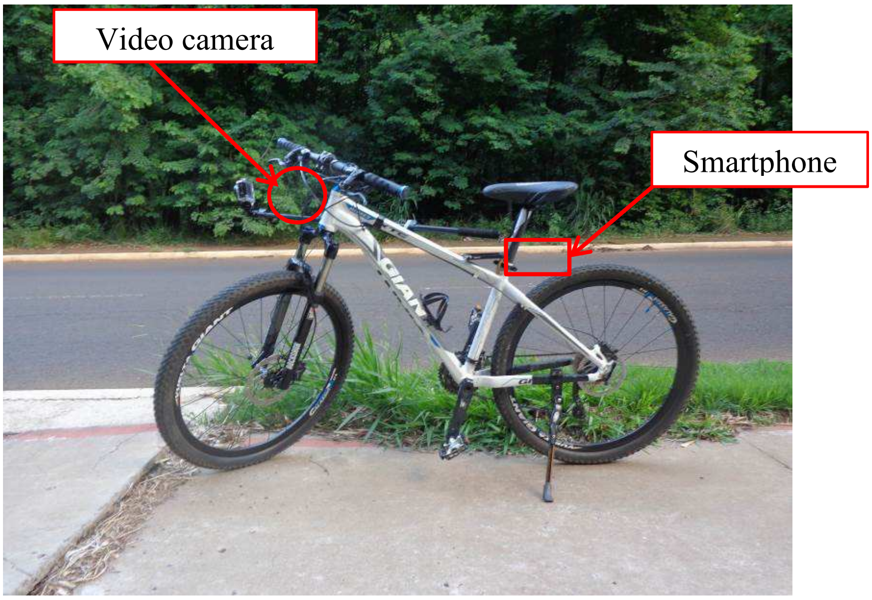


Figure 1. Bicycle with equipment used for inventory data collection

VIBRATION MEASUREMENTS

The analyses of the vibration levels on the cyclist's body were based on recommendations from ISO 2631-1, which was issued by the International Organization for Standardization (ISO 1997). In our evaluation, however, we considered only the vertical acceleration (the z direction informed by the smartphone), because that is essentially how the irregularities on the pavement surface are perceived by the cyclists. Acceleration values were classified according to the Root Mean Square (Equation 1 and Table 2). The first column of Table 2 indicates that ISO 2631-1 explicitly recognizes an overlapping of classes. In our case, the overlapping was not considered (as shown in the second column of Table 2), merely to prevent that any values may simultaneously belong to two different classes.

$$RMS = \sqrt{\frac{1}{N}\sum_{i=1}^{N} {x_i}^2} \qquad (1)$$

Where: N corresponds to the Nth value in a 5 meter interval and xi are the vertical acceleration values collected along the way.

Table 2. Comfort perceptions for different vibration levels (adapted from ISO 2631-1).

Acceptable values of vibration magnitudes for comfort (m/s²)		Likely user's reactions
As in ISO 2631-1	Values used in this study	
Less than 0.315	Less than 0.315	not uncomfortable
0.315 to 0.63	0.315 to 0.63	a little uncomfortable
0.5 to 1	0.63 to 1	fairly uncomfortable
0.8 to 1.6	1 to 1.6	uncomfortable
1.25 to 2.5	1.6 to 2.5	very uncomfortable
More than 2.5	More than 2.5	extremely uncomfortable

As the adopted data collection strategy generates a large volume of data, we decided to spatially aggregate the acceleration data. Groups of RMS values obtained for every 5 meter interval could then be classified according to the limits suggested in ISO 2631-1 and the outcomes subsequently mapped to show the locations with the largest vibrations. The sampling rate of the acceleration was 50Hz. A time-frequency analysis was carried out to assess the typical frequencies of the different types of pavements inspected.

INFRASTRUCTURE ASSESSMENT

For the assessment of the cycling infrastructures, the videos must be analyzed together with the information registered in inspection forms filled in for the different segments of the cycle paths. The inspection form was based on a data sheet developed for rating the conditions of asphalt and concrete pavements of cycle paths (Gharaibeh et al., 1998). We added fields for registering information about the following aspects: signaling, drainage, environment, obstacles, geometry and accessibility (Table 3). Some of these factors were also considered in the bicycle suitability methodology used by the Texas Department of Transportation (Turner et al., 1997). For interlocking concrete pavement, the inspection form was based on the distress manual issued by the Interlocking Concrete Pavement Institute (ICPI, 2007). Regarding the weights associated with the indicators, we adopted the same values originally proposed for BEQI (SFDPH, 2009), shown as percentages in Table 3.

Table 3. Indicators and weights used for infrastructure assessment, based on the BEQI method (adapted from SFDPH 2009).

Traffic 30.8%	**Safety/Other 9.3%**	**Land Use 14.6%**	**Street Design 45.4%**
Motor Vehicle Traffic (Volume and speed)	Control signs and markings	Sight distance	Curve frequency
	Drainage (part of the road/cycle path)	Bicycle parking	Accessibility/connectivity
	Ponding	Land use	Trees
	Obstructions		**Pavement defects**
	Presence of pedestrians		Asphalt * / Concrete ** / Interlocking ***
	Trees, poles, bollards		
	Manhole		
	Debris		
	Faulting		
	Potholes		
	Edge drop-offs		
	Bumps		
	Lighting		

Asphalt pavement defects *	**Concrete pavement defects ****	**Interlocking concrete pavement *****
Cracking	Raveling	Damaged Pavers
Patching	Spalling/scalling	Depressions
Raveling	Faulting	Edge Restraint
Train crossing/rough crossing	Settlement	Excessive Joint Width
Pumping	Cracking	Faulting
Rutting		Heave
Pumping		Horizontal Creep
Shoving and Corrugation		Joint Sand
Bleeding		Loss/Pumping
		Missing Pavers
		Patching
		Rutting

A global assessment strategy was subsequently adopted, in which the final values obtained from BEQI were combined with the vibration measurements, in both cases as rankings. In the first list, higher BEQI values are associated with better conditions of the infrastructure. Vibration measurements, on the other hand, have an opposite interpretation (i.e. higher values are more uncomfortable for the cyclists).

Results and discussion

The proposed method was applied in São Carlos, which is a medium-sized city in the state of São Paulo, Brazil. Most of the outcomes of the procedures described in Section 3 were stored in a GIS environment, which helps analyze the results and, as a consequence, manage the cycling infrastructures. The main results of the application are presented and discussed in this section.

INVENTORY

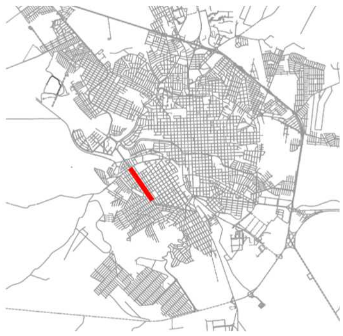
Developing cycling infrastructures is a relatively recent process in Brazil. Following the general trend of the country, cycle paths were implemented in the city of São Carlos only in 2009. Moreover, the process was not fast, as summarized in Table 4 and shown in Figure 2. Despite the limited extension of the existing network, not all stretches were selected for the trial application discussed in this paper. The five cycle paths selected (Figure 3), however, have distinct characteristics. These characteristics, which include attributes of the surrounding environment, were registered in the inventory process and subsequently stored in a GIS database.

Table 4. Main characteristics of cycle paths constructed in the city of São Carlos, Brazil.

Name	Length (m)	Year opened
Torres	1320	2009
Av. Trabalhador *	205	2010
SESC	734	2011
Trabalhadores 1	1255	2011
Trabalhadores 2	1012	2011
Comércio Chaminé *	1360	2012
SESC *	1690	2013
Artes *	990	2014
Ciclovia Parque Faber *	1690	2014
Trabalhadores 3	1872	2016
TOTAL	**12128**	

*Selected for analysis in this study

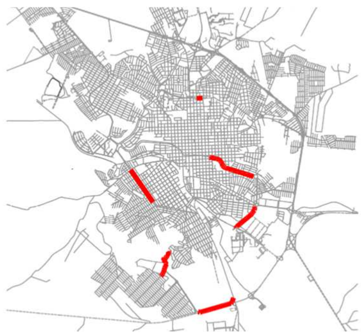
Total of 1.3 km in 2009



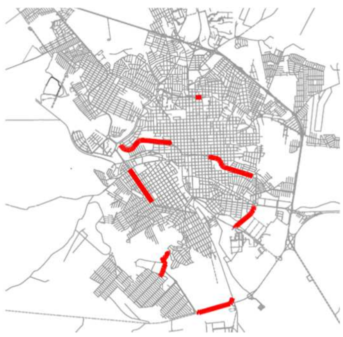
Total of 1.5 km in 2010

Total of 4.5 km in 2011

Total of 5.9 km in 2012



Total of 7.6 km in 2013



Total of 12.1 km in 2014

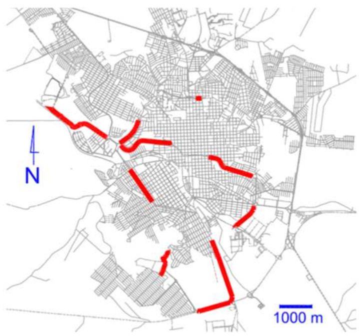


Figure 2. Development of the cycling infrastructures in the city of São Carlos, Brazil

Figure 3. Cycling infrastructures selected for this study in the city of São Carlos, Brazil

VIBRATION MEASUREMENTS

A 33 year-old male cyclist was responsible for collecting all the data, which reduced the variability in the process. In addition to constant body characteristics (64.5 kg and 1.71 m, for example), he tried to keep a regular speed between 15 and 20 km/h. The results of the vibration measurements were used to produce maps of RMS values grouped every 5 meters (as in Figure 4). The classification levels defined in Table 2 are shown in different colors to indicate the comfort perceptions for different vibration readings. Red was used to represent the worst conditions. These are high priority points for maintenance interventions planned to improve the comfort conditions for cyclists.

Typical patterns associated with the pavement material and maintenance conditions of the paths were detected considering the spectral analysis of the different cycle paths. Two amplitude regions were observed regarding the vertical acceleration signals based on the frequency peaks (Figure 5): values below 20 Hz and values above 20 Hz. High frequencies were predominantly observed on the cycle paths with irregular surfaces, such as "Faber Cycleway" and "Av. Trabalhador Cycleway".

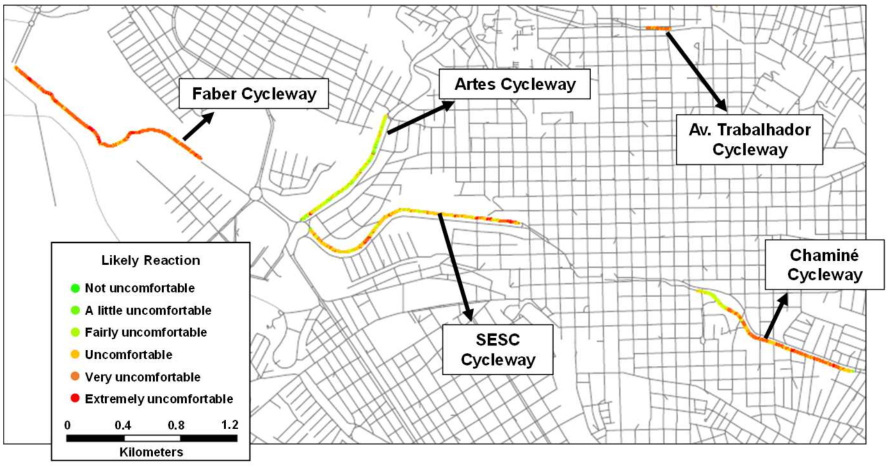


Figure 4. Vibration comfort of cycle paths based on ISO 2631-1

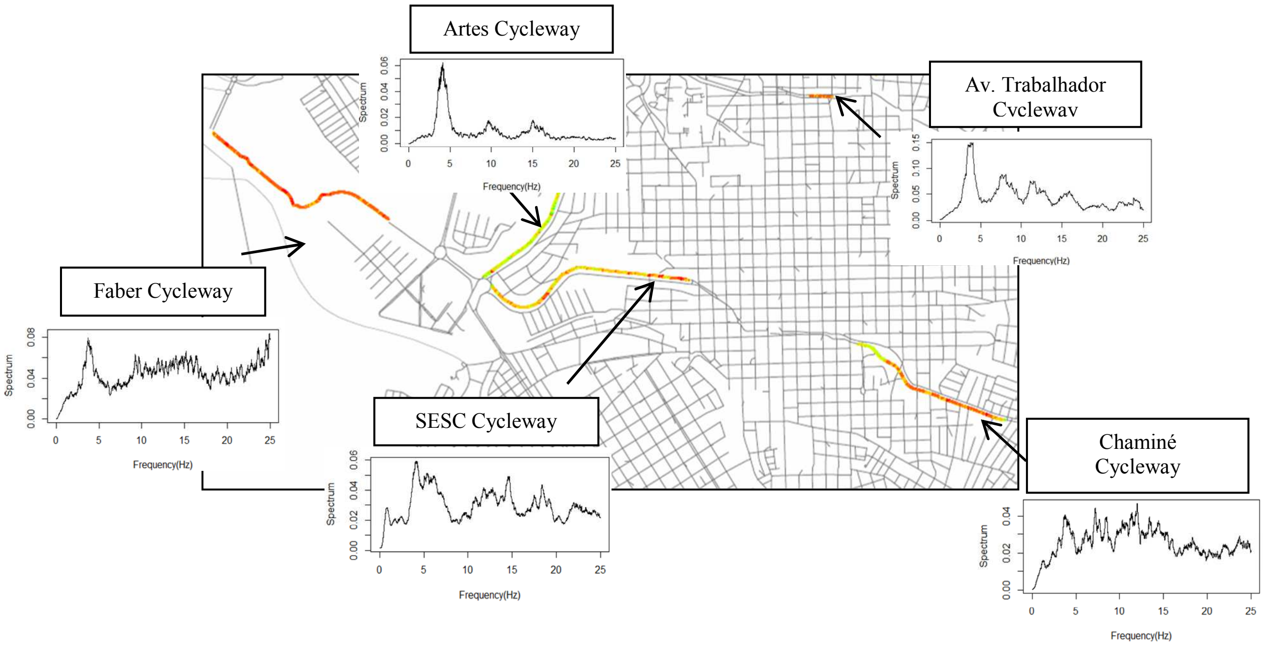


Figure 5. Frequency spectrum of the acceleration amplitude

INFRASTRUCTURE ASSESSMENT

The results of the evaluation based on BEQI values are shown in Figure 6. The red points indicate low index values, which means that these are the locations that are on the high priority list for improvement. The same logic applies to Figure 7, in which RMS values are also color-coded. Red points are those highly uncomfortable to the users. Therefore, these are priority locations for maintenance interventions from this point of view. Independent rankings of the results obtained from the two approaches were subsequently combined in a single list. This final list was a combination of the values of the independent rankings, which produced a new ranking, as shown in list 4 of Figure 8. Once again, red was used to show the worst conditions. Locations with high priority levels in both lists were identified and mapped, as in Figure 9.

Figure 6. Infrastructure assessment based only on BEQI values

Figure 7. Infrastructure assessment based only on RMS values

$$
\begin{bmatrix} Point \\ ID \\ P1 \\ P2 \\ P3 \\ P4 \end{bmatrix}
\overset{(1)}{\begin{bmatrix} BEQI \\ Rank \\ 3 \\ 2 \\ 4 \\ 1 \end{bmatrix}}
\overset{(2)}{\begin{bmatrix} RMS \\ Rank \\ 4 \\ 1 \\ 2 \\ 3 \end{bmatrix}}
\rightarrow
\overset{(3)}{\begin{bmatrix} BEQI\,Rank + \\ RMS\,Rank^{(1)+(2)} \\ 7 \\ 3 \\ 6 \\ 4 \end{bmatrix}}
\rightarrow
\overset{(4)}{\begin{bmatrix} Combined \\ Rank^{(3)} \\ 4 \\ 1 \\ 3 \\ 2 \end{bmatrix}}
$$

Figure 8. Example of the procedure used for the combination of BEQI and RMS rankings

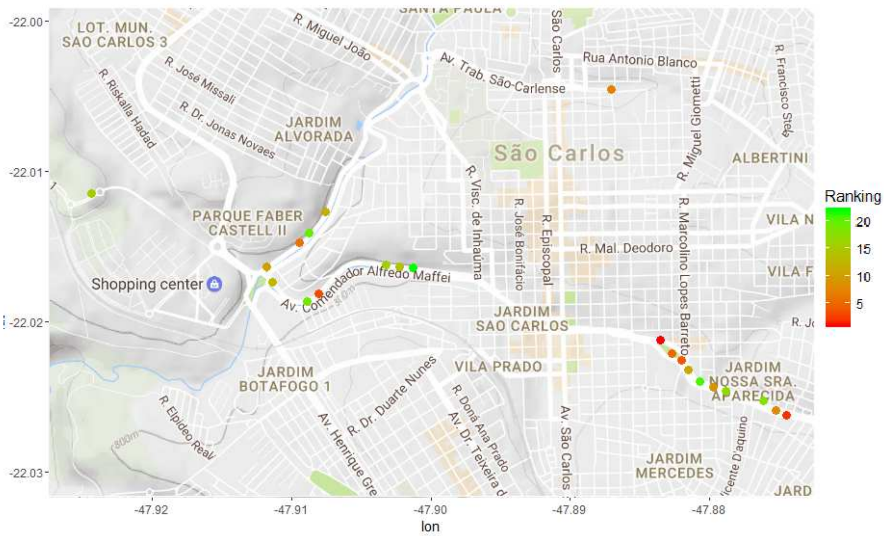


Figure 9. Selection of the 20 infrastructure locations with the highest priority for improvement based on a combination of BEQI and RMS rankings

CHAPTER III

VALIDATION OF A TOOL TO CHARACTERIZE TRAFFIC STRESS OF CYCLING ROUTES USING PHYSIOLOGICAL MEASURES

The Level of Traffic Stress (LTS) is proposed in the literature as a simple tool to assess cyclists´ level of stress in a context that does not reflect the reality of most cities around the world. In this chapter, the LTS was applied to a medium-sized Brazilian city to evaluate whether the LTS classification levels are similar to stress levels actually perceived by cyclists. Therefore, two routes were selected in the city of São Carlos to be traveled by a cyclist using equipment to measure both the skin conductance and temperature in order to calculate the individual's response to stressful events. The comparison of the results showed neither correlation nor agreement between the classification obtained with the LTS and the physiological measures. These findings deserve the attention of practitioners and planners who adopt this tool to evaluate stress.

Objectives

The objectives of this chapter are:

- To perform a comparative analysis between the LTS tool and the physiological stress data of a cyclist.
- To apply the LTS in a medium-sized Brazilian city and discuss its use in this context.
- To compare the results with a direct measure of stress based on the user´s physiological parameters of the user.
- To test adaptations in the method to increase their sensitivity to the Brazilian context

Characterization of the study area and data collection

The present study was developed in São Carlos, which is a medium-sized city with approximately 244,000 inhabitants and is located in São Paulo state, Brazil. For the data collection, two routes with very distinct general characteristics were considered, highlighting the fact that only one of the two had a road structure specifically for bicycle use (cycle path and cycle lane). Route 1 is 17.1 km long and includes four segments of cycle infrastructure of 4.2 km. This route mainly consists of wide roads, with several stretches which have a maximum speed limit of 60 km/h for motor vehicles, and the potential for bicycle use as it has a cycling infrastructure, low slopes, green areas and mixed-use from the soil. Route 2 is located in the central area of the city in narrower lanes, higher density of land use, a regulated speed between 30 and 50 km/h and no cycling infrastructure (Figure 1). For further data analysis, these trajectories were divided into small segments, having the road intersections as a cut-off point. Thus, Route 1 comprised 130 road segments and Route 2 consisted of 59 segments.

Except for LTS, which does not suffer temporal variation and traffic volume, the other variables were collected on typical days of the week (Tuesday, Wednesday and Thursday), specifically during peak hours in the morning (7:30 a.m. to 8:30 a.m.) and the afternoon (5:30 p.m. to 6:30 p.m.). Weather conditions in São Carlos are characteristic of the humid subtropical climate zone with an average temperature of 19.3°C in September. Rainfall in this month is low and during the day of campaigns, there was no rain.

The study adopted a methodological approach based on the combination of different stress quantification tools for the cyclist, such as the application of LTS or the stress measurement to which the cyclist is exposed to when cycling on selected routes. Considering the need to fully analyze the factors that influence the cyclist's well-being, information was also collected to characterize the level of road service. Each of these processes is presented in detail below.

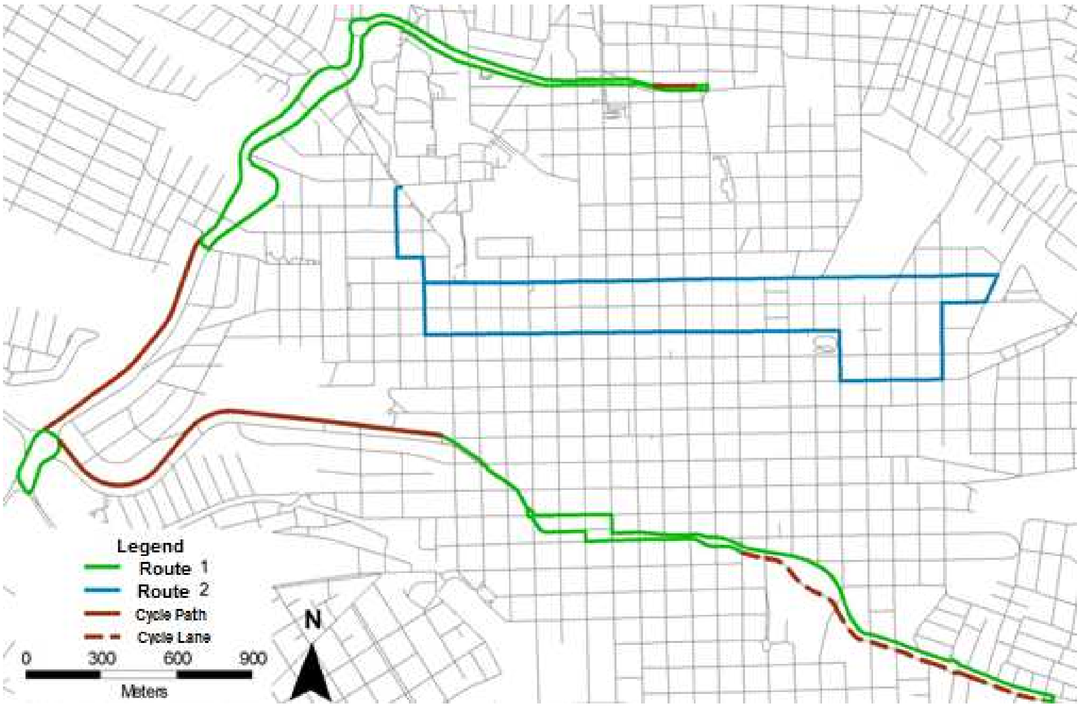


Figure 1. Routes for data collection in São Carlos, SP, Brazil

Level of traffic stress (LTS)

As already presented before, the LTS was created to evaluate the level of traffic stress to which a cyclist is subjected in an objective and segmented way, combining physical information of the roads. For its application, a database with all the road segments inserted in the two study routes was constituted, as well as the transversal sections adjacent to these, according to the methodology defined by Mekuria et al. (2012). The information collected was: bicycle infrastructure (existence and characteristics), speed limits, road width, the presence of parking and characteristics of the intersections.

The data were processed on both spreadsheets and a Geographic Information System, resulting in the classification of all road segments into four categories: LTS 1, LTS 2, LTS 3 and LTS 4, according to criteria previously presented.

Levels of Service (LOS)

Traffic level data were obtained from Google Maps for the characterization of real traffic levels of the streets. The tool from Google called Traffic classifies the road segments into four categories ranging from fast traffic to slow traffic, that is, more fluid and less fluid, respectively. To generate these data, Google Maps analyze GPS coordinate information transmitted by a large number of mobile phone users. When calculating the speed of users along a route, a traffic map is generated in real time and also the usual traffic for each day of the week and time. Raw data on locations received from mobile devices are processed, excluding anomalies (for example, a postal delivery vehicle that stops frequently). When a limit of users is observed in a given area, there is an overlap along the pathways and the map changes color (Matthews, 2013). According to Google, by combining the speed of thousands of phones moving around the city at all times, a good estimation of the traffic conditions can be obtained (Barth, 2009).

For the present study, fast traffic was designated as "A" LOS and slow traffic as "D" LOS. Considering that this classification is not necessarily coincident with the road segments adopted by the present study, in cases where the segments consisted of more than one classification, the worst classification was adopted.

Physiological measures of stress

To assess the level of stress, a Smartband was used to collect skin conductance and temperature sensor at a sampling rate of 10 Hz (Zeile et al., 2016; Nuñez et al., 2017). The electrodermal activity (EDA) response is based on the galvanic response of the skin and can measure changes in skin conductance and temperature and monitor the response to certain physiological emotions (Caviedes et al., 2017). Currently, the EDA response seems to be the most reliable parameter for this purpose. Zeile et al. (2013) have shown in several case studies that reliable results can be obtained for urban planning purposes.

In a stressful event, when a negative experience occurs, the skin conductance increases and the temperature decreases (Kreibig, 2010; Rodrigues da Silva et al., 2014). Once this stressful event is identified, its intensity is characterized as the time (in seconds) that the subject remained in this condition. Since the physiological stress may increase as a function of the duration of the trip (Wener et al., 2003), it was decided to adjust the time/ intensity of the stress as a function of the total time spent cycling through the segment.

Thus, we created the BSI (Bicycle Stress Index). This index is calculated by the time of the stress peaks (duration of stress-DOS) divided by the time spent on cycling in the segment. According to this index, segments with higher values of BSI are considered more stressful as there is a greater proportion of time in a state of stress.

LTS adjusted by (LTS+LOS)

Since the LTS does not take into account the LOT of the roads, a variable composed by the combination of both was created. To aggregate these two variables, the LTS was assumed as the main variable and the level of traffic as the secondary variable. Thus, 16 new categories were possible, varying from the best possible picture - 1A (LTS 1 with LOS A) to the worst possible frame - 4D (LTS 4 with LOS D).

Results and discussion

Considering that the original nature of the LTS data and LOS are already presented in four categories and the stress data are continuous variables, we chose to divide them into quartiles so as to compare them on a similar scale. To do this, the BSI quartile was divided according to the LTS distribution. For example, when all grouped trips were analyzed (all three days, both times and both routes), 41.0% of the segments were classified as LTS 1, 11.6% as LTS 2, 13.2% as LTS 3 and 34.2% as LTS 4. Thus, the cutoff points to define the BSI quartiles were the values corresponding to the 41.0, 52.6 and 65.8 percentiles.

To evaluate the correlation of BSI with LTS and with LTS + LOS, the Spearman Correlation test was performed. In addition, the Kappa Coefficient was used to verify the agreement of the BSI with the two other methods mentioned above (LTS and LTS + LOS). Finally, the same analyses were carried out in a stratified manner by route and period of the day (morning and afternoon). For all analyses, the SPSS Software version 25.0 was used and a p-value <0.05 was adopted.

Description of the results and correlation analysis

In general, the results indicate that there is no relationship between the stress based on the characteristics of the environment (LTS) and the stress based on physiological measurements (BSI). Table 1 shows the distribution of the segments according to the variables and the paths analyzed. It can be seen that for the LOS there were no C or D segments. Due to this fact, instead of having 16 categories, the LTS +

LOS consisted of only 8 categories, ranging from 1A to 4B. Specifically for Route 2, no LTS 4 segments were observed. Thus, for this particular route, the BSI needed to be categorized in tertiles and not in quartiles as in the other groups.

Table 1. Description and data distribution for LTS, LOS, LTS + NS and BSI, layered by route.

	Total			Route 1			Route 2		
	n	**(%)**		**n**	**(%)**		**n**	**(%)**	
LTS			n=190			n=131			n=59
1	78	41.1		35	27		43	72.9	
2	22	11.6		9	7		13	22	
3	25	13.2		22	17		3	5.1	
4	65	34.2		65	50		-	-	
LOS			n=182			n=128			n=54
A	118	64.8		100	78		18	33.3	
B	64	35.2		28	22		36	66.7	
LTS+LOS			n=190			n=131			n=59
1st	24	12.6		10	8		14	23.7	
1B	54	28.4		25	19		29	49.2	
2nd	12	6.3		8	6		4	6.8	
2B	10	5.3		1	1		9	15.3	
3rd	19	10		19	15		3	5.1	
3B	6	3.2		3	2		-	-	
4th	63	33.2		63	48		-	-	
4B	2	1.1		2	2		-	-	
BSI			n=190			n=131			n=59
1	75	39.5		35	26.7		50	84.7	
2	25	13.2		9	6.9		6	10.2	
3	25	13.2		21	16		3	5.1	
4	65	34.2		66	50.4		-	-	

Table 2 shows the results of the Spearman correlation and the Kappa coefficient for Route 1, Route 2 and the global routes (considering the two routes data). Similarly, BSI was not related with LTS + LOT and it not significant. The hypothesis was that, by adding information related to traffic, the correlation and agreement would improve, however this hypothesis was not confirmed.

Table 2. Correlation analysis and agreement between BSI and LTS; BSI and LTS + LOS, global (including all the data of the routes) and stratified by route.

		Quartile BSI				Spearman correlation		Kappa		n
						Value	*p*-value	Value	*p*-value	
Global	**LTS**	1	2	3	4	-0.1	0.15	-0.07	0.12	190
	1	23	14	10	31					
	2	12	1	5	4					
	3	11	2	4	8					
	4	29	8	6	22					
	LTS+LOS					-0.01	0.20	0.01	0.91	190
	1A	8	5	3	8					
	1B	15	9	7	23					
	2A	6	1	3	2					
	2B	6	0	2	2					
	3A	10	1	3	5					
	3B	1	1	1	3					
	4A	27	8	6	22					
	4B	2	0	0	0					
Route 1	**LTS**					-0.01	0.95	-0.01	0.80	131
	1	6	5	8	16					
	2	3	0	3	3					
	3	4	2	4	12					
	4	22	2	6	35					
	LTS+LOS					-0.01	0.95	-0.001	0.94	131
	1A									
	1B	5	2	6	12					
	2A	2	0	3	3					
	2B	1	0	0	0					
	3A	4	2	4	9					
	3B	0	0	0	3					
	4A	22	1	5	35					
	4B	0	1	1	0					
Route 2	**LTS**					0.01	0.94	-0.01	0.89	59
	1	38	5	0						
	2	11	1	1						
	3	3	0	0						
	LTS+LOS					-0.03	0.83	0.01	0.74	59
	1A	12	2	0						
	1B	26	3	0						
	2A	3	0	1						
	2B	8	1	0						
	3B	3	0	0						

Figure 2 shows the mean BSI values for each LTS level separated by paths 1, 2 and global (considering the data of the two routes). It can be observed that there is a tendency in terms of the higher the LTS, the higher the BSI values.

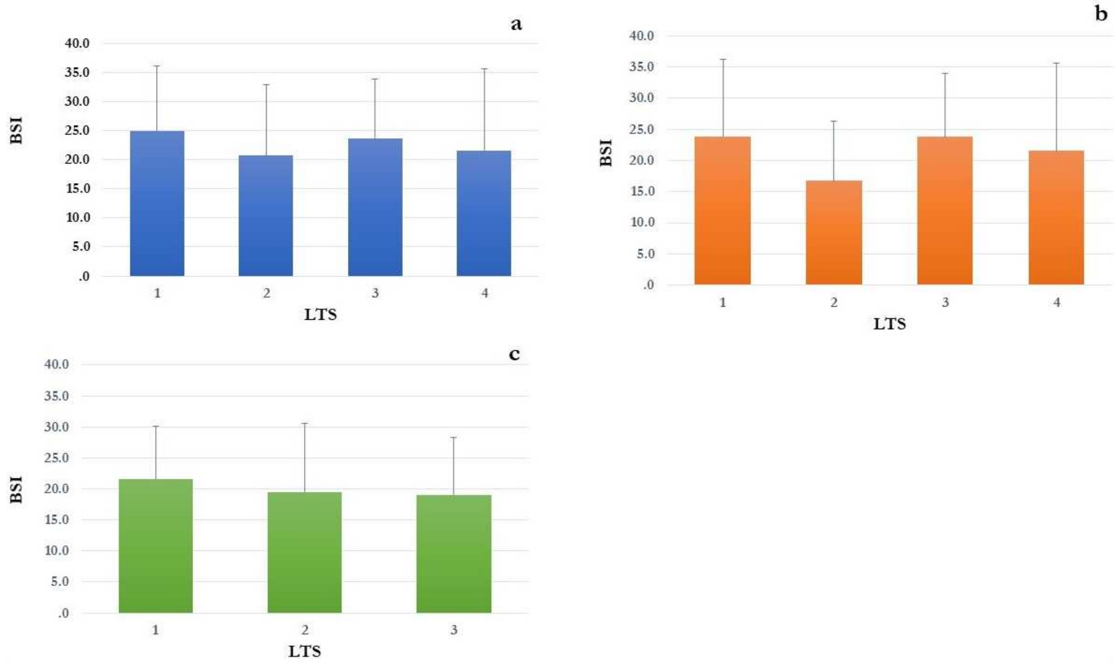


Figure 2. BSI mean values for each LTS group and layered by route. a) Global; b) Route 1; c)Route 2. Error bars represents standard deviation respectively.

When analyzed from the point of view of the day period, an inverse proportional correlation between BSI and LTS and BSI with LTS + LOT was observed during the morning (Table 3). When observing the distribution of data, it can be seen that 37 segments were classified as LTS 4 (more stressful), but presented low-stress values (Quartile BSI 1). At the other end, 34 segments classified as LTS 1 (less stressing) presented high stress values (Quartile BSI 4). A similar behavior was observed for the adjusted LTS.

Table 3. Correlation analysis and agreement between BSI and LTS; BSI and LTS adjusted by LOS and layered by day period.

		Quartile BSI				Spearman correlation		Kappa		n
						Valor	*p*-valor	Valor	*p*-valor	
Morning	**LTS**	1	2	3	4	-0.22	<0.01*	-0.14	<0.01*	190
	1	20	13	11	34					
	2	10	1	4	7					
	3	9	5	2	9					
	4	37	3	6	19					
	LTS+LOS					-0.2	<0.01*	-0.35	0.13	190
	1A	15	11	6	21					
	1B	5	2	5	13					
	2A	10	1	4	7					
	3A	9	5	2	9					
	4A	37	3	6	19					
Afternoon	**LTS**					0.03	0.68	0.03	0.57	189
	1	30	11	12	24					
	2	10	3	5	4					
	3	8	4	3	10					
	4	29	4	5	27					
	LTS+LOS					0.04	0.6	-0.03	0.15	189
	1A	5	4	5	5					
	1B	25	7	7	19					
	2A	2	1	2	3					
	2B	8	2	3	1					
	3A	7	3	1	5					
	3B	1	1	2	5					
	4A	29	4	5	23					
	4B	0	0	0	4					

* p < 0,05

Usually the values for the Kappa coefficient vary between zero and one, and the closer to zero, the lower the agreement between the instruments and, the closer to number one, the greater the agreement. Yet in the analyses considering only the morning period, it was observed that the relationship between the BSI and the LTS presented a negative value for the Kappa coefficient, indicating that there was no agreement and there is a significant discrepancy between the measurements (Table 3). For the afternoon period, no significant correlation and agreement were found for LTS and LTS + LOS.

CHAPTER IV

THE INFLUENCE OF NOISE, VIBRATION, CYCLE PATHS, AND PERIOD OF DAY ON STRESS EXPERIENCED BY CYCLISTS

This chapter presents a method for the evaluation of cycling stress by means of objective measurements of physiological parameters such as conductance and temperature of the skin in cyclists. Measurements of noise and vibration levels were performed simultaneously to investigate the influence that these environmental variables may have on stress. Therefore, was investigated the influence of noise, vibration, cycle paths, and period of day on stress experienced by cyclists

Objectives

This chapter has the following objectives: 1) to elucidate a method of monitoring stress from objective measurements intrinsic to the cyclist and generate maps showing the critical points of stress; and 2) to analyze, using logistic regression models, the relationship of stress measurements with noise, vertical acceleration (pavement surface roughness), presence of cycle paths, and period of the day.

In order to shed some light on the effects of potential stressors on cyclists, the following questions were formulated for this research:

- Is it possible to identify, directly and objectively, critical points of stress along cycling routes?
- What is the importance of external variables such as noise, vibration, presence or not of a cycling infrastructure, and the period of the day on stress experienced by cyclists?

Method

In this section, we introduce the equipment used to monitor cycle paths, a description of the routes selected, the method developed for processing and fusing information obtained from each sensor, and the process for analyzing the importance of environmental variables in stress using logistic regression models.

Equipment for Stress, Noise, and Vibration Measurements

The sensors used in the stress, noise, and vibration measurements, which were adapted to bicycles and cyclists to record different input data, are presented next. A smartband designed to monitor physiological changes in real-world conditions (Zeile, 2018) was used to monitor stress levels. In this case, it was used to measure stress responses in real cycling scenarios. Placed around the wrist of the cyclist's nondominant hand, the smartband basically combines data of skin conductance levels (SCLs) and skin temperature to identify stress peaks. These data are georeferenced using a Global Positioning System (GPS). Both the conductance data and temperature data were obtained at an acquisition rate of 10 Hz, and the GPS acquisition rate was 1 Hz.

To measure noise, a noise sensor (Dekoninck et al., 2014, Ramos, 2015) was adapted to a backpack to be easily carried by the cyclist during the ride. The noise sensor assembly consists of the sensor, a data acquisition and storage system, and a coupled GPS to georeference the measurements along the path. The acquisition rate of the data supplied by the sensor was 8 Hz, and of the GPS was 1 Hz. Once the collections are made, the acquisition system is connected to the internet network to upload the data to a server for processing, and then the data are downloaded.

For the vibration measurements, a system was designed to measure the magnitude of vibrations along the route. The data were collected using a mountain bike (MTB) equipped with a conventional smartphone attached to the frame, just below the saddle. The smartphone records the vertical acceleration data using the accelerometer embedded into the device, and its position is registered simultaneously using the device's GPS. Two Android applications were used to collect the data: one to measure vertical acceleration (Accelerometer Analyzer) and the other to record position (Geo Tracker).

The accelerometer acquisition rate was 50 Hz and the GPS rate was 1 Hz. A GoPro video camera was adapted to attach to the shoulder straps of a backpack carried by the cyclist so that the sources of stress could be identified visually.

ROUTES SELECTED

The proposed method for monitoring stress and environmental characteristics was used in São Carlos, a medium-sized city (approximately 244,000 inhabitants) in the state of São Paulo, Brazil.

Two routes were selected for data collection (Figure 1). Route 1 corresponds to a path of 17.1 km, which includes 4.2 km of cycle paths (red lines in Figure 1). Route 2 corresponds to a path of 5.7 km, without specially designed cycling infrastructure. The days selected for analysis were 12–14 September 2017, during the morning rush hour (between 7:00 a.m. and 9:00 a.m.) and the afternoon rush hour (between 5:00 p.m. and 7:00 p.m.).

Route 1 crosses a considerable part of the city, with segments of cycle paths disconnected from each other. This route is adjacent to a main avenue with medium traffic flow and medium speed limits. The topography of this route has medium to low slopes. Route 2 is in a central area of the city, without cycling infrastructure, and has excellent potential to attract cyclists due to the privileged location of this area in the city. This route also presents medium to low slopes. Weather conditions in São Carlos are characteristic of a humid subtropical climate zone, with an average temperature of 19.3°C in September. Rainfall in this month is low, and during the campaign days there was no rain.

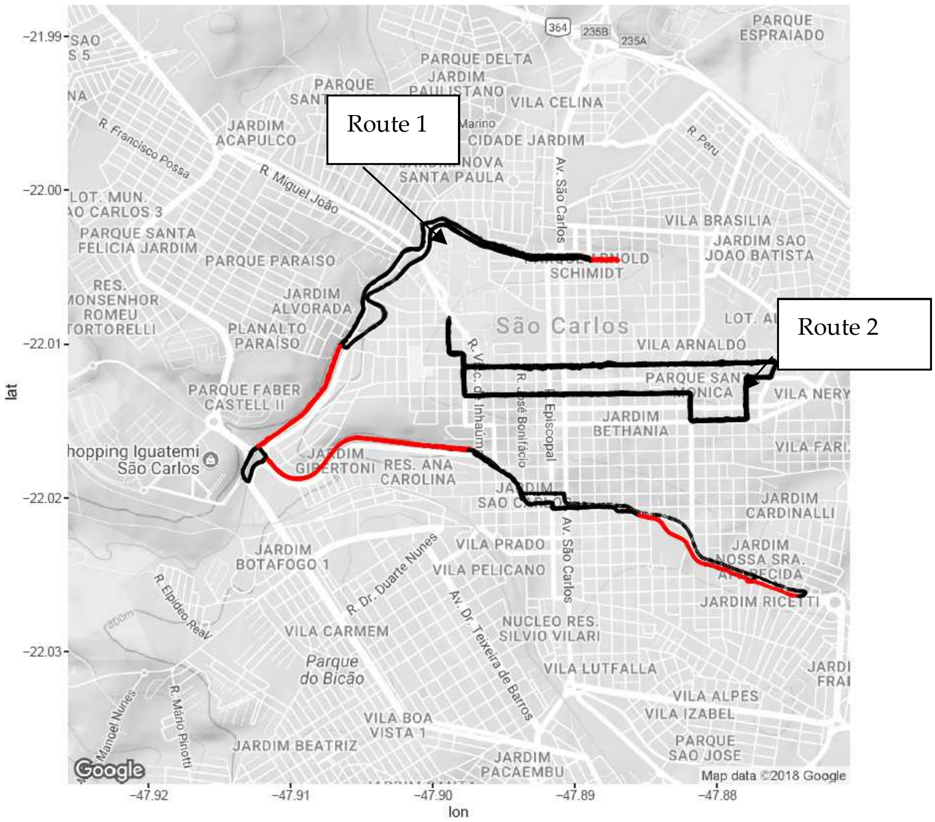


Figure 1. Routes selected for data collection (red lines indicate section with cycling infrastructure).

PROCESSING AND FUSING SENSOR INFORMATION

In order to fuse the sensor information, the time records of the sensors, obtained separately, were matched with GPS data. The data collected in this study (over 3 days, 2 periods of the day, and 2 routes) resulted in a large number of records obtained with different acquisition rates and registered with different formats. This required advanced computational tools to ensure that obtaining the information would be carried out automatically and efficiently. In the case of noise sensor data, for example, data in text format with more than 1 million rows were classified and combined with GPS information.

In order to process and fuse the information obtained from the sensors, a code was developed for reading, processing, and analyzing the data using the R program. R is a freely available language and environment for statistical computing. The general scheme of the algorithm of the program developed for processing and merging the information is presented in Figure 2. According to this scheme, first all the data of the sensors are stored, read, classified, and processed independently for each sensor. After this process, the data are mixed and aggregated over time to generate a database that will be the basis of the statistical analysis. Each stage of processing the obtained data will be explained in detail.

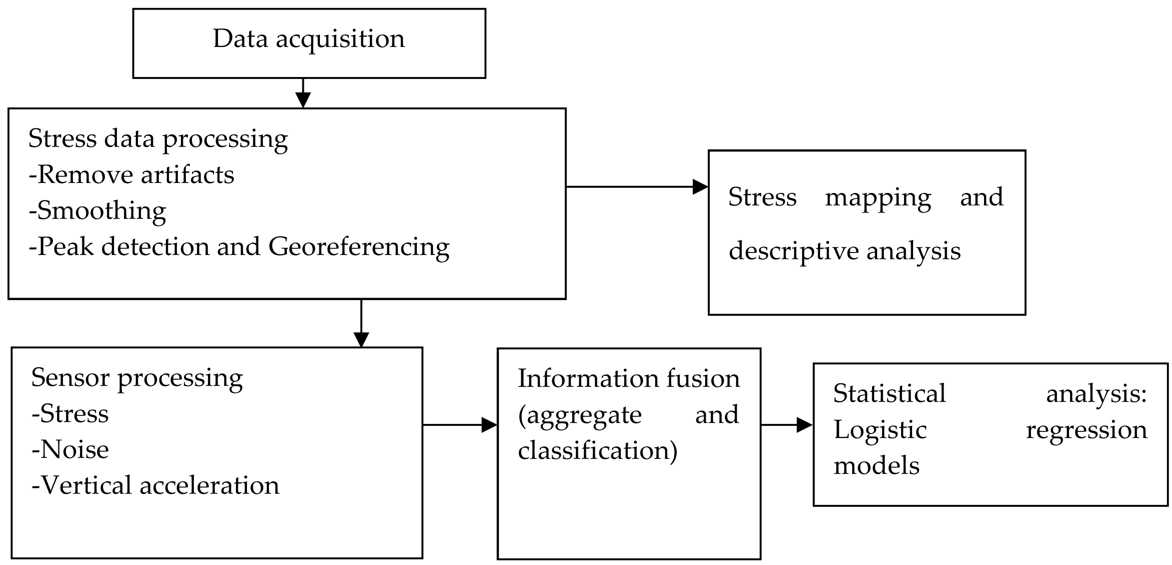


Figure 2. Processing and fusion of sensor data

STRESS DATA PROCESSING

In order to process the stress sensor data, a preprocessing phase consisting of a series of steps was performed as follows: cleaning the signal, eliminating artifacts, and smoothing the signal. After this preprocess, the skin conductance and temperature data were combined with GPS data through an algorithm implemented in the Quantum Geographic Information System (QGIS) program for peak detection and georeferencing. This algorithm generates .shp files as output with the georeferenced information of the stress peaks. The files can be imported into a geographic information system (GIS) to be analyzed later in the form of maps or combined with the information of the other sensors (Beyel 2016).

Stress peaks obtained from physiological measurements were calculated using the first derivative of the skin conductance and temperature. These derivatives are intended to identify whether there is an increase or decrease in the slope. To detect whether there is a peak or stress event, it is necessary to know whether the level of skin conductance is increasing; the score for this event is +1 and the skin temperature should decrease to -1. At the end of the evaluation, the 2 columns with binary data were analyzed. A peak or stress can be identified if the signal shows a decrease in skin temperature 3 s after the skin conductance level has significantly increased.

NOISE DATA PROCESSING

For the noise sensor data, the algorithm steps are as follows: (1) read and classify the noise sensor data, (2) match the time records of the noise sensor and GPS data, (3) aggregate the noise levels per second, and (4) classify these levels according to Table 1 (Ramos et al., 2015). To aggregate the noise data, a logarithmic sum of the sound levels was made, using the following equation:

$$LAeq = 10 \log \sum_{i=1}^{n} 10^{\left(\frac{l_i}{10}\right)} \quad (1)$$

where LAeq is the value of noise aggregated by second and l_i is the ith noise value collected by the sensor.

Table 1. Noise levels categories (adapted from Ramos et al. 2015)

Noise (*LAeq[dB]*)	Categories for the Model	Category
Less than 75	Low noise	1
75 to 85	Moderate noise	2
More than 85	Loud noise	3

VIBRATION DATA PROCESSING

To process the accelerometer data, the algorithm steps are as follows: (1) read the accelerometer and GPS data, (2) match the time records of the accelerometer and GPS data, (3) calculate root mean square (RMS) value per second, and (4) classify these values according to Table 2. For the RMS calculation, the following equation was used:

$$RMS = \sqrt{\frac{1}{N}\sum_{i=1}^{N} x_i^{\,2}} \tag{2}$$

where RMS is the root mean square value, N corresponds to the N acceleration value, and x_i is the values for vertical acceleration.

Table 2. Comfort perceptions for different vibration levels (adapted from ISO 2631-1 (International Standards Organization, 1997)).

Acceptable values of vibration magnitudes for comfort (RMS[m/s²])		Likely User's Reactions	Category
As in ISO 2631-1	Values used in this study		
Less than 0.315	Less than 0.315	not uncomfortable	1
0.315 to 0.63	0.315 to 0.63	a little uncomfortable	2
0.5 to 1	0.63 to 1	fairly uncomfortable	3
0.8 to 1.6	1 to 1.6	uncomfortable	4
1.25 to 2.5	1.6 to 2.5	very uncomfortable	5
More than 2.5	More than 2.5	extremely uncomfortable	6

Once the data from the stress, noise, and acceleration sensors were processed and combined, a unified database was constructed with the following variables: time, coordinates, noise, acceleration, presence or not of infrastructure, and time of day. This unified database was the same one used for descriptive statistical analysis and logistic regression models.

LOGISTIC REGRESSION MODELS

Logistic regression models are used to model binary responses in which there are 2 types of output: “success” or “failure.” These are types of generalized linear models (GLMs) (McCullagh and Nelder, 1989), which have 3 components: (i) the random component, which is identified as the response variable and has a binomial distribution; (ii) the systematic component, which specifies the explanatory variables of the model; and (iii) the link function (in this case, the logit function, Equation (3)), which the GLM relates to the explanatory variables through a prediction equation having a linear form (Equation (4)) (Agresti, 2007).

$$Y = \log\left(\frac{\pi}{1-\pi}\right) \tag{3}$$

$$Y = \beta_0 + \beta_1 x_1 + ... + \beta_k x_k \tag{4}$$

The proposed model explores the relationship of the response to stress using 4 explanatory variables: noise, vibration, presence of cycle paths, and period of the day (morning and afternoon peak traffic times). Continuous variable noise (LAeq) and vibration (VA) were categorized according to Tables 1 and 2 and were considered as factors in the model. The model is represented by Equation (4.5)

$$Y = \beta_0 + \beta_1 Noise + \beta_2 VA + \beta_3 PCI + \beta_4 Period + e \tag{5}$$

where LAeq corresponds to the category of noise level (Table 1), VA is vertical acceleration classified according to the category of vibration level (Table 2), PCI corresponds to the presence (1) or absence (0) of cycle paths, and Period corresponds to the period of the day (0 for the morning and 1 for the afternoon).

In logistic regression models, odds and odds ratio analyses are used to determine the importance of the explanatory variables in the model. For our model, the odds of response 1 (i.e., the presence of stress) are calculated as the exponential function of the *b* exponents of Equation (6):

$$\frac{\pi(x)}{1-\pi(x)} = \exp(\beta_0 + \beta_1 Noise + \beta_2 VA + \beta_3 PCI + \beta_4 Period + e) \tag{6}$$

In this expression, for every 1-unit increase in X, the odds value is multiplied by e^b. Consequently, if b = 0, then e^b = 1 and the odds value does not change as X changes. To select the variables to be included in the model, on the one hand, the model considered should be complex enough to provide a better fit, but on the other hand, simpler models (with fewer variables) may be easier to interpret (Agresti, 2007). Based on these considerations, a selection of stepwise variables (stepwise variable selection algorithms) was implemented.

Based on these considerations, a selection of stepwise variables (Stepwise Variable Selection Algorithms) was implemented, which consists in adding or eliminating predictors of a model in a sequential manner. A forward selection adds terms in a way until there is no improvement in the adjustment. And the backward selection begins with a more complex model and terms are eliminated.

To determine the fit of the model in terms of the ability to explain the model based on the selected variables, the Cox and Snell and Nagelkerke and Akaike information criterion (AIC) techniques were used (Cox, 1989; Nagelkerke, 1991). The Cox and Snell and Nagelkerke techniques, used to determine the fit of the logistic regression models, known as pseudo R^2, are similar to those used in traditional regression analyses in which R^2 is calculated. The adjustment values can be between 0 and 1, so that the closer to 1, the better the values fit the model.

The AIC judges a model by comparing how similar adjusted values tend to be the true expected values. An optimal model tends to have its values closest to the true probabilities of the result, that is, the model that minimizes AIC = 2 (log probability: number of parameters in the model) (Agresti, 2007).

Thus, the lower the AIC value, the better the adjustment of the data to the model. Finally, the selected model was validated by dividing the database into two parts, one for training the model, with 70% of the data, and the other for validation, with 30%.

Results and discussion

In this section, the results of applying the method to monitor stress as described above are presented. In the following subsections, maps with the results of the descriptive analysis of stress and of the logistic regression models are shown.

STRESS MAPS

The results of stress peaks and duration of stress (DOS) from the stress sensor can be represented and analyzed descriptively using maps. In these maps, the duration of stress can be associated with the intensity of the stress peak and can be represented in heat areas. Larger areas and more intense colors indicate higher concentrations of stress at certain points. In these points of greater intensity, considered as critical stress points, planned interventions that improve the cyclist's comfort could be proposed. Figure 3 shows the results of the heat maps of the routes evaluated combining all the days and periods.

Figure 3 shows some highlights of high concentrations of stress where it would be interesting to make some improvements that reduce the levels of stress experienced by cyclists. Points A to D highlighted in the figure represent locations with a predominance of stress peaks in areas where the cycling infrastructure begins and ends without a transition or connection to the road. This missing connection forces an abrupt incorporation into mixed traffic, which causes high levels of stress. Actual images of these points extracted from video recordings are presented in Figure 4a. The upper left image shows a cyclist crossing the street to access the cycle path that begins at the median strip. The end of the cycling infrastructure without any connection to allow the cyclist to safely get onto the road can be observed in Figure 4a (upper right image).

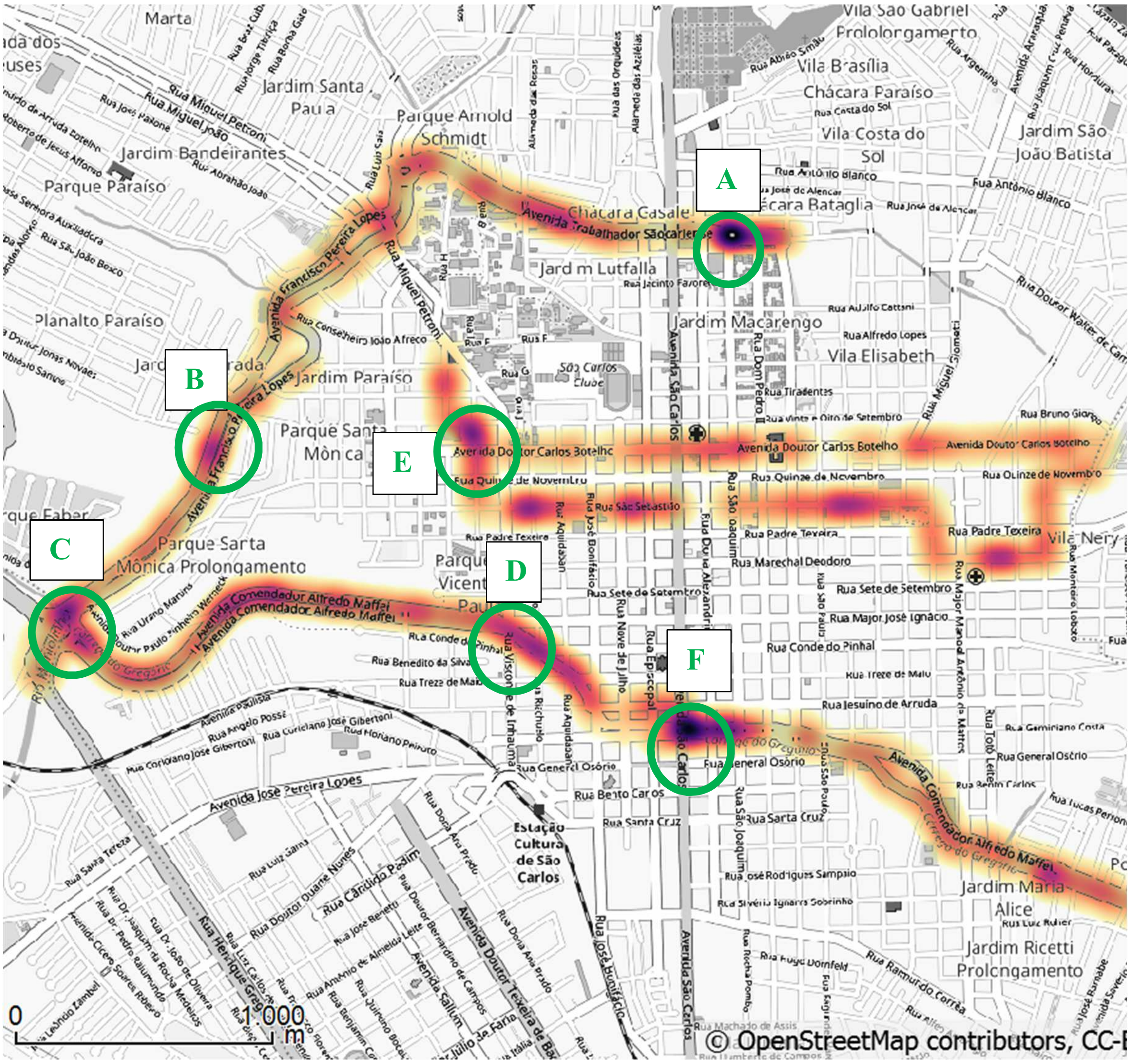


Figure 3. Heat stress map areas resulting from the combination of all the days and periods analyzed. Larger areas and darker colors indicate higher concentrations of stress at certain points.

In addition, the lack of safe spaces for cyclists and points of conflict at intersections (points E and F in Figure 3) can result in a high concentration of stress points. In general, high-frequency stress points were observed in the vicinity of intersections. Images at point F show the lack of space and unsafe traffic conditions for cyclists at this intersection (left and right images of Figure 4b, also captured from videos recorded during actual rides).

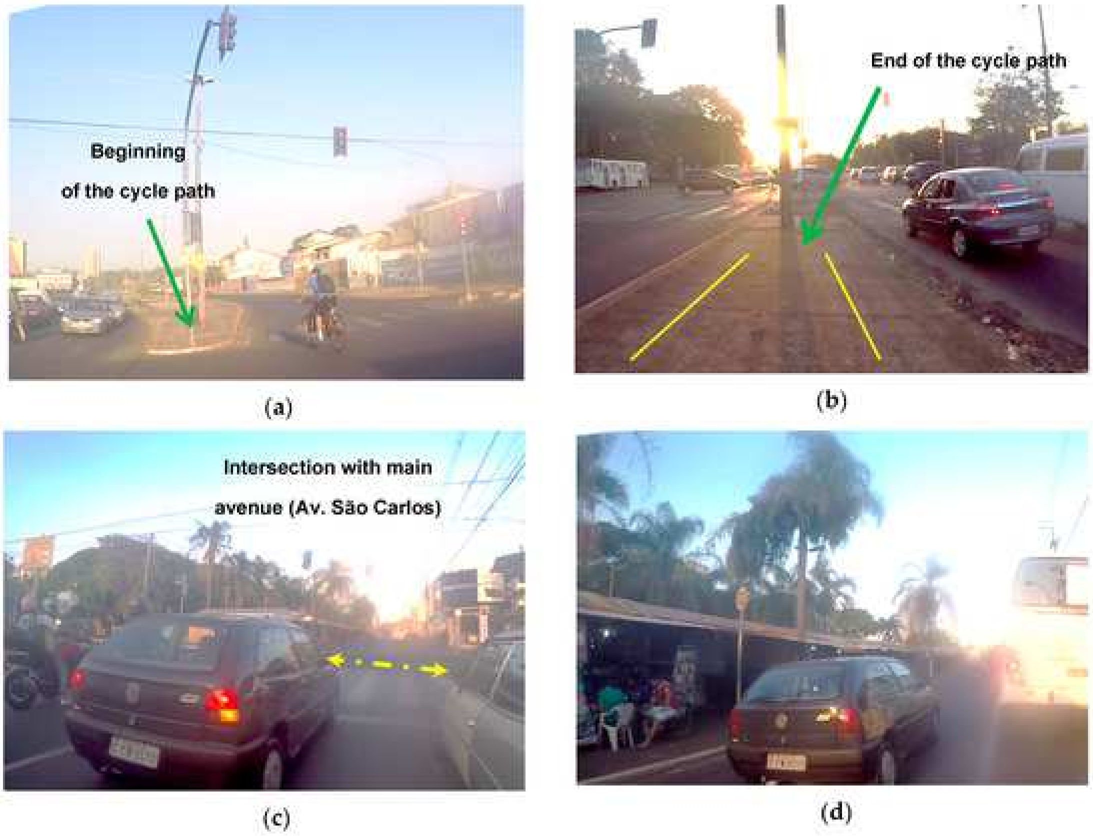


Figure 4. Images of critical stress points. (**a**) Detail of point A in Figure 3: cyclist crossing the street to access the cycle path. (**b**) Detail of point A in Figure 3: cycling infrastructure without any connection. Details of point F in Figure 3: (**c**) points of conflict at an intersection and (**d**) lack of space to accommodate bicycles.

Table 3 shows the results of descriptive statistics for the days selected. The results in this table include the mean, median, maximum, and minimum values, the first and third quartiles, and standard deviations, separated by morning and afternoon periods. It can be observed that the average duration of stress was 8.3% higher on average for the afternoon period, and the mean noise values were slightly higher (3.7%) in the afternoon period.

Concerning noise levels, the mean values indicate values considered to represent moderate noise (Table 1) along the routes. For vertical acceleration, it can be observed that, on average, the value was 1.5 m/s2 for the two periods. This acceleration value is classified as a condition of uncomfortable vibration, as shown in Table 2.

Table 3. Results of the statistic descriptive by period of day

Morning Rush Hour							
Variable	**Min.**	**1st**	**Median**	**Mean**	**3rd**	**Max.**	**σ**
Stress (*DOS* (s))	5	5	7	9.55	12.25	28	5.70
Noise (*LAeq* (dB))	57.47	71.30	75.60	75.97	80.33	108.10	6.22
VA (*RMS* (m/s^2))	0.01274	0.8736	1.142	1.431	1.621	11.62	0.99
Afternoon Rush Hour							
Variable	**Min.**	**1st**	**Median**	**Mean**	**3rd**	**Max.**	**σ**
Stress (*DOS* (s))	5	6	8	10.34	11.5	43	7.60
Noise (*LAeq* (dB))	45.65	75.46	78.91	78.80	82.18	107.60	5.44
VA (*RMS* (m/s^2))	0.001	0.9036	1.241	1.579	1.8	18.09	1.21

* *DOS,* duration of stress; *LAeq*, noise level; VA, vertical acceleration; RMS, root mean square.

RESULTS OF LOGISTIC REGRESSION MODELS

The results of the stress measurements were modeled from a logistic regression model as a function of the environmental variables noise (Noise), vertical acceleration (VA), presence or not of infrastructure (PCI), and period of the day (Period). A total of 19,007 records were analyzed, considering four categorical predictors: noise (three categories), vertical acceleration (six categories), presence (one) or absence (0) of cycling infrastructure, and period of the day (morning, zero; afternoon, one).

First, an analysis was carried out to determine which variables should be included in the model using a selection of stepwise variables (stepwise variable selection algorithms). Table 4 presents the results of adjusting the logistic regression models for each variable and combinations of variables. The adjustment was verified using the techniques proposed by Cox and Snell and Nagelkerke and AIC. In this table, lower AIC values are desirable for a good fit, and in the case of the criteria established by Cox and Snell and Nagelkerke, the closer to 1, the better the fit.

MODEL SELECTION STRATEGY

Firstly, an analysis was carried out to determine which variables should be included in the model. Considering that the model should be complex enough to fit the data well but at the same time simpler models can be easier to interpret, a selection of stepwise variables was carried out (Stepwise Varible Selection Algorithms).

Table 4. Adjustment of logistic regression models. AIC, Aikake information criterion.

Variables	Adjustment Criteria		
	Cox and Snell	Nagelkerke	AIC
Noise	$7.85x10^{-5}$	$1.25x10^{-4}$	19,748
VA	$2.07x10^{-3}$	$3.20x10^{-3}$	19,716
PCI	$3.68x10^{-4}$	$5.70x10^{-4}$	19,741
Period	$2.06x10^{-3}$	$3.19x10^{-3}$	19,708
Noise + VA	$2.16x10^{-3}$	$3.35x10^{-3}$	19,719
Noise + PCI	$4.46x10^{-4}$	$6.90x10^{-4}$	19,743
Noise + Period	$2.23x10^{-3}$	$3.45x10^{-3}$	19,709
VA + PCI	$2.23x10^{-3}$	$3.46x10^{-3}$	19,715
VA + PCI + Period	$4.03x10^{-3}$	$6.23x10^{-3}$	19,683
VA + Period	$3.85x10^{-3}$	$5.97x10^{-3}$	19,684
PCI + Period	$2.42x10^{-3}$	$3.75x10^{-3}$	19,704
Noise + VA + PCI	$2.32x10^{-3}$	$3.60x10^{-3}$	19,717
Noise + VA + PCI + Period	$4.20x10^{-3}$	$6.49x10^{-3}$	19,684

In Table 4, it can be observed that the model with all variables (Noise, VA, PCI, and Period) has the lowest AIC value and the best values of fit using the Cox and Snell and Nagelkerke criteria ($4.20x10^{-3}$ and $6.49x10^{-3}$), which would put this model in first place in the selection. The model with three variables (VA, PCI, and Period) presented adjustment values similar to those of the model with all four variables ($4.03x10^{-3}$ and $6.23x10^{-3}$). However, although a simpler model may be desirable, the difference between the adjustment values did not improve significantly. In addition, the model with more variables allows a more in-depth analysis of the variables that can influence stress and its importance.

Based on the above, we selected the logistic regression model that includes all variables for subsequent analysis. Regarding the validation process, after obtaining the estimated stress probabilities and classifications, the accuracy (i.e., number of correct estimates divided by total number of cases considered for validation) obtained for the selected model was 0.78%, with a 95% confidence interval equal to (0.7714, 0.793). A summary of the results obtained with the selected model is presented in Table 5.

Table 5. Results of the selected logistic regression model.

Explanatory Variables	Estimate	Std. Error	z Value	Pr (>|z|)	Odds Ratio exp(β)	95% Confidence Interval for exp(β)	
Intercept	−1.35361	0.12286	−11.017	<2x10^{-16}	0.258306	0.201986	0.327135
Noise (*LAeq* (dB))							
75 to 85 (*Noise2*)	−0.0552	0.03791	−1.456	0.1454	0.946295	0.878529	1.019304
>85 dBA (*Noise3*)	0.03948	0.07115	0.555	0.5790	1.040268	0.903712	1.194528
RMS (m/s^2)							
0.315 to 0.63 (*VA2*)	0.123	0.13285	0.926	0.3545	1.130885	0.874831	1.473401
0.63 to 1 (*VA3*)	−0.14451	0.12533	−1.153	0.2489	0.865442	0.679883	1.111831
1 to 1.6 (*VA4*)	−0.02449	0.12479	−0.196	0.8444	0.975804	0.767435	1.252346
1.6 to 2.5 (*VA5*)	0.05507	0.12754	0.432	0.6659	1.056614	0.826331	1.363036
>2.5 (*VA6*)	0.12673	0.12852	0.986	0.3241	1.135114	0.885927	1.467004
PCI	−0.07269	0.04071	−1.785	0.0742	0.92989	0.858353	1.006886
Period	0.21814	0.03652	5.974	2.32x10^{-9}	1.243759	1.157868	1.336069

The importance of each variable to stress levels can be analyzed from the odds ratio values

The importance of each variable to stress levels can be analyzed from the odds ratio values presented in Table 5. This parameter refers to the effect of each variable on the probabilities controlling the other factors. The logistic regression model obtained is:

$$\begin{aligned}\text{logit}[\pi\hat{}(x)] = &-1.35361 - 0.0552*Noise2 + 0.03948*Noise3 \\ &+ 0.123*VA2 - 0.14451*VA3 - 0.02449*VA4 + 0.05507*VA5 + 0.12673*VA6 - \\ &0.07296*PCI + 0.21814*Period\end{aligned} \tag{7}$$

Even though loud noise increased the odds of experiencing stress by 4%, very uncomfortable vibrations increased the odds by 14% and the presence of cycle paths decreased the odds by 8%, the analysis of p-values and the odds ratio confidence intervals showed, with a 95% confidence level, that only the period of the day had an influence on stress, as confirmed by the data. In this case, the odds of experiencing stress increased by 24% in the afternoon rush hour compared to the morning rush hour.

BINARY TREATMENT OF ORDINAL NOISE PREDICTORS

In the previous models the categories of noise and acceleration were treated in an ordinal way, assuming a linear variation between categories. That is, in the case of the variable noise {1,2,3} and in the case of vertical acceleration {1,2,3,4,5,6}. However, noise levels do not have a linear scale. This suggests that another potential score for the model could be {0,0,1}, that is, Noise = 1 for noise levels greater than 85dB (considered high noise levels) and Noise = 0 in the other cases. The results of these models are presented in table 4.

Table 6. Results of the logistic regression model considering the noise predictor as binary

Explanatory variables	Estimate	Std.Error	z value	Pr(>|z|)	Odds Ratio (expβ)	95%Confidence interval for exp(β)	
Intercept	-1.43746	0.03603	-39.897	< 2e-16	0.2375292	0.221297	0.254869
Noise	0.06191	0.06795	0.911	0.3622	1.0638663	0.929893	1.213816
VA	0.03609	0.01501	2.405	0.0162	1.0367511	1.006487	1.067491
PCI	-0.0987	0.03979	-2.481	$1.31x10^{-2}$	0.906011	0.837805	0.979235
Períod	0.21706	0.03547	6.119	$9.40x10^{-10}$	1.2424224	1.158992	1.331898

The values of the coefficients of the fit of the model using the criteria Cox & Snell and Nagelkerke ($2.76x10^{-3}$ and $4.28x10^{-3}$). Although this model provides simpler interpretations and better levels of significance, the adjustment coefficients show that these values do not fit the model very well, being even smaller than those of the selected model that considers all the variables.

MODELS WITH INTERACTION BETWEEN THE VARIABLES

The previous models have considered the lack of interaction between the variables. The interaction can be enabled by adding the cross product of the noise and vertical acceleration terms. In this sense each noise level has a different curve that relates the vertical acceleration with the stress probability so that the comparison of two noise levels varies according to the value of the vertical acceleration.

For the previous model where the ordinal variables were modified, in which high noise levels are 1 and 0 otherwise, the results are shown in the following table:

Table 7. Results of the logistic regression model considering interaction between the variables Noise and VA

Explanatory variables	Estimate	Std.Error	z value	Pr(>|z|)	Odds Ratio (expβ)	95%Confidence interval for exp(β)	
Intercept	-1.43402	0.02882	-39.185	< 2e-16	0.238348	0.221814	0.2560323
Ruido	0.01325	0.0732	0.117	0.907	1.0133348	0.8106759	1.2651062
AV	0.03385	0.0523	2.171	0.03	1.0344312	1.0030578	1.0663108
PIC	-0.09835	0.03993	-2.471	1.35×10^{-2}	0.9063301	0.8380915	0.9795906
Período	0.21688	0.03548	6.114	9.74×10^{-10}	1.2421941	1.1587725	1.3316601
Ruido x AV	0.03072	0.19677	0.539	0.59	1.0311983	0.9198708	1.1511267

The model with an interaction term has the following equation.

$$\log it[P(Y=1)] = 1.434 + 0.01325 Noise + 0.03385 VA + 0.03072 Noise * VA \\ -0.09835 * PCI + 0.21688 * Period \quad (10)$$

For low noise levels (below 85 dB), Noise = 0:

$$\log it[P(Y=1)] = 1.43402 + 0.03385 VA - 0.09835 * PCI + 0.21688 * Period \quad (11)$$

For high noise levels (more than 85 dB), Noise = 1:

$$\log it[P(Y=1)] = 1.42077 + 0.06458 VA - 0.09835 * PCI + 0.21688 * Period \quad (12)$$

As observed in the previous equations, the curve for noise levels considered high (Equation 11) presents a faster rate of increase. These curves intersect at the vertical acceleration value AV = 0.43m/s^2, corresponding to category 2, which is known as not very comfortable. This indicates that high noise values have a higher estimated probability of having stress practically in all vibration ranges (staring from the category 2).

The values of the coefficients of the model adjustment using the Cox & Snell and Nagelkerke criteria (2.78×10^{-3} and 4.31×10^{-3}) continue to be lower than the model initially selected.

CHAPTER V

SUMMARY, CONCLUSIONS AND FUTURE WORK

This investigation presents a new perspective in terms of planning and evaluating bicycle transport by incorporating objective measures based on using intelligent sensors. Within this approach, a series of contributions were achieved which converge in: i) developing a procedure for a systematic literature review applied to the design and evaluation of transportation cycling systems; ii) developing a method for combining environmental quality assessment of bicycle infrastructures with vertical acceleration measures; iii) validating a tool to characterize traffic stress of cycling routes with physiological measures; and iv) investigating the influence of environmental factors such as noise, vibration and the presence or absence of infrastructure and time of day on stress experienced by cyclists.

The following sections present a summary of the main findings obtained in the different areas of this study.

Systematic literature review using data mining resources: an application to design and assess cycling transportation systems

This section proposed a method that consists of an algorithm to select studies in databases, and later cluster analysis to classify the selected studies. The cycling system design and evaluation were the topics chosen to test the method. Based on the results found by adapting data mining techniques to make it more effective to implement systematic literature review procedures in the transport area, some general conclusions were obtained.

First, it was observed that the proposed approach can help identify the most relevant research on a certain subject, besides ensuring that the results from the literature review are reproducible. Second, the cluster analyses proposed by the method can provide relevant information about the state of the art of a certain subject and, thus indicate both salient points and research gaps.

In the specific case of the theme selected for applying the method, related to the design and evaluation of bicycle systems, the following points deserve attention:

The cluster analyses pointed to a large number of studies that focus mainly on the network level, as well as a significant number of studies that include only data collection based on surveys and field information. Additionally, a high concentration of studies was observed focusing on the design and evaluation of fully segregated cycling infrastructures. On the other hand, there is a lack of research that involves the design and evaluation of infrastructure scenarios shared with motor vehicles.

A predominance of studies classified in Subjective criteria was also observed and most of the research identified aimed at studying the totally segregated type of infrastructure. The clusters involving spatial coverage characteristics of the studies, i.e., if they were urban or suburban, indicate a predominance of studies that cover the urban context, and few studies exclusively in the suburban area.

Combining environmental quality assessment of bicycle infrastructures with vertical acceleration measurements

This section proposed a low cost and practical method for inventory and assessment of cycling infrastructures that is based on smartphone sensors and a video camera. The approach was developed to be used immediately in real-world applications aiming to identify priority locations for maintaining and improving cycling networks. The following conclusions were drawn from a trial application of the method in a medium-sized Brazilian city:

- The proposed procedures can be effectively combined as an inventory in a single GIS database, in which physical characteristics, construction and maintenance activity periods, as well as general information are all stored together.
- As anticipated, vibration measurements indicate that comfort values may be strongly influenced by the type of pavement. Concrete pavements, which have a high proportion of frequencies below 20 Hz, consisted of the most comfortable surface. The interlocking concrete pavement, on the other hand, showed a wide spectrum of frequencies above 20 Hz. As a result, it was not comfortable for cyclists, even considering that the case studied involved a recently built infrastructure.

- The combined approach for cycling infrastructure assessment complements evaluations based only on BEQI. Introducing a physical measure to the assessment strategy can easily help identify priority points for intervention, with a broader perspective.

The proposed method is useful to evaluate and compare the conditions of different types of cycling infrastructures using the same data collection procedure. From a practical standpoint, this is a positive point. However, as the results are strongly dependent on bicycle features, data acquisition rates and attenuations of the accelerations produced by the smartphone, further research is needed to calibrate the measurement system. The bias resulting from the bicycle used, for example, could be eventually compensated by a dimensionless parameter that is independent of the type of vehicle and cyclist characteristics. Moreover, other aspects of the data collection procedure could be added or improved, for example video processing techniques combined with machine learning techniques could be implemented to automatically identify the different aspects considered when evaluating the cycle path.

Validation of a tool to characterize traffic stress of cycling routes with physiological measures

Based on the results of the present study, it is concluded that although LTS was created with the purpose of evaluating the level of traffic stress to which a cyclist is exposed to, these measurements do not seem to be reliable when applied to a medium-sized city in a Brazilian context. When comparing the data of this indirect measurement of stress with a direct measurement based on physiological parameters, it was observed that there is no correlation and little agreement between the parameters. It is also emphasized that even when incorporating information on the flow of vehicles to the LTS, it was not significantly related to stress from the perspective of the cyclist.

Thus, using LTS as a stress level predictor should be treated with caution, because although it potentially represents the conditions of the routes for bicycle use, it does not reflect the level of real stress to which the subjects are submitted.

The Influence of Noise, Vibration, Cycle Paths and Period of Day on Stress Experienced by Cyclists

A method to evaluate stress experienced by cyclists using objective measurements of physiological parameters, such as skin conductance and temperature, was proposed in this study. The main objective was to investigate the relationships between stress and noise, vibration, presence or absence of infrastructure and the period of the day. This method was validated in a medium-sized Brazilian city with only a few segments of cycling infrastructure.

Regarding the proposed methodology, this study presents contributions for planners and bicycle transport operations adopting a new approach. Unlike other approaches in which stress is inferred from the extrinsic characteristics of the cyclist (such as track width and general characteristics of the infrastructure), this new approach focuses on the perspective of monitoring parameters intrinsic to the user, such as emotions. From this perspective, stress level indicators are direct measurements of physiological responses in cyclists along cycle paths. This approach takes advantage of technological resources to extract user information through sensors and allows this information to be used in an integrated way to improve the cycling infrastructure.

Regarding the analysis of the model outcomes, the only possible conclusion was related to the period of the day. The results of the models suggest that there may be differences in stress levels between the morning peak hour and the afternoon peak hour. According to these results, the odds of experiencing stress increased by 24.3% in the afternoon peak compared to the morning peak.

Future Research

Future research could examine subjectively and objectively the impact of other types of infrastructure that are still not well addressed in the literature, such as infrastructure shared with vehicles and shared with pedestrians. Consolidated methods in other countries, such as HCM, DBLOS and BEQI in the United States, need to be adapted to Brazilian cycling infrastructure characteristics, because as was observed, the major focus in these surveys is on the segregated infrastructure, which is not common in Brazil.

Further research must be carried out to take into account the general path conditions experienced by cyclists. In addition to the particular characteristics (of the vehicle and the infrastructure) that result in vibration, the cyclists' comfort is also closely related to external elements of the environment, such as lighting and greenery. These elements are seldom explicitly considered in management systems for car infrastructures, essentially because in this case, users are in a protected environment (i.e. the vehicle itself).

Future research can focus on evaluating the various factors that can cause stress. Future developments may be geared to collecting direct and continuous information from sensors to assess the impact of the surrounding environment and its relation to physiological changes and emotions.

The findings of the study, however, were limited by the small sample. In addition to a greater number of people, more days would provide better statistical support and give more power of generalization to the conclusions. Further studies using the methodology presented in this paper can include larger samples and subjects with different characteristics, such as gender, age and other individual characteristics, in addition to various infrastructure types and conditions. In addition, external variables, such as weather (e.g., heat waves, rain, wind) and environmental conditions (e.g., air pollution) should be included.

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