Data-Driven Analysis of Bicycle Lane Safety in Mexican Cities: Towards a Real-Time Route Recommendation System for Cyclists

Carlos Alberto Domínguez-Báez[1,2][a], Ricardo Mendoza-González[1][b]
and Huizilopoztli Luna-García[2][c]
[1]*Tecnológico Nacional de México / IT Aguascalientes, Av. Adolfo López Mateos, 1801 Ote., Aguascalientes, Mexico*
[2]*Universidad Autónoma de Zacatecas, Ramón López Velarde 801, Zacatecas, Mexico*

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Abstract: This study initiated a project to identify urban cycling routes with a focus on cyclist safety in Mexican cities. A Data-Driven Analysis approach was implemented to map the riskiest and safest cycling routes by analysing traffic accident data from national, state, and local datasets. The accident hotspots were visually integrated into the urban map of Guadalajara city (Jalisco, Mexico), to identify high-risk zones for cyclists. The integration of diverse data sources and geospatial analysis allowed for an accurate characterization of accident patterns, providing a clear identification of critical areas. Key results from this initial stage of the project included an accurate risk-zones identification, a replicable methodology for data integration, and a first approach to developing algorithms for cyclist accident analysis. These preliminary findings hold promise for enhancing urban cycling safety and supporting urban eco-mobility strategies in Mexican cities. Additionally, the results served as a foundation for future exploration of machine learning techniques to refine data processing and develop a real-time safe bicycle lane recommender prototype aimed at guiding cyclists toward safer alternatives.

1 INTRODUCTION

Effective transportation system planning must address not only the mobility needs of individuals but also ensure safety and sustainability, promoting eco-friendly strategies. According to the World Commission on Environment and Development, sustainable development involves meeting the needs of the present without compromising the ability of future generations to meet their own needs. In this context, transportation systems play a crucial role in sustainable development by facilitating access to economic and social opportunities, which is essential for balanced growth across economic, social, and environmental spheres (Visser, 2017).

One of the major challenges in creating sustainable transportation networks is overcoming natural barriers and reducing environmental impact (Mahfouz, et al., 2023). Transportation infrastructure must evolve to ensure sustainable mobility, not just through the construction of adequate road networks, but also by integrating solutions that minimize environmental harm (Bahmankhah & Coelho, 2017). Urban transport sustainability is closely linked to the implementation of innovative systems that foster public trust and promote less polluting transport modes, such as cycling (Bahmankhah & Coelho, 2017; Černá, et al., 2014).

Cycling has emerged as a prominent option within urban eco-mobility strategies (Ogryzek, 2020). Although in many developing countries, bicycles are primarily used for recreational purposes, their potential as a daily transportation mode is significant (Heesch & Sahlqvist, 2013). Promoting cycling can drastically reduce CO2 emissions, alleviate traffic congestion, and improve air quality (Nasir, 2024; Batool, et al. 2024). Bicycles, as an eco-friendly mode of transport, play a key role in reducing vehicle emissions, minimizing congestion, and lowering transportation costs, in addition to benefiting the

[a] https://orcid.org/0000-0001-8820-5518
[b] https://orcid.org/0000-0002-8934-8067
[c] https://orcid.org/0000-0001-5714-7482

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physical and mental health of users (Gulati, 2024). Numerous studies have shown that policies promoting cycling significantly improve urban quality of life. As a result, many governments worldwide are implementing initiatives to encourage its use (Kosmidis & Müller-Eie, 2024).

Despite the numerous benefits of cycling, its integration into cities must account for the safety of cyclists and pedestrians, which is compromised in cities where cycling infrastructure is inadequate or poorly located (Liu, et al., 2024). The development of safe and dedicated cycling infrastructure, such as exclusive bike lanes, is critical to encouraging cycling (Khademi, et al., 2024). While some studies suggest that increased infrastructure availability can boost cycling trips, it is also emphasized that simply improving infrastructure is not enough; these spaces must be safe, particularly for cyclists and pedestrians and other aspects need to be addressed too, such as perceptions of insecurity, and cultural barriers (Al-Ansari & Al-Khafaji, 2024; Khademi, et al., 2024). This necessitates planning that includes physical separation from motorized traffic, speed reductions, and educational campaigns that promote road safety from an early age (Toski, et al., 2024).

Moreover, social attitudes and norms play a pivotal role in the adoption of sustainable transport modes (Kočková, et al., 2024). People living in bike-friendly environments, such as cities with adequate infrastructure, are more likely to use bicycles frequently than those in areas with fewer facilities (Khademi, et al., 2024; Useche, et al. 2024). Promoting favourable attitudes toward cycling through public policies and community support is essential to shifting transportation habits (Khademi, et al., 2024; Kočková, et al., 2024).

In several countries such as Mexico, strategies are being successfully implemented in favour of the use of bicycles as a means of transportation, such as: EcoBici in Mexico City (Peralta, 2016), and MiBici (https://www.mibici.net/), in Guadalajara; however, these alternatives tend to be visualized only in a few large cities. In most of the territory the needs of infrastructure, social awareness, and safety are still very evident (Lagunas-Millan, 2018). Investments in cycling infrastructure often fail to meet the needs of regular cyclists, who are mostly from low-income backgrounds (Lagunas-Millan, 2018; Peralta, 2016). Additionally, the lack of connectivity and poorly planned cycling routes expose cyclists to safety risks, as they are forced to share roads with motorized traffic without proper lanes (Lagunas-Millan, 2018; Peralta, 2016). This highlights the need for planning and forecasting tools that integrate built environment characteristics to prioritize infrastructure investments in high-need areas (Etminani-Ghasrodashti, 2018).

In this context, optimizing cycling routes and infrastructure is crucial to maximizing the benefits of cycling mobility (Komarica, et al. 2024). Advanced technologies such as Artificial Intelligence (AI) and Machine Learning (ML) enable the analysis of data on road safety, traffic flow, and emissions to design more efficient solutions (Komarica, et al. 2024; Younus, et al. 2025). AI can help identify optimal routes for cyclists by considering variables such as safety, travel time, emissions, and user preferences (Younus, et al. 2025). Integrating multi-objective optimization enables balancing traffic performance, safety, and emissions, thereby promoting the use of more sustainable transport modes like cycling (Avina-Bravo, et al. 2022; Koska et al. 2021).

In summary, advancing toward more eco-friendly and safe urban mobility requires integrating innovative technologies that optimize infrastructure and urban planning. These solutions must ensure the safety of cyclists and pedestrians, maximize transportation system efficiency, and reduce harmful emissions. Cycling, as an eco-friendly transport mode, plays a vital role in this process, and its effective integration into cities depends on policies and technologies that consider local characteristics and user needs.

To address this gap, we have initiated a project aimed at identifying urban cycling routes with an emphasis on cyclist safety in Mexican cities. From an initial literature review (see Section 2 for methodology details), we identified four key papers that are directly relevant to this project. A summary of these related works is provided below, ordered by relevance, to establish the context and highlight their contribution to the current research.

1. Seoudi et al. (2023) proposed a multi-criteria route planning strategy that optimizes the comfort, health, and safety of cyclists. Their system operates independently of specific bike lane information or traffic regulations, incorporating real-time weather data to improve the optimization of urban cycling routes.
2. Ferreira and Costa (2024) developed an innovative low-cost integrated system to improve cycling safety in urban environments. The system assesses proximity to emergency services and uses GPS coordinates to determine dynamic levels of risk for cyclists, generating real-time alerts when crossing high-risk areas.
3. The research of (Pindarwati & Wijayanto, 2019) describes an integrated web-based

system for personalized navigation that uses crime hotspot data from local agencies, social media, and user reports. The system offers rerouting options and a crime risks zones map, aiming to recommend safer routes to users.

4. Chavez et al. (2019) presented the Safe Commuting System (SCS), a solution designed to improve urban commuting safety through crowdsourced mobile device data. The system implements real-time user alerts for safety incidents and provides alternative routing options by categorizing data into three main domains: criminal activity, perceived danger, and suspicious behaviour.

These studies serve as a foundational basis for the proposed approach, offering valuable insights and guiding the development of insights to evolve the proposal. In this case, for this initial stage of the project, we mapped the riskiest and safest cycling routes by analysing traffic accident databases available at national, state, and city levels. This analysis was then visually represented by overlaying accident hotspots onto the urban map of Guadalajara, Jalisco, Mexico. The results from this stage are expected to serve as the foundation for developing a real-time urban cycling route recommender system. This system will guide cyclists by suggesting safer alternative routes and providing safety-related information, thus contributing to improved urban mobility and eco-friendly transportation solutions.

The rest of the article is organized as follows: Section 2 describes the methodology employed to carry out this stage of the project. Section 3 details the development of the first stage and presents the results obtained so far. Finally, Section 4 offers the conclusions of this stage and outlines potential directions for future work.

2 METHODOLOGY

A literature review was conducted using the Semantic Scholar tool (https://www.semanticscholar.org). This review led to the identification of a final pool of 22 relevant sources (out of an initial pool of 669), comprising 12 peer-reviewed research articles, eight conference papers from international forums, one international project report, and one article from a blog. The selected sources were filtered based on their relevance to the topic, considering citation counts and recency, with a focus on publications from 2017 to 2024.

The analysis of the selected literature provided insights into the general strategy for constructing the accident analysis database (BD) and highlighted various technological strategies that could be implemented in subsequent project phases.

As part of the methodology, an initial database was created using official traffic accident and vehicular flow records from the following sources:

1. National Institute of Statistics and Geography (INEGI, Mexico): The INEGI database serves as a primary source of national traffic accident data in Mexico. This dataset includes 43 distinct fields, including: a) Geospatial information: accident latitude and longitude; temporal data: year, month, day, hour, and minute; b) Accident characteristics: type, cause, and road conditions; c) Vehicle information: types (including bicycles) and numbers of vehicles involved; d) Victim data: number of injuries and fatalities by user type; e) Contextual information: type of roadway, urban/suburban conditions. The detailed structure of the database allowed for an in-depth analysis of the specific circumstances surrounding each incident, facilitating the identification of contributing factors and patterns.
2. Institute of Statistical and Geographical Information of Jalisco (IIEGJ, Mexico): This regional database complements the national dataset (BD1) with local context-specific details. It includes 20 fields, focusing on: a) Unique incident identifiers; b) Detailed temporal data; c) Precise location with cross-referenced street information; d) Detailed accident typology, such as cyclist involvement; e) Demographic characteristics of the involved individuals; f) Specific consequences of the incidents. This dataset is particularly valuable due to its regional focus, providing contextual information specific to the metropolitan area of Guadalajara (Jalisco, Mexico).
3. "*GDL en Bici Program*", Jalisco State Government (Mexico): This database is part of a comprehensive traffic infrastructure dataset, containing geospatial data critical to the existing network of bicycle lanes. It operates within a GeoJSON framework, including a) Precise geometry of bicycle lanes; b) Infrastructure attributes such as the type of segregation; c) Temporal information on construction and modifications; d) Design technical characteristics. The inclusion of this dataset was particularly important, given its

focus on bicycle infrastructure, offering vital information to assess areas with higher cyclist risk in urban settings.

These databases were selected because of their thoroughness and the fact that they are publicly accessible within Mexico. They provided detailed information on traffic accidents, with a particular emphasis on cyclist involvement, which is critical for evaluating the safety of cycling routes in urban environments using both dedicated bike lanes and conventional traffic lanes.

The analysis of these datasets allowed for the identification of patterns that will support the development of strategies aimed at improving urban mobility and reducing accident rates related to cycling. For this preliminary analysis, the data were processed using Python to detect patterns and suggest specific locations on the map interpreted as high-risk and low-risk accident zones. Finally, the results were visualized using Geographic Information System (GIS) software, including QGIS (freeware, https://www.qgis.org) and OpenStreetMap (freeware, https://www.openstreetmap.org).

3 DEVELOPMENT AND FIRST RESULTS

This section summarizes the development actions corresponding to the first stage of the project. These actions include the integration, processing, and visualization of the three selected databases; the processing and visualization of hot spots; and the risk weighting of cycling routes.

3.1 Integration, Processing, and Visualization of the Selected Databases

The integration process began with an extensive pre-processing stage, involving the following actions:

1. Format Normalization: it consisted in standardization of geographic coordinates to a unified system (EPSG:32613), the homogenization of temporal formats, and unification of accident and vehicle type nomenclatures
2. Data Cleaning: This step was characterized by the identification and correction of outliers, the validation of geographic coordinates, and the consistency checks for key fields.

Subsequently, the databases were unified through a Python-based algorithm, implementing the following steps: a) Identification of common fields; b) Standardization of field names; c) Duplicate identification based on spatial and temporal proximity.

Duplicate records were identified based on spatiotemporal criteria, considering records as duplicates if they met the following conditions: a) Spatial distance of less than 3 meters; b) Temporal difference of less than 1 hour; c) Matching accident type and involved vehicles.

The integration process resulted in a unified database containing 829 filtered bicycle accident records, with a temporal coverage from January 2015 to June 2024. The results of this initial data processing and representation are shown in Figure 1.

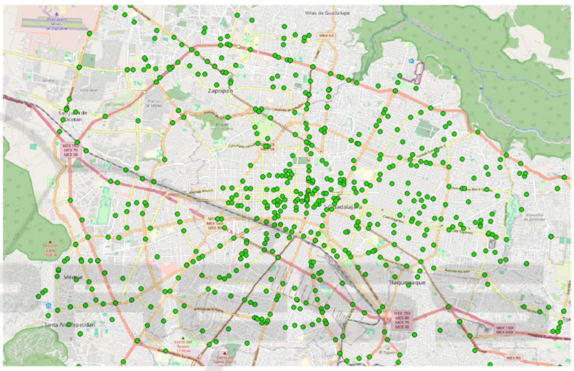

Figure 1: The 829 filtered bicycle accident records.

3.2 Processing and Visualization of Hot Spots Processing

The spatial analysis of hotspots was executed using QGIS 3.34, implementing a multiscale method for the generation of the heat density map. The configuration parameters were set according to specific technical criteria:

- Radius of influence: 20 meters (determined by standard safety braking distance).
- Maximum value: Automatic configuration based on data distribution.
- Chromatic gradient: Turbo spectrum.
- Rendering resolution: Medium.

The application of this analysis allowed the identification and categorization of critical zones, resulting in three high-risk and seven moderate-risk areas. Figure 2 presents the spatial visualization of these critical points resulting from the analysis.

3.3 Risk Weighting of Cycling Routes

A Python algorithm was developed to assign risk weights to cycling route segments, considering the following criteria:

- Spatial proximity to the cycling route segment.
- Temporal frequency of incidents.

The initial results of this processing are presented in Figure 3.

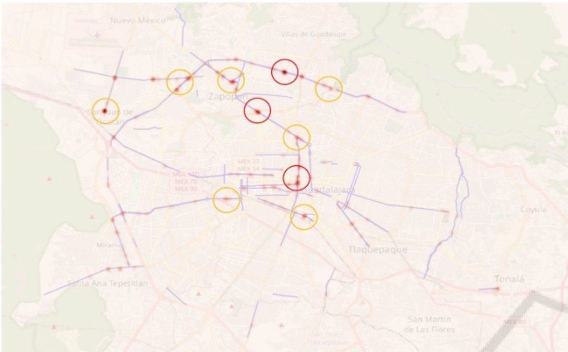

Figure 2: Map representation of the three high-risk areas and seven moderate-risk areas (Note: Hotspots were highlighted manually in this figure to facilitate their identification within the article).

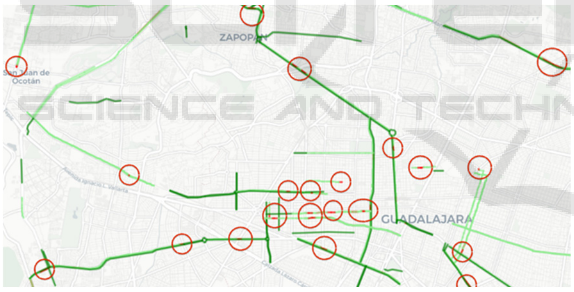

Figure 3: Map representation of the weighted risk bicycle routes (Note: Weighted lanes were highlighted manually in this figure to facilitate their identification within the article).

4 CONCLUSIONS AND FUTURE WORK

Obtained results demonstrate the effectiveness of the proposed methodology for identifying high-risk zones in bicycle lanes. The integration of multiple data sources allowed for a more precise characterization of accident patterns, while the geospatial analysis facilitated the objective identification of critical areas. This Data-Driven Analysis strategy implemented this strategy offers several advantages compared to related works, including a) More accuracy in identifying risk zones; b) A replicable method for database integration in different urban contexts; and c) A first approach to the development and implementation of specific algorithms for cyclist accident analysis was summarized.

Thus, we infer that these preliminary results could serve as a reliable foundation for the development of intelligent technological solutions that provide real-time safe route recommendations for cyclists. This could significantly improve urban cycling safety in Mexican cities and, in the medium term, contribute to secure urban eco-mobility strategies with real-world applicability across much of the national territory.

The next stages of the project involve exploring machine learning techniques for data processing to translate current analysis and results to real–time route recommendations for cyclists.

It is important to note that the code generated as part of the project is intended to be fully accessible; however, at this initial stage, it is not yet available as it is still undergoing testing and will be part of a broader solution. Eventually, much more details on the algorithms developed to assign risk weights to cycling route segments, and the full code will be made publicly available to promote collaboration and knowledge generation.

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