Towards intelligent dynamics of an active transport system for biking

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Executive summary: Due to the COVID-19 pandemic, Bogotá (Colombia) created 84 km of temporary bike paths to reduce SARS-COV-2 transmission in the public transport system. We developed a methodology that integrates complex systems modelling with data analytics to understand the impact of the temporary bike paths on the system's dynamics, complexity, mobility, health, and safety. The methodology and results could serve other cities that are implementing temporary bike paths and transforming their transport systems.

Contents

Tags: temporary bike paths, COVID-19 pandemic, sustainable transportation, urban, Colombia, South America, Global South, group model building, causal loop diagram, agent-based modelling

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Context

On 11 March 2020, the World Health Organization publicly declared the COVID-19 a pandemic. At the same time, the Colombian government declared the country in a state of health and sanitary emergency because of the COVID-19 pandemic. This declaration mobilised multiple government sectors to devise strategies to cope with this new global public health scenario.

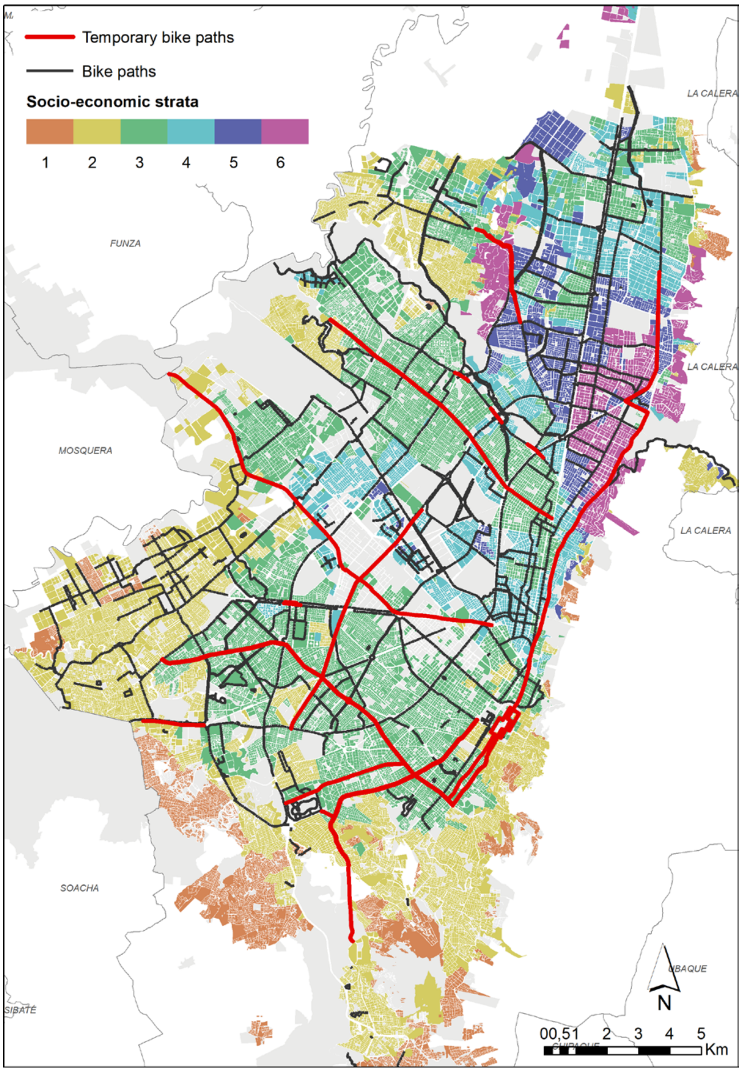
On 20 March 2020, the city of Bogotá (Colombia) entered a strict lockdown. The Mobility Secretariat, the public agency in charge of urban transport, looked for innovative ways to guarantee mobility throughout the city while reducing the congestion of the public transport system to meet the physical distancing recommendations to decrease SARS-CoV-2 transmission [1]. Just before the pandemic, 34% of the daily trips generated in Bogotá were made on public transport, being the most used mode of transport in the city [2]. Because of its high demand and characteristics, including sharing a closed environment, the public transport system was considered a public service with high contagion risk. For this reason, it was critical to promote alternative transport modes to ensure social distancing. Based on the established bike culture in the city, the bicycle was targeted as the primary solution.

At the beginning of the pandemic, the city already had over 550 km of dedicated bike paths, which with the Sunday *Ciclovía Recreativa,* were valuable assets to use and adapt to face the health and mobility challenges presented. The *Ciclovía Recreativa* is a multisectoral programme in which streets are closed off to motorised vehicles so that people have a safe and inclusive space for recreation and for being physically active. Historically, urban bicycle use in Bogotá has a long tradition that dates back to 1976, when the city's mayor decided to allocate main roads as temporary circuits for cyclists' leisure time on Sundays and holidays. Since then, this weekly event in which 128 km are closed to motorised vehicles and open for people, known as *Ciclovía Recreativa*, has been continuously held and has become a city's landmark and living proof of its vibrant bike culture. Through the years, the local administration has developed bike paths over the main roads of the city.

In the third week of March of 2020, the temporary bike paths were implemented, adding 22 km of cycling infrastructure to the already vast bike path system. The initiative was a coordinated action of different local authorities such as the Mobility Secretariat, the Recreation and Sports Institute of Bogotá (IDRD, for its acronym in Spanish), TransMilenio (Bogotá's Bus Rapid Transit system agency), and the National Police. The idea of the temporary bike paths was to connect the existing infrastructure, to mirror main transport corridors, and to provide access to peripheral neighbourhoods and surrounding municipalities where many workers live. By June 2020, the city counted with 84 km of temporary bike paths [3]. This policy made Bogotá one of the first cities in the world to conceive the bicycle as an inclusive transport solution during the COVID-19 pandemic. By June 2021, 21 km of the temporary bike paths were transformed into permanent bike paths, and 28 km of temporary bike paths are still in place. **Figure 1(a)** shows the map of Bogotá, divided by socioeconomic strata [4] with the permanent (in black) and temporary bike paths (in red) in 2020. In addition, **Figure 1(b)** shows a picture of a temporary bike path, where a portion of the road has been reserved for cyclists at the left margin of the street separated by orange movable road barriers. Finally, **Figure 1(c)** shows a picture of a temporary bike path transformed into a permanent bike path and is now part of the bicycle path network.

The temporary bike paths strategy, created by the Mobility Secretariat, was developed in three stages: first, bike trips assessment; second, technical planning; and third, implementation. In the assessment stage, the number of bike trips before the pandemic was estimated at 880,000 trips per day. The city projected that 285,000 trips could migrate from public transport to biking by the end of 2020, especially those involving mandatory trips. As part of the implementation stage, the Mobility Secretariat proposed this project to the Health Secretariat. As a result, Public Decree No.804 from 2021 declared the bicycle a priority for mobility and transport in the city, recognising its environmental and health benefits [5]. With this public support, health, and transport agencies started to promote, assess, and incentivise cycling as an active, safe, and individual transport mode during the COVID-19 pandemic. This initiative also changed the idea of cycling as a mere leisure activity, turning it into an active, safe, and healthy transport mode. Furthermore, it helped to strengthen safety and allow women to move and feel safer while cycling. This essential active transport mode naturally promotes social distancing and improves public health, physical activity, and air quality in the city.

Keeping temporary bike paths has been a challenge. As they use a whole lane of regular traffic, vehicle owners feel they have lost space and the road barriers used to segregate the bike paths have suffered damages during their use. Also, there have been reports of attacks against the IDRD (local government) staff that assist bike users. Most of this uncivil behaviour took place during the social protest of May 2021. As a result, some bike paths have been permanently closed, leaving gaps in the bike network that force cyclists to use the open roads. Regardless of these challenges, up to June 2021,



a) Map of Bogotá in 2020 with permanent and temporary bike paths

b) Temporary bike path

c) Temporary bike path that became permanent

Figure 1. (a) Map of Bogotá in 2020 with the geographic distribution of permanent (black lines) and temporary bike paths (red lines). The coloured areas are block units, and their colour denote the socioeconomic strata (1, being the lowest income; and 6, the highest income). Photographs of (b) a temporary bike path and (c) a temporary bike path that evolved into a permanent bike path. Photographs taken by Camila Fernández

28 km of temporary bike paths were in operation.

The benefits of temporary bike paths have inspired a positive outlook towards the future of cycling as an alternative transport mode. As a result, people are more conscious of the importance of the city's transformation towards new bicycle infrastructure. As a result, there is a broader space in the public agenda to improve the cycling infrastructure, to establish new education programmes for cyclists and underrepresented groups, and to connect the bicycle path network with quality bike paths. The case of Bogotá has also served as an example for implementing bike paths in other cities in the world during the COVID-19 pandemic. Globally, governments have incentivised cycling as a low-cost, healthy, sustainable, equitable, and space-saving mode of transport that reduces the risk of COVID-19 transmission [6]. By July 2020, at least 94 cities in 20 countries from the Americas, Europe, Asia, and Oceania had implemented or expanded bike paths to support social distancing and traffic safety [7]. Thus, the fast provision of new bike infrastructure during the COVID-19 pandemic in a city, such as Bogotá, from a middle-income country, is a suitable policy to assess its safety and health potential impacts.

1. Within this context, the aims of the case study are to:
2. describe the performance of Bogotá's bicycle transport system and the measures taken to manage the COVID-19 pandemic, integrating

complex-systems modelling and data analytics (henceforth referred as to systems analytics)

3. evaluate the potential impact of policy decisions on the bicycle system in terms of safety, health, efficiency, and flexibility

provide evidence of the potential impact that an emerging transport system could have on preventing SARS-CoV-2 transmission.

This report is organised as follows. Section 1 defines Bogotá's bicycle transport system. Section 2 describes the systems analytics methodology for the case study. Section 3 describes and analyses Bogotá's bicycle transport system as a complex system. Section 4 assesses the impact of the temporary bike paths in the performance of the system. Section 5 shares the learnings of the methodology and this case study. Finally, Section 6 looks into future work and lessons learned.

1. Bogotá's bicycle transport system

Bogotá's bicycle transport system satisfies mobility needs and facilitates access to city services using a sustainable mode of transport. Within this system, bicycle users interact with other road agents, such as pedestrians, motorised vehicles, and other active transport vehicles, on a mixed-use road network and the bicycle path network. The system incorporates rules for using the infrastructure; and regulators who enforce the correct use of the system and can modify the infrastructure and its rules. Through its use and regulation, stakeholders seek to satisfy the needs of bicycle users and improve the condition of it to generate more trips in this mode.

Bogotá's bicycle transport system includes multiple stakeholders with different roles, needs, aims, and incentives. We describe the system's missional activities and relations among stakeholders identifying the system *T*ransformations, *A*ctors, *S*uppliers, *C*onsumers, *O*wners, and *I*nterveners, known as the TASCOI tool [8]. **Figure 2** shows the system's four missional activities (transformations).

The first activity, *commuting*, is done by cyclists whose purpose is to mobilise throughout the city. In this activity, the system's performance depends directly on cyclists' decisions while using the infrastructure and their interaction with other actors. These decisions can be affected by the level of stress, the security and connectivity of the route, and the perception of collision risk. Government agencies collaborate with cyclists to enable commuting, creating regulations guiding the correct use of the infrastructure and developing safer and more connected infrastructure. The second activity, *infrastructure maintenance and development*, is conducted by government agencies and by bicycle collectives, which work together, but from different angles, to design and create better infrastructure. They both transform the existing cycling infrastructure for the benefit of cyclists. The third activity, *public policy development and enforcement*, is performed in coordination by several government agencies, which adjust and implement new policies based on the system's performance measurements trying to improve the actors' wellbeing. Specific policies could affect negatively motorised vehicle users, as some of these policies may encourage the use of sustainable modes of transport over the others. The fourth activity, *system monitoring*, is performed by government agencies in charge of collecting data, analysing, and providing evidence of the system behaviour. These agencies regularly collect and report statistics that assess

Missional activities	Commuting	Infrastructure maintenance and development	Public policy development and enforcement	System monitoring
Actors	Cyclists	Mobility Secretariat, Planning Secretariat, Urban Development Institute, Bicycle collectives	Mobility Secretariat, Planning Secretariat, Women Secretariat, Health Secretariat, Urban Development Institute	Mobility Secretariat, Health Secretariat, Women Secretariat, National Police
Suppliers or collaborators	Mobility Secretariat, Planning Secretariat, National Police		National Police, Recreation and Sports Institute, Bicycle collectives	
Beneficiaries (B) or Harmed actors (H)	Cyclists	B: Cyclists H: Motorised vehicles	B: Cyclists H: Motorised vehicles	Citizens
Owners and Interveners		Government	Government	

Figure 2. Stakeholders and main missional activities of Bogotá's bicycle transport system.

collision rates, the volume of cyclists, and perception of safety, among other outcomes.

For this case study, we analyse the bicycle transport system of Bogotá between 2019 and 2020. We consider 2019 as the *baseline* period for the evaluation, as the system was operating without disruption. The year 2020 is the *follow-up* period, when the COVID-19 pandemic appeared as the major disruptor, challenging the system's performance.

2. Systems analytics methodology

We propose a systems analytics methodology to understand the impact of the temporary bike paths on the system's dynamics and complexity and assess their impact on the system's performance. The methodology relies on integrating systems theory with data analytics. Systems theory allows us to describe the system's complexity and understand its dynamics. Data analysis allows us to compute system's metrics (that is, indicators) and predict system's changes via statistical and machine learning models. The synergy of systems theory with data analysis allows an agent-based model (ABM) [9] to simulate the system's behaviour over time. Our methodology allows the stakeholders to measure the users' reaction to the system's transformations and design actions (or controls) to prevent possible systemic failures.

Figure 3 presents the proposed systems analytics methodology. From the left, using the group model building (GMB) methodology, we define the complex system, its boundaries, its dynamic rules, and the system's functionality metrics by deriving a causal loop diagram (CLD) co-created with the stakeholders (Boxes 1 and 2). Box 3 shows an ABM [9] that simulates different scenarios for the system and estimate its KPIs. Based on the systemic approach (output from Boxes 1 and 2) and the assessment of the system's metrics estimated by the ABM (output from Box 3), Box 4 shows the step where stakeholders design and evaluate different scenarios regarding infrastructure changes. Then, in Box 5, the decision maker selects those policy interventions that best meet the stakeholders' interests, in terms of safety and efficiency of the system, and use the results of the evaluation to support the decisions regarding the policies implementation. As time passes by, the system adapts, and the system's actors react to those interventions. New data is generated based on the interaction with the intervened system. Box 6 shows the step where new data is collected to re-estimate the KPIs through the recalibration of the statistical and machine learning models following an observation period.

Boxes 7 through 10 show the data analysis components of our methodology, with their key inputs and outputs labelled in their incoming and outgoing arcs, respectively. Boxes 7 and 8 show the steps where we calculate the collision rates and the Level of Traffic Stress (LTS) classification at a granular scale (for example, street level). These two KPIs were proved significant to model the cyclists' behaviours and are proxies of the safety of our system. Box 9 shows the step in the methodology where the mobility patterns are inferred from the Origin–Destination (OD) matrix. Box 10 shows the third KPI of the system, namely, the physical activity assessment as a primary benefit from using the bicycle. This KPI is assessed through the estimation of the metabolic equivalents (METs) generated while using the bicycle and through the Health Economic Assessment Tool (HEAT) from the World Health Organization (WHO) [10], which estimates the impact of the physical activity on prevented mortality through an economic value assessment. Finally, the collision rates, the LTS, and the mobility patterns (outputs from

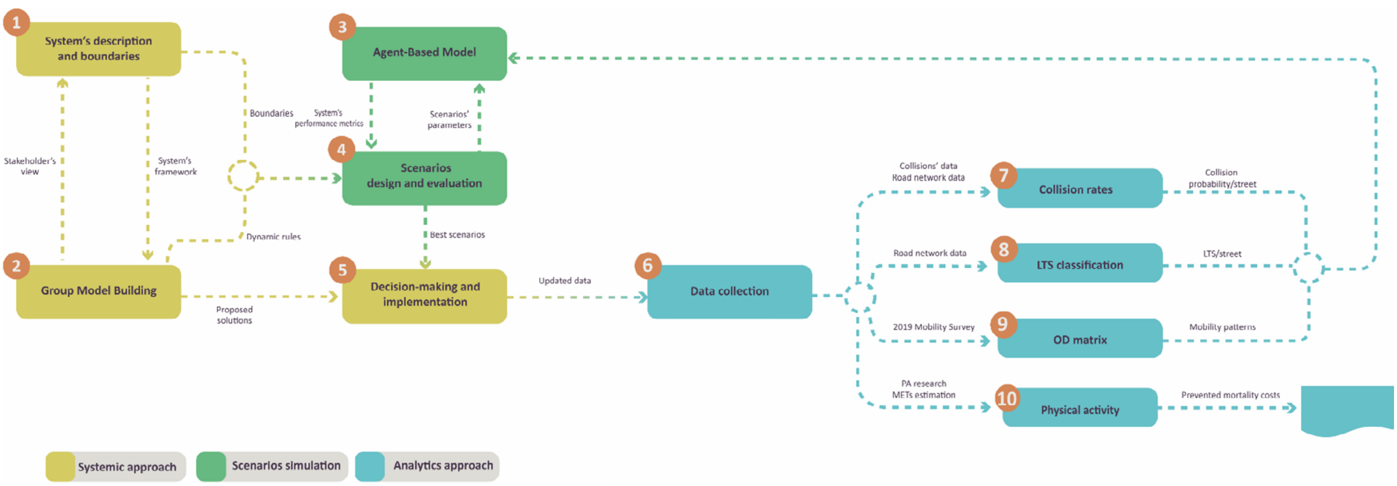


Figure 3. Systems analytics methodology (PA: physical activity; LTS: level of traffic stress; OD: Origin-Destination matrix).

Boxes 7, 8, 9) feed the ABM (inputs to Box 3).

The following sections describe the main components of the methodology.

2.1 Group model building

GMB is a methodology for developing community-based system dynamics (CBSD) workshops to identify the system variables and individual worldviews of the actors involved [2,3]. The primary outcome of the GMB is a causal loop diagram (CLD) that reflects the dynamics of the main variables of Bogotá's bicycle transport system. The GMB was developed through a workshop that included stakeholders of the system. The first part of the workshop comprised of an introductory session with a general presentation of the system and an overview of the complex systems approach. The workshop continued with a series of activities in working groups that generated a shared mental model of the system, modelled by a single shared CLD built by the working groups and further validated with semi-structured interviews with experts. Participants of the workshop and validators were selected according to their area of expertise to enrich the CLD with different perspectives.

For the case study, we conducted a half-day session in Zoom with Mural as the virtual blackboard, where participants developed the group activities. The whole session was recorded to help the compilation and validation of the CLD. The workshop held 17 participants representing the Health Secretariat, Planning Secretariat, Mobility Secretariat, Women's Secretariat, bicycle activists, and researchers. After the workshop, we conducted five interviews with bicycle users, motorised vehicles users, researchers, and bicycle activists to validate the CLD. The CLD is a critical input to describe the system's complexity and to define the ABM's boundaries.

2.2 Agent-based model

The ABM recreates the use of the road network and the collision dynamics of Bogotá's bicycle users. The model simulates the commute of bicycle users (agents) to estimate the collision rate per year, flow density per segment, and distribution of LTS per travelled metre. The model evaluates the impact of changes in the infrastructure on collision rates, road flow per year, and LTS at the population level.

The environment where the agents move is the city's road network for 2020 with and without the temporary bike paths, divided into road segments. Each road segment has three initial attributes: LTS classification per segment, segment length, and initial collision probability per segment. The methodology to determine the LTS level and initial collision probability per segment are described in Sections 2.4 and 2.5, respectively. The road segment length is estimated directly from the road network.

The agents of the model represent the bicycle users. Each agent has the following attributes: origin ZAT (acronym in Spanish for Transport Analysis Zone) and geographic location within the ZAT; destination ZAT and geographic location within the ZAT; and risk profile. The origin and destination zones are based on the OD matrix. The agents are classified into one of three risk profiles: risk-averse, risk-neutral, and risk-prone. The risk profile is assigned randomly, following the distribution of risk profiles assessed in Bogotá [12] and Portland (Oregon, USA) [13], where cyclists are classified by the potential risk they are willing to take regarding road segments' safety, depending on sociodemographic characteristics and travel distances.

In the ABM, each agent performs a round trip per day. The agent chooses between following the shortest path or a path that balances distance and risk. For the latter, each road segment has an aggregated weight that combines distance and risk. The selection of the route depends on the risk profile of each agent. For each trip, the model generates random probabilities that follow the collision probability for each segment to simulate a collision. If an agent suffers a collision, the agent becomes more prone to choose the path that gives higher weight to the (low) risk over distance. After each trip, the risk profile of the agent and the safety index of each segment, which reflects the updated collision probability, are updated depending on the collisions that occurred in the trip. The model assumes that all agents have complete information about the safety index of the road network. **Figure 4** shows the logic of the ABM in a flow diagram. At the end of each trip, the model records the number of collisions, LTS distribution per travelled metre, and the traversed segments. The results are summarised yearly.

We calibrated and validated the model based on annual collision records. After validating the model, we were able to estimate performance metrics for several scenarios. The ABM input parameters are travel rates, collision probability, and the LTS per road segment. For this case study, we modelled three scenarios: 1) baseline scenario in 2019, 2) follow-up scenario in 2020 with temporary bike paths, and 3) follow-up scenario in 2020 without temporary bike paths.

We coded the ABM in JavaScript using the GAMMA 1.8 platform [14] ecology, or economy, and more generally to study (spatially explicit. Appendix B describes the model's main components under the ODD + D protocol used to describe the ABM [15].

2.3 OD matrix and cycling paths

The OD matrixes describe the spatial distribution of daily trips. Although these matrixes are

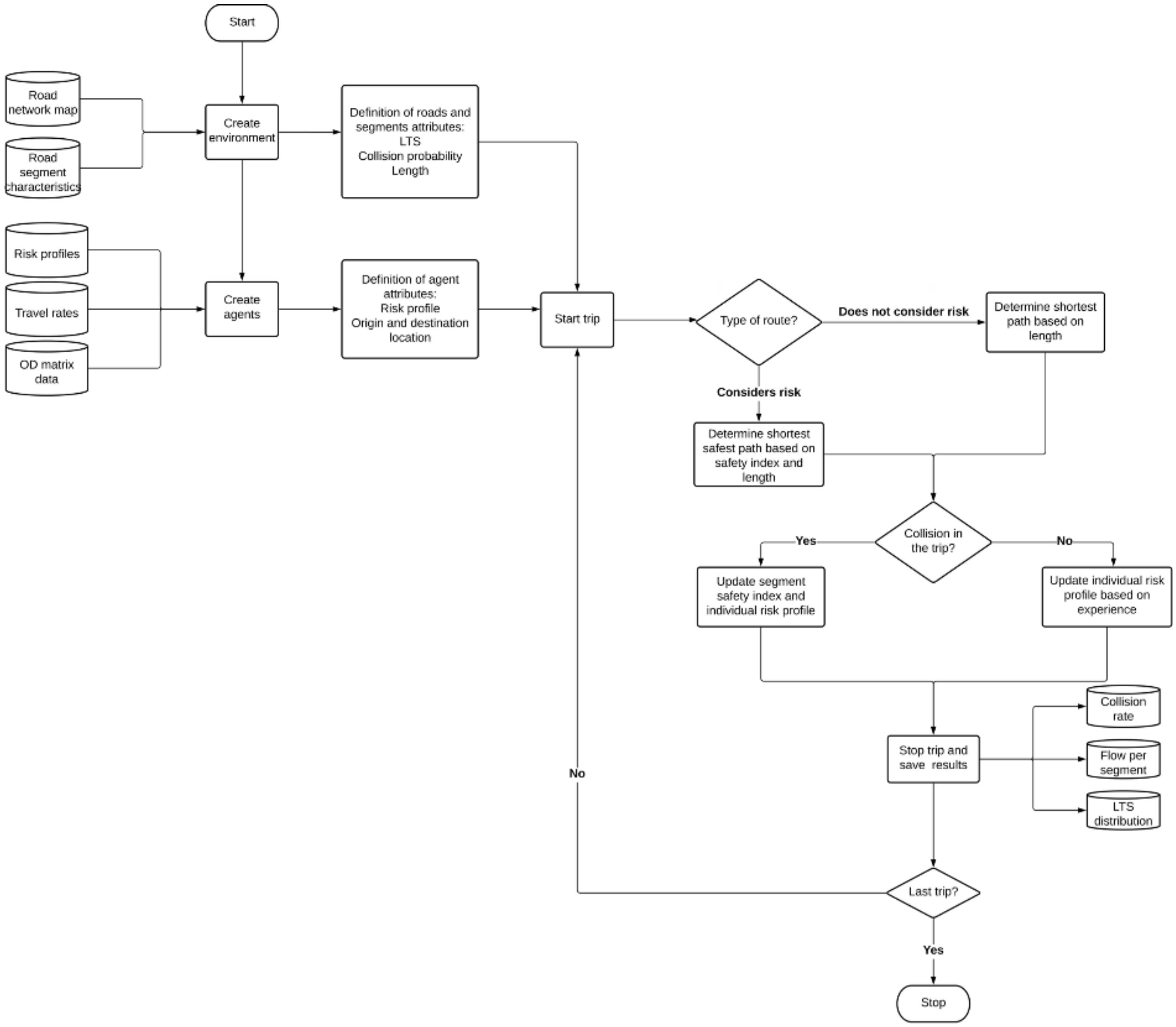


Figure 4. Flow diagram of the ABM

usually generated for motorised vehicles, an OD matrix for bicycles is essential for decision-makers to allocate resources effectively [16]. The OD estimation describes the zonal distribution of bicycle trips and the road network use at different (zone) levels. For our case study, the OD matrix is the source for estimating the most likely routes followed by cyclists, and these routes, in turn, are vital for estimating the mean LTS per trip and the trip flows for each segment.

Higuera et al. [17] estimated an OD matrix for bicycles in Bogotá using the 2015 Mobility Survey. This OD matrix considered only mandatory trips during weekdays within Bogotá. The aggregation level of this OD matrix was the ZAT. The number of trips estimation for each OD pair used the sample design representative weights to recreate the city's dynamics. Following the same methodology, we estimated an OD matrix for the pre-pandemic baseline scenario (2019) using the 2019 Mobility Survey [2]. We considered only trips where the bicycle was the primary transport mode, with origin and destination within Bogotá's limits, and where the trip purpose is other than recreation and sport. The OD matrix (per day) expands to yearly trips, assuming the same daily travel pattern.

For the follow-up scenarios with (and without) temporary bike paths, we used the relative change in trips per day estimated by the Mobility Secretariat from 2019 to 2020 to expand the 2019 OD matrix. This estimation of the OD matrix assumes that neither the travel patterns of the cyclists nor the percentage of trips per OD pair changes.

2.4 Level of traffic stress

When commuting, bicycle users are exposed to different external stressors that can motivate or demotivate the use of the bicycle. One of the stressors is the road they use, which is related to being more likely to suffer a road accident [18–20]. The LTS is a proxy of the potential stress experienced by cyclists due to road network attributes [21,22]. This indicator estimates how much perceived stress a road segment imposes on a cyclist and can be used to plan infrastructure interventions that improve cycling as a mode of active transport.

Huertas et al. [23] developed a two-step machine learning methodology (unsupervised clustering and multinomial logistic regression) to classify the road network segments of Bogotá according to the LTS using both physical and functional attributes. The methodology considers physical attributes of the road network such as roadway width, number of lanes, presence of public transport lines, and presence of cycling infrastructure, and functional attributes such as congestion, traffic flow, traffic density, and vehicle speed.

Since 2018, several bike paths different types have been implemented in Bogotá. Therefore, we extended the methodology to include the type of cycling infrastructure as a new input variable for this case study. According to the Colombian Transport Ministry [24], these types of cycling infrastructure are bike paths over the sidewalk with no segregation, bike paths over the sidewalk with physical segregation, bike paths over mixed-used roads with physical segregation, bus-bicycle paths, and unidirectional bike paths over the sidewalk. We calibrated the model using new road network data for 2019 for the pre-COVID baseline and the new classification of cycling infrastructure. After calibration, we classified the 2019 and 2020 road segments. For the follow-up scenario (with temporary bike paths), the temporary bike paths were categorised as bike paths over mixed-use roads with physical segregation. For the vehicle speed in the road network, the speed of 2018 was used as a proxy for 2019, whereas the speed of 2021 was used as a proxy for 2020. This is because of data access limitations to the Google API engine, yet the traffic behaviour consistently captures the pre-and follow-up COVID scenarios.

2.5 Collision analysis

The collision rate is one of the main safety estimators for cyclists. This rate relates the number of bicycle users who ride in a zone of interest per day, month, or year to the number of collisions (fatal and nonfatal) registered in that zone. Thus, collision rates allow us to assess road safety and how it changes by year.

Carvajal et al. [25] developed a methodology to compare the collision rates in Bogotá per month. The methodology considers collision rates standardised by: 1) the total cyclists' population; and 2) the daily vehicle kilometres travelled (VKmT) per ZAT. The VKmT is estimated with the OD matrix.

We estimated the collision rates for cyclists for Bogotá per million cyclists and per ZAT per 100 million VKmT using the collisions records for 2019 and 2020 and the 2019 Mobility Survey. We only considered collisions that involved a cyclist as an actor. The number of collisions per year was taken from the reported collisions in the SIMUR (acronym in Spanish for the Integrated Information System of Urban and Regional Mobility), the official mobility database of the city fed with police records.

We used a collision predictive model (CPM) based on a negative binomial regression model to estimate the probability of collision per segment for the ABM. This model reflects the relation between segment characteristics and collisions and predicts a collision rate per segment [26]. For the CPM, the independent variables are the number of road lanes, land use, type of bicycle infrastructure, vehicle congestion, vehicle speed, vehicle flow, and segment width. The dependent variable is the number of collisions per year for each segment. We estimated the probability of collision per segment, dividing the number of collisions per segment by the flow per segment or the mean flow per ZAT segment.

We conducted these analyses using R [27] and its packages tidyverse [28] and sf [29]. We used QGIS for spatial data visualisation [30].

2.6 Physical activity analysis

Physical activity while commuting has potential significant effects on the health of commuters, as it promotes physical activity during the week. In addition, physical activity contributes to preventing and treating noncommunicable diseases such as cardiovascular diseases, cancer, hypertension, and diabetes [31] and reduces symptoms of depression and anxiety [32]. For adults, WHO recommends 150 minutes of moderate or 75 minutes of vigorous physical activity, which translates into 500 Metabolic Equivalents (MET) per week for being physically active [33]. The intensity of physical activity is measured in METs. A MET represents the oxygen spent per minute performing an activity, increasing with vigorous activities and decreasing with sedentary activities.

We estimated the physical activity contribution through cycling and the health and economic value of the bicycle transport system in terms of preventable mortality. First, to estimate the contribution in METs for bicycle users in Bogotá, we estimated the average travel time per trip with the 2019 Mobility Survey and multiplied it by the METs per minute from the *Compendium of Physical Activities* (CPA) of commuting bike trips. The CPA compiles MET values for different activities that have published evidence, developed by Arizona State University and the National Cancer Institute [34]. We assumed that the average travel time per trip was the same in 2019 and 2020, as there is no updated information for 2020. We estimated METs at trip, person, and day level.

Second, the impact of the physical activity performed while cycling can be measured in terms of the economic value of mortality rate improvement through the Health Economic Assessment Tool (HEAT) [35]. HEAT is a tool developed by the WHO designed to conduct economic assessments of the health impacts of cycling [35]. The HEAT tool serves to estimate the value of reduced mortality that results from regular cycling. This tool is based on the best available evidence and transparent assumptions, making it easy to use, with minimal data input requirements, adaptable to local contexts, and scientifically robust [10]. The HEAT tool is designated to be used for professionals in different fields of knowledge, making it an integral and interdisciplinary tool for health and economic analysis.

We used the HEAT tool for assessing the health and economic value of reduced mortality resulting from regular cycling after the temporary bike paths were implemented during the pandemic in 2020 in Bogotá compared to the pre-pandemic cycling patterns in 2019. As HEAT defines, the measurement can be performed only for the population between 20 and 64 years old. After estimating the input parameters for 2019 and 2020, the tool calculates the health and economic value of the bicycle transport system in terms of preventable mortality. The parameters used are described in Appendix C.

3. Analysis of the complexity of Bogotá's bicycle transport system

To better understand the cause-effect relations between the variables that affect Bogotá's bicycle transport system, we created a CLD, integrating different stakeholders' perspectives that emerged from the GMB workshop. **Figure 5** shows the CLD that represents the system dynamics with 24 feedback loops (20 reinforcement loops; and four balance loops) grouped into six domains. The first domain, *civic culture,* involves personal behaviours, civic culture programmes, and norm appropriation that reinforce safe environments for cyclists. The second domain corresponds to *cycling motivation*. The internal motivators are supported through cycling groups accompaniment, whereas the external motivators are affected by the infrastructure, substitute transport modes, and civic culture. The third domain corresponds to *substitute transport modes*. In this domain, the bicycle as the primary transport mode is impacted by the offer of substitute transport modes, which is reinforced by their quality and cost, compared to using a bicycle. The fourth domain corresponds to the *quality of life*, reinforcing cycling as a physical and mental health promoter. The fifth domain corresponds to *infrastructure for bicycle use*, in which road maintenance is crucial for increasing the use of the bicycle as a transport mode. Finally, the sixth domain corresponds to *citizen participation*. In this domain, women's cycling activism impels the visibility of cyclists, which leads to public policies for improving the mixed-use road network and bike paths, and political power to react towards a pandemic with tactical urban health.

Two of the most relevant feedback loops are reinforcement loops three and twelve. Reinforcement loop three shows that the rise in bicycle use leads to a better design, increased cycling infrastructure, and improved connectivity. With these improvements, cycling travel time is reduced, motivating more cycling trips. This motivation leads to a rise in bicycle ownership, increasing bicycle use. The reinforcement loop twelve shows that the increase in bicycle use recognises women in public spaces, thus promoting changes in cycling behaviours. These changes improve civic culture, create safe environments for cyclists, and improve safety perception. A better safety perception increases bicycle use. Appendix B shows the description of the 24 feedback loops.

Sheard et al. [36] suggest that the complexity of a system is created by the interaction of actors, organisations, and their environment, resulting from the system's diversity and interactivity. As shown in the CLD, the heterogeneity of the actors, the intricate relation between the cyclists' behaviour and the benefits of the system, and the multiple stakeholders that interact with the environment to improve the system without affecting other systems make Bogotá's bicycle transport system a complex system. Understanding the complexity of a system is vital for developing improvement actions, which will help the system's evolution in the short, medium, and long term.

Figure 6 describes the bicycle transport system in Bogotá as a complex system, following the University of York's framework [37]. Our system description is based on the system identity and dynamics described by the TASCOI tool and the CLD built by the stakeholders. The transport system described in **Figure 6** unfolds the complexity in six major elements: causes of complexity, consequences of complexity, exacerbating factors, design-time controls, operation-time controls, and possible systemic failures.

The leading causes of complexity are the heterogeneity in the rules and the system's evolution that relies on the same actors, specifically on the interaction among bicycle users with the infrastructure and other

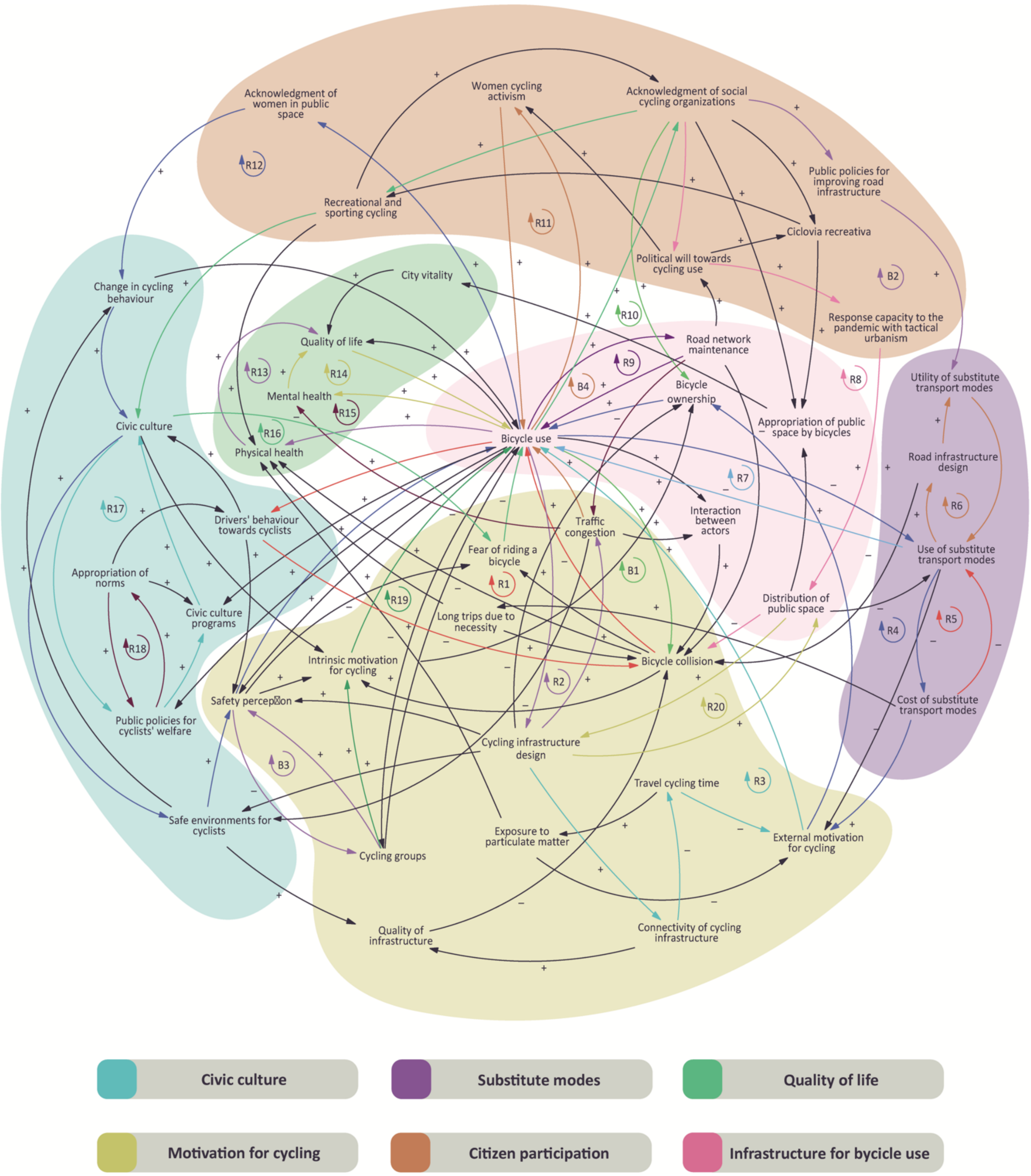


Figure 5. Causal loop diagram of Bogotá's bicycle transport system

road agents. These causes of complexity, exacerbated by some factors and alleviated by design-time controls, have consequences. The system adapts slowly, and competing objectives create an ever-increasing tension between motorised and alternative transport modes actors.

As shown on the CLD, six variable domains affect the system's behaviour. Identifying these domains was vital for describing the exacerbating factors, where civic culture and motivation for cycling appear consistently in each layer. In addition, women's empowerment, and programmes to promote bicycle use are critical design-time controls that affect the system's behaviour.

At the GMB, and with the help of the stakeholders, we identified five possible systemic failures that impact the safety of bicycle users. The failures vary from a shift toward nonactive transport

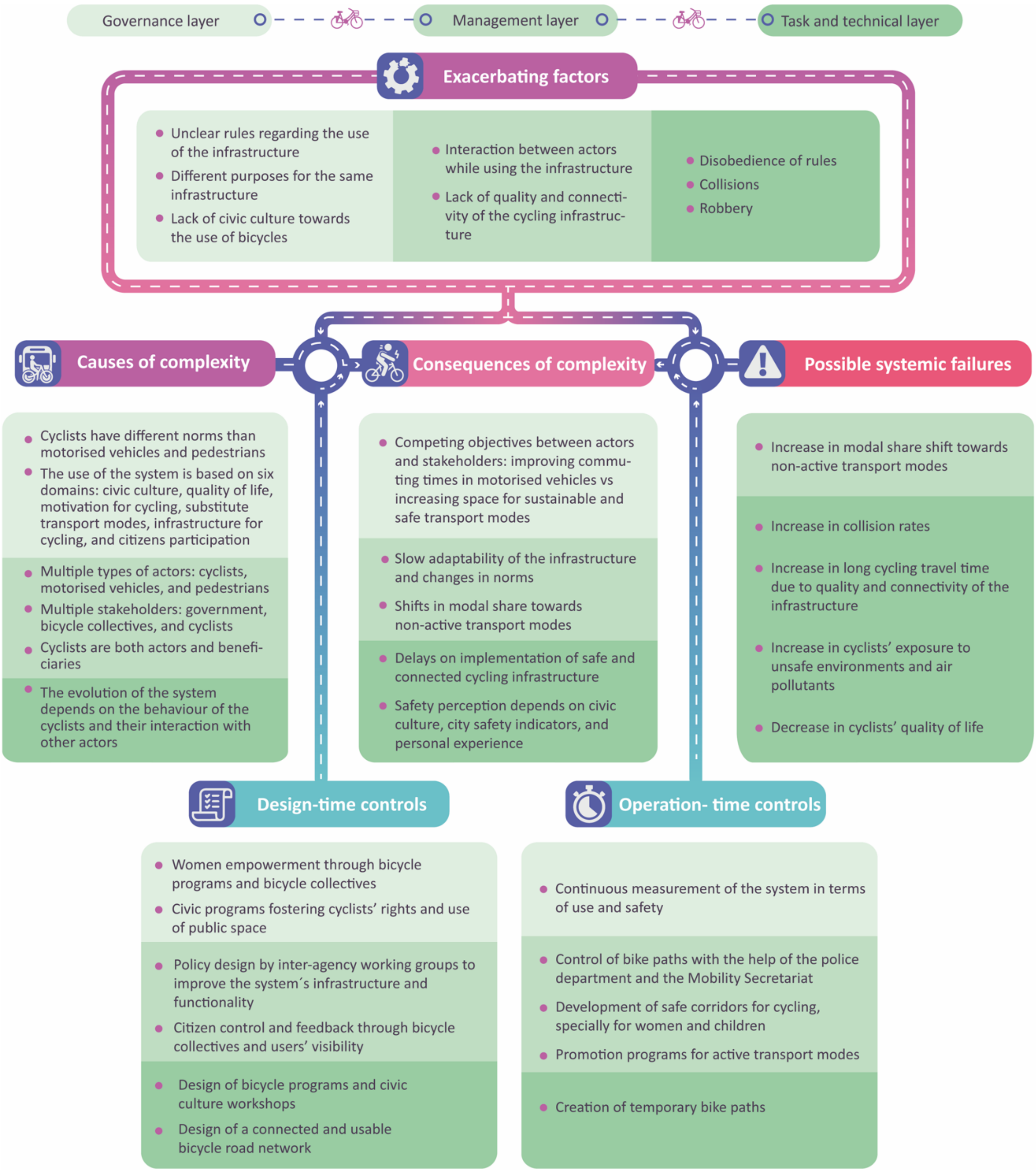


Figure 6. Complex system description via the Complex Systems Framework by University of York

modes to bicycle users' safety. Two of the most critical possible systemic failures are the increase in collision rates of bicycle users and a decrease in quality of life because of high levels of traffic stress, pollutants, and unsafe environments.

To reduce the likelihood of a systemic failure, we identified at least one operation-time control at every system's layer (that is, governance, management, and task and technical). These controls continuously improve the system's operation in terms of use, safety, and security; and explicitly involve new underrepresented groups, such as women and children. In particular, the creation of temporary bike paths is one of those controls designed and implemented during the COVID-19 pandemic. In this case study, particularly in the ABM, we evaluate the impact of the temporary bike paths, as operation-time controls, on the possible systemic failures related to a rise in collision rates and stress levels.

4. Analysis of the impact of the temporary bike paths on the performance of the system

4.1 Scenarios

After describing the complexity of Bogotá's bicycle transport system, we implemented the ABM to analyse the impact of the bike paths on the system's performance. Our analysis considered three scenarios: 1) baseline scenario in 2019 (henceforth called *scenario 1*), follow-up scenario in 2020 with temporary bike paths (henceforth called *scenario 2*), and 3) hypothetical scenario in 2020 without temporary bike paths (henceforth called *scenario 3*). Having a baseline, a follow-up, and a hypothetical scenario sheds light on determining whether the implementation of temporary bike paths helped the city avoid a systemic failure.

For scenario 1 (baseline), we used the 2019 Mobility Survey information to assess the daily trip rates and the number of bicycle users. For scenarios 2 (follow-up) and 3 (hypothetical), as there is no Mobility Survey or specific data describing changes in travel patterns, we considered the relative change (in %) in the number of bicycle trips from 2019 to 2020 as the only behavioural change. According to data of the Mobility Secretariat, from 2019 to 2020, the number of trips per day was reduced by 26% (880,000 in 2019 [2] vs 650,000 by the end of 2020 [38]). This reduction affects the estimated OD matrix for 2020.

A comparison of the performance of these three scenarios is presented in the following sections in terms of LTS distribution per travelled metre, collision rate, use of bicycle infrastructure, and physical activity.

4.2 Level of traffic stress

As for the LTS, our first KPI of the system, we updated the LTS classification model, adding the type of bicycle infrastructure as a new variable. **Table 1** contains the relevant characteristics of the road segments for the new classification. We categorised these road characteristics by their mean, classifying these values as low, average, and high (except for road width, which is classified as narrow, average, and wide).

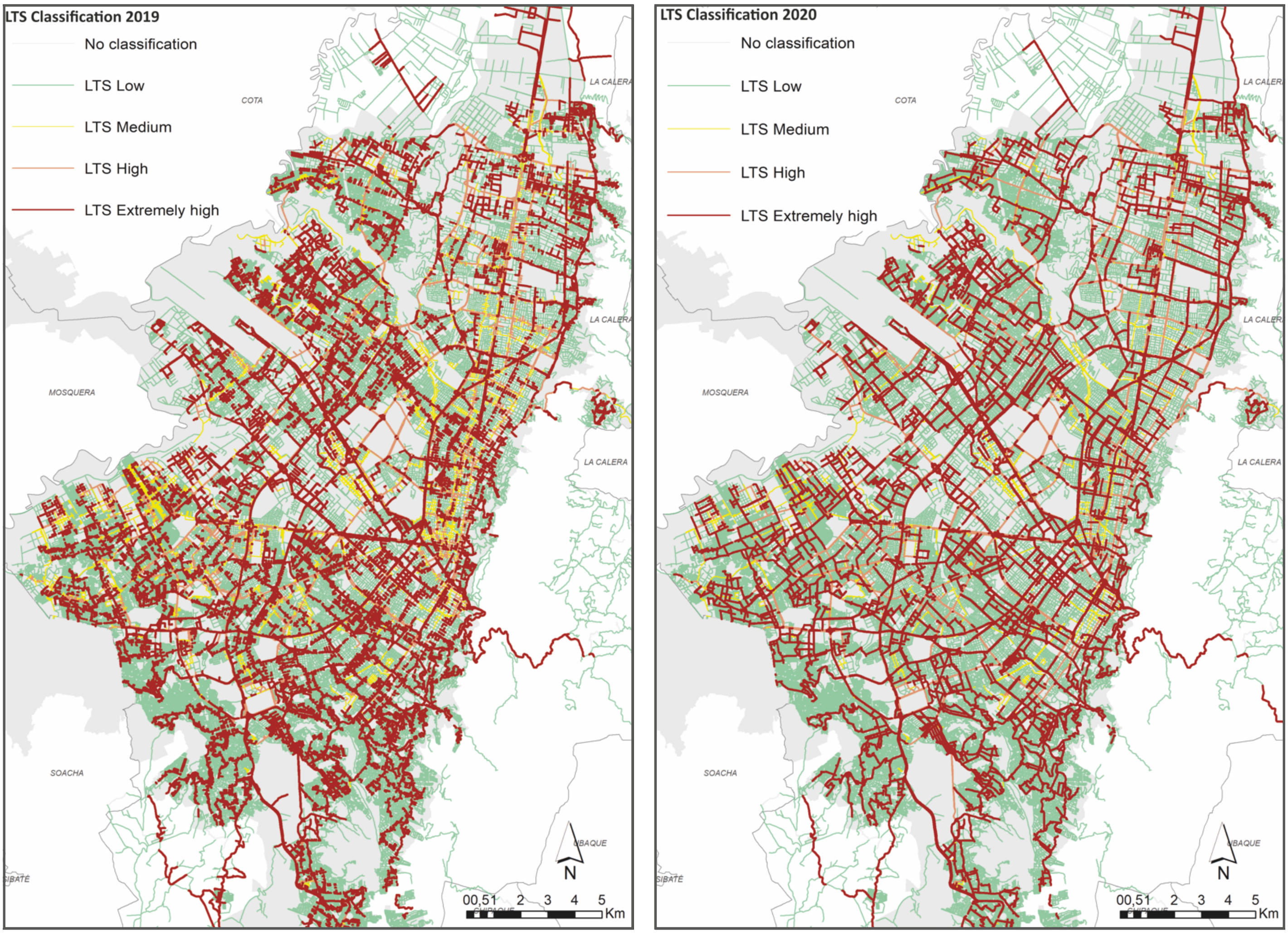
With this new classification model, our results are consistent with the findings of Huertas et al. [23], as there are still four levels for traffic stress, classifying road segments by LTS from *low* to *extremely high*. Notably, the inclusion of the type of bicycle infrastructure and the new bike paths throughout the city transformed the LTS medium category. In our new classification, road segments with bicycle infrastructure, but no public transport lines (heavy traffic) are naturally reclassified from LTS high to LTS medium.

We trained the multinomial logistic regression with the new classification of LTS to classify the road segments for 2019 (scenarios 1 and 3) and 2020 (scenario 2). **Figure 7** shows the classified segments for a) 2019 and b) 2020. Although the map shows changes for someone familiar with Bogotá, Table 2 summarises the distribution of road segments per LTS category for 2019 and 2020, making these changes more evident (**Table 2**).

More notably, for 2020, 73% of the road segments were classified as LTS low, increasing by 4% compared to the baseline of 2019. In addition, the reduction of more stressful road segments, classified as LTS 2, 3, and 4, shows a significant reduction of the overall LTS of the city.

Variable	LTS assignment			
	LTS Low	LTS Medium	LTS High	LTS Extremely high
Road width (m)	Narrow	Average	Wide	Average
Number of lanes	Low	Average	High	Average
Vehicles speed (km/h)	Low	Low	High	High
Traffic density (cars/h)	Low	Low	High	High
Traffic flow (cars/km)	Low	Low	High	High
Congestion	Low	Low	High	High
Presence of cycling infrastructure (% of km with)	Low	High	High	Low
Presence of public transport lines (% of km with)	None	None	High	High

Table 1. LTS classification variables



a) 2019 (scenarios 1 and 3) b) 2020 (scenario 2)

Figure 7. Maps with road segments classified by LTS levels for (a) 2019 (scenarios 1 and 3) and (b) 2020 (scenario 2)

Level of LTS	Distribution of road segments (%)	
	2019	2020
LTS Low	69.20%	73.27%
LTS Medium	4.46%	2.37%
LTS High	6.78%	6.51%
LTS Extremely high	19.55%	17.85%

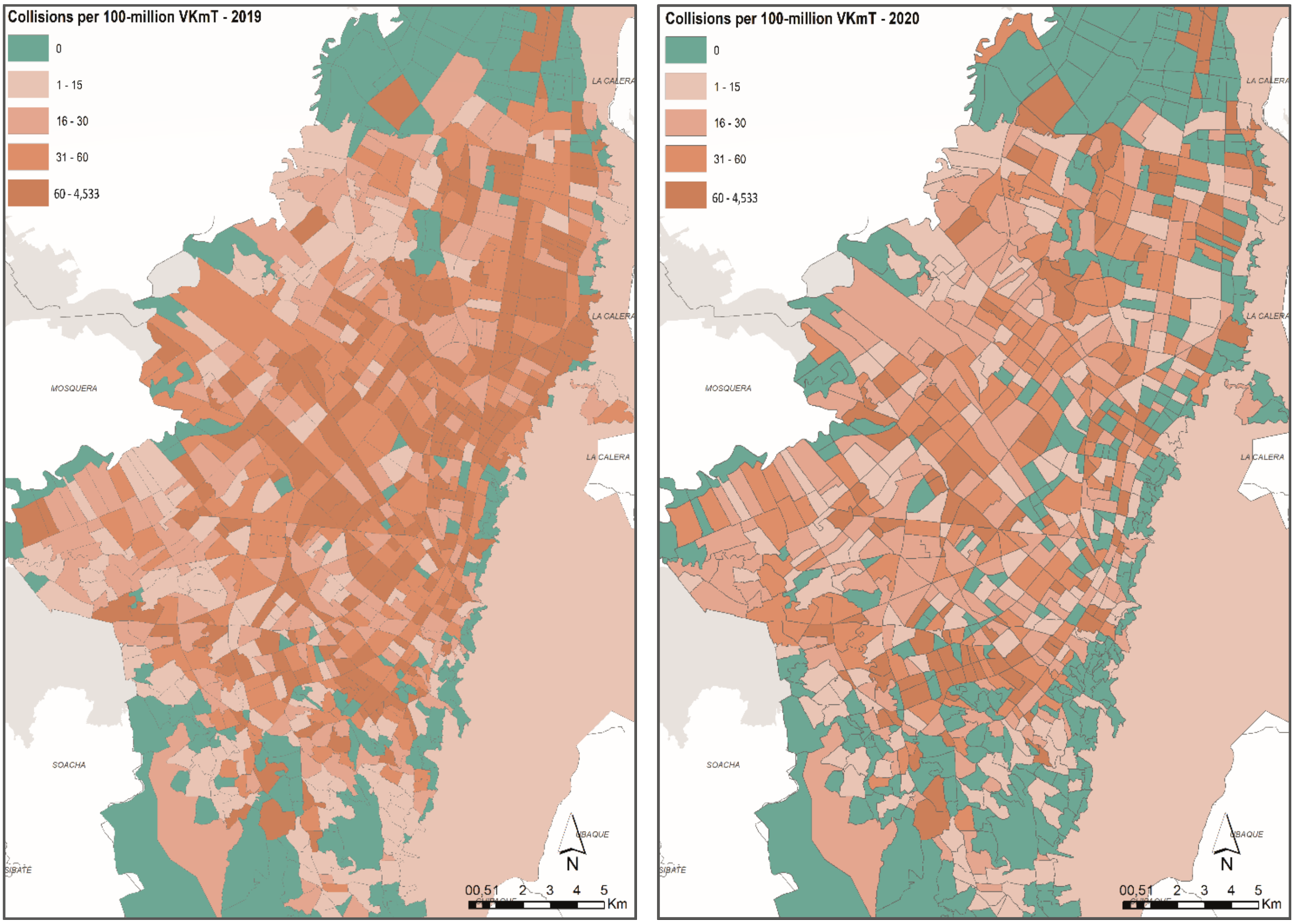
Table 2. Distribution of road segments classified by LTS per year

We partially attribute these changes to the temporary bike paths, which took a lane of the road for bicycles and changed these segments' speed, congestion, density, and flow.

4.3 Collision analysis

As for our second KPI, we estimated collision rates by population density and by exposure (use of the road network). To enable comparisons with previous findings [25], we show monthly collision rates. The mean monthly collision rate for 2019 was 1.37 [95% CI 1.24; 1.52] per 1,000 cyclists, while the mean collision rate for 2020 was 0.97 [95% CI 0.83; 1.12]. These rates show a reduction of 29.73% ($p<0.001$) between 2019 and 2020.

In the same way, we estimated the mean monthly collision rate per ZAT, standardised per 100-million VKmT. In 2019, 20.99% of the ZATs showed zero collisions, whereas in 2020, this fraction increased to 34.54%. We also compared the collision rates per 100-million VKmT per ZAT in terms of their median. The median collision rate per ZAT for 2019 was 23.62 collisions per 100-million VKmT, while the median collision rate for 2020 was 13.46 collisions per 100-million VKmT. These rates show a reduction of 43% ($p<0.001$) between 2019 and 2020. **Figure 8** shows the monthly collision rate per 100-million VKmT for each ZAT in a) 2019 and b) 2020.



a) 2019 (scenarios 1 and 3)

b) 2020 (scenario 2)

Figure 8. Maps of mean monthly collision rates per 100 million VKmT per ZAT for (a) 2019 (scenarios 1 and 3) and (b) 2020 (scenario 2).

We further investigated the change in monthly collision rates of the ZATs where the temporary bike paths were implemented. For these ZATs, the mean monthly collision rate reduces from 64.69 [55.16; 74.23] to 38.94 [95% CI 32.66; 45.22], which shows that there was a significant reduction of 45% (p<0.001) in the collision rate per ZAT.

4.4 Agent-based model (ABM)

The ABM combines the two previously described KPIs to estimate the bicycle transport system's performance. This model requires data at the agent and road network levels. As for the agent data, we consider roundtrips; 267,119 (for 2019) and 197,668 (for 2020) agents per day; and a risk profile distribution of 19.92% (risk-averse agents), 41.12% (risk-neutral agents), and 38.96% (risk-prone agents), both for 2019 and 2020. As for the road network data, we used the road network and road segment length of 2020; the LTS road segment distribution shown in **Table 2** for 2019 and 2020; and the trip collision probability per segment.

We calibrated the ABM recreating the collisions of 2019 and 2020. For scenarios 1 and 3, we calibrated the model with the collisions of 2019. The calibrated model generates a mean of 4,211.94 [95% CI 3,080.96; 5,323.42] collisions, compared to 4,582 officially registered collisions in 2019. For scenario 2, we calibrated the model recreating the collisions of 2020. The calibrated model generates a mean of 1,989.47 [95% CI 1,455.26; 2,514.47] collisions, compared to 2,164 officially registered collisions in 2020.

Table 3 shows the results for each performance indicator KPI of the system for the three scenarios.

When analysing the number of collisions, scenario 3 (hypothetical, without temporary bike paths) estimates 56% more collisions than scenario 2 (follow-up, with temporary bike paths). This result shows that the operation-time control of implementing the temporary bike paths in the city made this complex system safer compared to the hypothetical

KPI		Scenario 1 (2019)	Scenario 2 (2020 with temporary bike paths)	Scenario 3 (2020 without temporary bike paths)
LTS per metre	LTS Low	55.94%	62.16%	55.94%
	LTS Medium	4.54%	1.76%	4.54%
	LTS High	13.16%	11.70%	13.16%
	LTS Extremely high	26.36%	24.38%	26.36%
Annual collisions		4,211.94 [3,080.96; 5,323.42]	1,989.47 [1,455.26; 2,514.47]	3,116.83 [2,270.91; 3,939.34]

Table 3. Results of ABM for each scenario. All results report the estimated value and the 95% confidence interval in squared keys.

scenario without temporary bike paths. Regarding LTS distribution per travelled metre, scenario 2 LTS low increased by 6.22%, while the other LTS were reduced by 2% on average, compared to scenarios 1 and 3. Furthermore, the use of the new bicycle infrastructure was estimated at 0.05%, looking at all road segments that presented flow in 2019 and at 0.06% in 2020. It is worth noting that temporary bike paths only account for 0.09% of the whole road network.

4.5 Physical activity

As an extra assessment, the third KPI measured for the system was physical activity. We measured physical activity in terms of METs generated while using the bicycle as a transport mode and its health and economic impact. This analysis shows the changes from scenario 1 (baseline, 2019) to scenario 2 (follow-up with temporary bike paths, 2020).

Table 4 shows the input parameters for estimating the METs while using the bicycle as a transport mode for 2019 and 2020.

The average METs per trip for 2019 and 2020 are 236.27 [95% CI 227.35; 245.18]. The average METs per person who bikes for transport per day are 506.54 [95% CI 488.37; 524.70]. As we assume that the only change from 2019 to 2020 is the total number of daily trips in Bogotá, the average METs generated per day in Bogotá for using the bicycle as a transport mode in 2019 are 126.46 million [95% CI 121.92 M; 130.99 M] while in 2020 are 93.58 million [95% CI 90.22 M; 96.94 M]. Therefore, the reduction in METs for 2020 depends only on the reduction of daily trips by bicycle. Even though there was a reduction, this reduction could have been up to 60% if the number of trips per day had remained constant [38], and 34% if the bicycle transport system had followed the same level of activity as the city [39].

Furthermore, we estimated the health and economic value of the bicycle transport system of Bogotá with the adult population of Bogotá aged 20-64 years old, which in 2018 was 4,358,003 inhabitants

Parameters	2019	2020
Mean travel time per trip (minutes)	34.81	34.81
Number of trips in bicycle per day per person	2	2
Number of trips in Bogotá per day	534,239	395,337
MET per minute	6.80	6.80

Table 4. Parameters for estimating the METs generated in 2019 and 2020

[40]. **Table 5** shows the parameters used for the analysis.

After estimating the necessary parameters, we used the HEAT tool for the estimation of the average amount of daily physical activity, prevented premature deaths per year value of statistical life (in millions of euros, as the HEAT tool is based on euros), and economic impact per year (in millions of euros) of the Bogotá's bicycle transport system. **Table 6** summarises the main results.

The analysis with the HEAT tool shows that from 2019 to 2020, the average amount of daily physical activity by cycling decreased by 0.8 minutes. In 2019 the prevented premature deaths were 199 deaths with an economic value of 224 million euros. In 2020 the prevented premature deaths were 145 deaths with an economic value of 164 million euros. The number of prevented deaths and the economic impact attributed to the amount of physical activity generated by cycling in 2020 is not negligible and continue to be significant. Despite there being no evidence of how the cycling situation would have been without the temporary bike paths, this measure implemented by the local government may have contributed to prevented deaths with a significant economic value.

4.6 Stakeholders' perspective

After analysing the system's response to the implementation

Results	2019	2020
Population (millions)	4.35	4.35
Average travel time per trip (minutes)	36.56	36.56
Number of bicycle users per day	205,081	151,759
Number of trips per person per day	2.14	2.14
Percentage of trips in bicycle per person	87%	87%

Table 5. Parameters for estimating the health and economic value of the system in 2019 and 2020

Results	2019	2020
Population average of physical activity by cycling (minutes/person/day)	3.01	2.20
Prevented premature deaths per year	199	145
Value of statistical life (millions of euros)	1.13	1.13
Economic impact per year (millions of euros)	224	164

Table 6. Summary of HEAT results

of the temporary bike paths and simulating the three scenarios, we held a meeting with the system's primary stakeholders to gather their feedback and final thoughts. At the meeting, staff from the Mobility Secretariat's Planning Division and the Bicycle Management Division discussed the study results and possible ways the study could support decision-making.

In terms of public policy, they reported that the case study results could be used to diagnose the system and the impact of the intervention. In addition, the study is essential for the Mobility Master Plan for Bogotá and Bogotá's Land Use Master Plan (known as POT, for its Spanish acronym), where more bike paths will be supported. Finally, the Bicycle Manager for Bogotá stated, "we consider fundamental to show this study to the local bicycle councils, to bring academy closer to policy decisions, and to improve Bogotá's bicycle transport system".

Regarding the complexity of the system, the stakeholders reported that the findings of the CLD, especially the social domains as fundamental pillars, reinforce the idea of developing social infrastructure in the city. Along this line, the Mobility Secretariat currently works with the community to create safer infrastructure supported by the improved bike culture. Also, an ongoing project of the Mobility Secretariat related to the case study, is the creation of the Mobility Observatory, from which they plan to share data dynamically and understandably with the citizens. Our project could certainly support this initiative to bring results closer to the public.

Finally, in terms of follow-up studies for the city, next steps could consider emissions of air pollutants, how bicycles impact these emissions, and estimating the risk for cyclists in terms of inhaled dose and respiratory diseases. Likewise, other studies could focus on expanding the methodology to prescribe actions related to the network's connectivity and flow segment analysis.

5. Key findings and learnings

5.1 Learnings from the case study

This case study describes and assesses the city's response towards the COVID-19 pandemic and its evidence of the importance of creating exclusive bike paths for cyclists in Bogotá. Temporary bike paths are part of a complex and multidimensional system. This system was associated with mitigation of the risk of a systemic failure, as it could reduce the collision rates, increase the metres of segments with low levels of traffic stress, and continue promoting physical activity, which in turn is associated with yearly prevented premature deaths. Local stakeholders recognised the importance of this study for supporting the Mobility Master Plan for Bogotá, the Land Use Master Plan (POT, for its acronym in Spanish) for 2022 and the Mobility Observatory. The evaluation of this system has required local and international support and a multidisciplinary group with partnerships among researchers, stakeholders, and the community. Further research is needed to investigate whether this change is persistent and whether similar results can be achieved in situations outside the context of the COVID-19 pandemic.

During the COVID-19 pandemic, governments worldwide have incentivised cycling by provisionally redistributing street space. By July of 2020, at least 94 cities in 20 countries from the Americas, Europe, Asia, and Oceania created or expanded bike paths. In Europe, about 2,000 km of temporary bike paths had been implemented with a significant increase in cycling. North American cities, such as New York, Boston, Seattle, and San Antonio, among others, also implemented temporary bike paths [44,45]. In Latin America, cities like Mexico City, Lima, Buenos Aires, and Medellín carried out similar strategies with the adoption of temporary bike paths during the pandemic. Moreover, in Asia, the city of Jakarta in Indonesia also implemented temporary bike paths. It is also important to note that in many of these cities globally, including Bogotá, the implementation of temporary bikeways has involved legal disputes [44] and ongoing discussions about the right to use the space [44,45]. In North America, much of the controversy has focused on how to access opportunities for safe active mobility. Furthermore, it is important to underscore that although collision rates have decreased in the US, United Kingdom, Germany, Spain, and Canada, motor vehicle fatality rates, injury accidents, and speeding violations have increased, and remained elevated even as traffic began returning to pre-pandemic conditions [46] [47]. Specifically, in Colombia the total death rate for cyclists also increased from 0.84 to 0.87 per 100.000 inhabitants in 2020 [47]. However, in the city of Bogotá our study shows that bicyclists collisions decreased during the COVID-19 pandemic and could have been higher without the implementation of the cycling system infrastructure.

In this context, cities that implemented temporary bike paths and are willing to increase the kilometres of permanent bike paths, could perform a similar study to compare their results with ours, as the proposed methodology is based on a local perspective. With political and community support, these results could serve to advocate for the implementation of safe biking infrastructure for promoting cycling, which is a healthy, sustainable, equitable, and space-saving mode of transport that reduces the risk of COVID-19 transmission.

Several components of our methodology and results could serve as an example to other cities in the world. First, the GMB workshop and the CLD showed the different dimensions of the system's dynamics, where infrastructure, civic culture, motivation for cycling, citizens' participation, substitute modes, and quality of life affect the system's performance. This transdisciplinary and broad perspective helped us describe the system's complexity broadly, considering the performance indicators and the stakeholders' perspectives.

We assessed three system scenarios regarding collision rates, LTS distribution per travelled metre, and physical activity. The results showed that the temporary bike paths mitigated the risk of a systemic failure, as it reduced the collision rates and increased the travelled kilometres on street segments categorised LTS low. For instance, the collision rate could have been 56% higher in 2020 without temporary bike paths. Furthermore, the reduction of only 26% of bicycle users, in comparison to the 40% reduction worldwide, reduced the economic impact per year of the system from 224 million euros to 164 million euros.

Although the system improved its performance in terms of safety, the temporary bike paths could affect public transport and other motorised vehicle systems, as these paths reduced the number of lanes for buses, cars, and motorcycles. The different perspectives of the users and stakeholders towards implementing new cycling infrastructure affect the system's complexity. The government needs to balance the different drivers of the road actors, which could be conflicting if not viewed as a whole system. As shown in the GMB, cyclists lobby for more space with safer and connected cycling infrastructure. In contrast, motorised vehicle users demand safer roads that will reduce travel time. These different perspectives show that the implementation of infrastructure transformations must be analysed with a multisectoral approach with a broader system in mind. Only with a more systemic view and an understanding of the interaction of the different transport systems it might be possible to avoid the risk of a major systemic failure of the whole transport system of the city.

The response of the city towards the imminent threat of a pandemic served as an excellent operation-time control. In addition to reducing the collision rates and the LTS, the temporary bike paths presented the bicycle users with a transitional yet flexible intervention of the city. However, for future interventions, such as transforming the temporary bike paths into permanent ones, other road network users such as buses, cars, and motorcycles should be involved in a more comprehensive cost-benefit analysis, as their systems may be affected.

As learnings for the local government, the system could benefit from interactive planning, as described by Ackoff [48], where future designs progressively close the reinforcement gap. For example, the interactive planning of Bogotá's bicycle transport system demands constant monitoring of safety, road network use, collision hotspots, and social variables affecting the system. Collecting data and regularly measuring the system will enhance the transformation capacity of the system, increasing the potential benefits.

5.2 Key findings of the systems analytics methodology

The proposed methodology, developed by a transdisciplinary team, brings together elements from systems theory and analytics to combine the actors' perspectives with quantitative system measurements. As described by Beckford [49], this methodology proposes a shift in the current use of system information towards an intelligent organisation, where decision-makers consider the interaction of the structure, processes, actors' behaviours, and systems performance information to transform the system sustainably. Four pillars support the system's analysis: the use of systems theory; the use of statistical and analytics models to measure the impact of the interventions on different system dimensions; the development of an ABM for assessing the system's performance and evaluating transformations; and the health economic assessment. The systems analytics methodology is an innovative methodology for evaluating systems that combines actors' knowledge with data collected from possible system interventions. It uses analytics (descriptive, predictive, and prescriptive) models to measure the system regarding specific performance indicators. The proposed methodology is the first step to a broader methodology where the proposed scenarios can be further explored through optimisation and cost-benefit analysis, among other tools.

First, a community-based workshop allowed us to build a better description of the system and its complexity. By interacting with the system's actors, it is possible to better understand the underlying dynamics and the variables that affect its performance. In the workshop, the stakeholders and leading actors of the system (cyclists, users of motorised vehicles, public agencies, academia) guided the discussion towards the main concerns of a systemic failure and the key performance indicators necessary to assess the system transformation.

Second, statistical and analytics models help understand, describe, analyse, and compare the system's performance between baseline and alternative scenarios. Using an OD matrix, we described how cyclists use the road network. Estimating the LTS for the whole road network contributes to describing the distribution of potential stress in the city. The LTS analysis is also helpful to understand how changes in the road segments affect the potential stress inflicted on cyclists. Finally, estimating the collision rates at different granularity levels showed us how these rates were affected in the pandemic and how they are spatially distributed on hotspots with higher collision rates. After describing the system's performance, we were able to calibrate predictive models that estimate each KPI. These models are fundamental for assessing changes in the road network and are used as the initial parameters that feed the ABM.

Third, the ABM complements the outputs of the predictive models, as it allows to involve agents' decisions that respond to the evolution of the system's dynamics. Furthermore, the ABM can be scaled to another level of granularity and linked to different performance indicators, allowing analysis at multiple levels. Although the ABM is a simplified model of the reality, the fact that the ABM can be used to assess different scenarios is helpful for decision-makers. It reflects the actors' perspective and measures the impact of each scenario on the system's evolution and performance metrics.

Finally, the economic impact that the bicycle transport system has in terms of the contribution to preventing premature deaths reflects its importance for the general population. This assessment also reflects how the general population is affected when the system is intervened, as the economic impact changes when the travel rate and travel patterns vary.

Although the methodology provides insights into a complex system's behaviour when intervened, the methodology has some limitations. First, the ABM assumes that every agent knows the information about collisions in the entire system. Although this assumption is strong for natural systems, the purpose of the methodology is to compare the behaviour of the system in simplified scenarios that have the same set of ground rules. However, to improve the model's accuracy, the ABM could incorporate a local network approach, where agents know the information of their close network and may affect the perception of safety of their surroundings. Also, cellular data could provide a proxy of the use of the network and unreported collisions. Second, for the road segment safety index, the ABM currently considers only collisions. Further analysis could involve human factors and LTS levels to create a compound safety index. Lastly, the ABM does not consider the impact of the infrastructure changes on the other actors' performance. This could be addressed on a broader study, where not only KPI for bicycles, but costs of travel time, delays, air pollution, and health are considered for more actors.

As for data, this case study has limitations. First, the case study considers only bicycle users who travel within Bogotá's limits and use bicycles for mandatory trips. This consideration leaves out bicycle users for sport and recreation and work services (for example, deliveries). Second, there is no information on bicycle flows in Bogotá's road network. Without this information, the ABM had to be calibrated only with collision rates, yet it still may reflect a different travel pattern to reality. For 2020, there is no information on changes in cyclists' travel patterns. Therefore, the case study assumes no change in patterns due to the presence of temporary bike paths, nor new shortest paths exist, as temporary bike paths are parallel to the existing road network. Third, the ABM assumes that the road network is bi-directional, as proposed by Rosas-Satizabal et al. [12]. Lastly, the collision rate analysis focuses solely on bicycle users and does not consider the city's modal share.

This methodology is innovative for assessing future changes in complex systems where actors regulate the system and evolve their behaviour. The methodology could be expanded to other cities, primarily where other temporary bike paths were implemented (or planned) to transform the bicycle infrastructure, while keeping a context-specific perspective. As the methodology brings together the stakeholders' perspectives, other complex systems, such as pedestrian and motorised transport systems, should be considered to assess the impacts in changes of the infrastructure. Furthermore, complex systems in need of transformation could adopt the methodology and adapt the type of simulation model to assess the potential impacts of changes on its dynamics and metrics. Even if the models change, the methodology is still valid as it gives the study a solid ground in terms of norms, safety, and behaviour necessary for assessing the impact of new interventions in a particular setting.

6. Looking into the future

6.1 Target audiences

The findings of this case study are directed to local and global policymakers, regulators, NGOs, and bicycle collectives related to transport systems in a broad sense. Local and global policymakers could find this case study helpful to understand the system's complexity and to include multiple factors that affect safety when transforming the infrastructure. This study could be used as a first step analysis for estimating the possible impacts that future interventions may cause in the collision rates and LTS of the system. On the other hand, the system's regulators can use the description of the system's complexity and the CLD to reinforce their vigilance over the system and select key variables to monitor and address with the local government.

The case study successfully shows how flexible the bicycle systems are and how temporary interventions can be helpful for global policymakers. Furthermore, this case study could help cities where the funding for active transport is low. Finally, it shows that regardless of the type of bicycle infrastructure (in this case, temporary bike paths), the delimitation of paths for the exclusive use of bicycles improves the safety of the users.

The case study shows the importance of approaching systems with a systems analytics perspective. This perspective integrates qualitative and quantitative analysis of the system and an ABM where data and the individual behaviour of the agents empower and complement the predictive power of the models.

6.2 Key messages for target audiences

The key message for local and global policymakers is that transport systems are complex systems that need to be designed flexibly and resiliently to respond promptly to emergency disruptors. The local government could benefit from these results to provide evidence of the behaviour of the bicycle system during the pandemic, which will help support plans for transport development in the city. In addition, the global policymakers could use the case study as a reference on how bike paths may contribute to increase the safety of bicycle users and how to assess the impact of changes in the sustainable transport infrastructure.

The key message for regulators is that transport systems need knowledge from all actors and decision-makers to mitigate the risk of potential systemic failures. Thus, the transformation of the systems should consider the multiple actors' perspectives and the interactions among them. When systems are flexible, and decisions include the actors' perspective, the transformations will improve the quality of the system and the safety of its users.

The key message for NGOs and bicycle collectives is that there should be a constant collaboration among them and the policymakers to constantly improve the system. Also, they should be the leading promoters of generating feedback data of the system, as they represent the users.

As the stakeholders from the Mobility Secretariat stated, the results could support the Mobility Master Plan and the Land Use Master Plan, especially, to provide evidence to some stakeholders who may not be supportive of the new permanent and temporary bike paths.

6.3 Actions for improving safety

To improve safety, the system should be constantly monitored and measured in terms of collision rates, number of users, and users' purposes, segment flows, collision hotspots, robbery, and safety perception. The monitoring could be performed by creating intersectoral alliances for developing passive data collection instruments (mobile apps, image-detection models) and robust surveys. Furthermore, the system's interventions should be based on the experience of the bicycle users, the behaviour of those users, and the interactions with other motorised and non-motorised vehicles. Furthermore, the government should implement transformations aiming to reduce congestion, increase healthy environments, improve the road network and connectivity, and improve sustainable active transport. Furthermore, bicycle users should work towards safer systems, civic culture, better implementation and knowledge of norms and regulations, and improvement of their quality of life. Lastly, the legislation should be transformed to promote sustainable transport system modes, including active transport modes when suitable and low-to-non-emission motorised vehicles.

6.4 The success of the system

The system's success can be measured in terms of number of users, number of women and children riding bicycles, collision rates, quality of life, physical activity promotion, and prevention of premature deaths. In this sense, success would be an improvement in multimodal transport in the city and an improvement in the quality and connectivity of the bicycle infrastructure that responds to the users' needs. With these improvements, long mandatory trips will reduce travel time, exposure to collisions, robbery, and air pollutants.

6.5 Measure the progress

The progress of the system could be measured by improving the efficiency in collecting and analysing performance data. The constant measurement of the system will create the potential for transforming the system into a smart city system, where the users help collect data, and the data is efficiently used for designing interventions that the same users will try and use. However, the improvement on data collection could be truncated by the citizens' perspective of the use of the data, which should be a primary concern. Furthermore, regular perception surveys and community-based workshops will improve the understanding of the system's dynamics, translating into better transformation scenarios and a more efficient system transformation.

6.6 Innovative tools for disseminating the Safer Complex Systems learnings

Educational tools, such as interactive dashboards, videos, and simulators, could disseminate the learnings compiled in this case study. Simulators could show different audiences how decisions are taken and what would happen when a decision is implemented. Interactive dashboards are helpful to understand the interconnectivity of variables and how one small change can affect the whole system's performance. Lastly, interactive videos could tell the story of the case study, engaging the audience in a decision-making process.

6.7 Selection of the tools

We selected the tools based on the core competencies of our researchers and their experience applying them to case studies, in their classes, and their applied research projects. Our authors have been involved in multidisciplinary projects merging transport systems, systems thinking, and analytics models on problems with a public health perspective. This case study presented a unique opportunity to combine a methodology enriched with multiple perspectives to study a complex transport system. We expect the case study would effectively reach the target audience because these tools have been explained at different levels of detail. In addition, each tool specialises in specific learnings, allowing a complete immersion on the case from different perspectives.

Acknowledgements

We would like to thank the support of our mentors, John Beckford, Mikela Chatzimichailidou, Monika Szczyrba, and Gyuchan Thomas Jun, for their insightful comments and feedback. We are also grateful with Shelley Stromdale, who has provided significant support throughout the development of the case. In addition, we would like to acknowledge the researchers who had contributed to several parts of the case study. For their contributions to the Group Model Building workshop, we would like to thank Alex Quistberg, Álvaro Rodríguez, Andrea Sanabria, Lorena Figueroa, Andrés Vergara, Deyanira Ávila, Ethel Segura, Gabriel Michel, Germán Barrero, Jeff Vargas, Luis F. Alarcón, Mario Avellaneda, Paula Bonilla, Paula Guevara, Sebastián Posada, Thomas van Laake, Jose D. Meisel, Ana M. Guerra, and Ana M. Jaramillo. For their contribution to the analytics methodologies and data analysis we would like to thank Andrés Felipe Aguilar, Laura Rojas, Diego Martínez, Juan C. Pico, Sebastián Leiva, Camilo Falla, Juan E. Rojas, and María A. Rubio. For their work on digital photography, maps, and image design and editing, we would like to thank Camila Fernández, Jose D. Pinzón, and Jason Fonseca. Lastly, we would like to thank the Mobility Secretariat of Bogotá for sharing their datasets and shapefiles of the temporary bike paths.

Funding

This project was supported by the Royal Academy of Engineering and the Lloyd's Register Foundation under the Safer Complex Systems – Call for Case Studies – Stage 1B (Research) scheme.

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Acknowledgements

This work was supported by a grant from the Safer Complex Systems mission of Engineering X, an international collaboration founded by the Royal Academy of Engineering (the Academy) and Lloyd's Register Foundation (LRF). The opinions expressed in this publication are those of the author(s) and do not necessarily reflect the views of the Academy or LRF. This case study is an abridged version of a longer research report also available at the Safer Complex Systems website.

We would like to thank our mentors, John Beckford, Mikela Chatzimichailidou, Monika Szczyrba, and Gyuchan Thomas Jun, for their support, insightful comments and feedback. We are also grateful to Shelley Stromdale, who has provided significant support throughout the development of the case. In addition, we would like to acknowledge the researchers who contributed to several parts of the case study. For their contributions to the Group Model Building workshop, we would like to thank Alex Quistberg, Álvaro Rodríguez, Andrea Sanabria, Lorena Figueroa, Andrés Vergara, Deyanira Ávila, Ethel Segura, Gabriel Michel, Germán Barrero, Jeff Vargas, Luis F. Alarcón, Mario Avellaneda, Paula Bonilla, Paula Guevara, Sebastián Posada, Thomas van Laake, Jose D. Meisel, Ana M. Guerra and Ana M. Jaramillo.

For their contribution to the analytics methodologies and data analysis, we would like to thank Andrés Felipe Aguilar, Laura Rojas, Diego Martínez, Juan C. Pico, Sebastián Leiva, Camilo Falla, Juan E. Rojas and María A. Rubio. For their work on digital photography, maps and image design and editing, we would like to thank Camila Fernández, Jose D. Pinzón and Jason Fonseca. We would also like to thank the Mobility Secretariat of Bogotá for sharing its datasets and shapefiles of the temporary bike paths.

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Appendix A. Protocol for interviews

We conducted two semistructured interviews with representatives of the Mobility Secretariat and the Health Secretariat with people involved in the implementation process of the temporary bike paths in Bogotá. The interviews were based on a questionnaire guide with the flexibility to get more information [50]. This process allowed us to collect data regarding the emergency, implementation, and projection of Bogotá's temporary bike paths. This initiative changed the idea of cycling as a mere leisure activity, turning it into an active, safe, and healthy means of transportation. The interviewees gave their informed consent to be recorded during the interview, and the University's ethics committee approved the entire protocol.

Appendix B. Feedback loops of the CLD description

Feedback loops	Description	Variables
R1	Reduction in Bicycle collision rate due to drivers' behaviour towards cyclists. The rise in the use of bicycles improves the drivers' behaviour towards cyclists, reducing the bicycle collision rate, which increases the use of bicycles.	Bicycle use – Drivers' behaviour towards cyclists – Bicycle collision rate
R2	Increase in traffic congestion due to design of cycling infrastructure. The increment of bicycle use raises the cycling infrastructure design, which leads to an increase in traffic congestion, which impulses bicycle use.	Bicycle use – Cycling infrastructure design – Traffic congestion
B1	Reduction in bicycle use due to the increase of bicycle collision rate.	Bicycle use – Bicycle collision rate
R3	Increase of bicycle use due to external motivation for cycling. The rise of bicycle use leads to increased cycling infrastructure design and creates better cycling infrastructure connectivity. With these improvements, the travel cycling time reduces, generating more external motivation for cycling. These motives lead to a rise in bicycle ownership, increasing the use of the bicycle.	Bicycle use – Cycling infrastructure design – Cycling infrastructure connectivity – Travel cycling time – External motivation for cycling – Bicycle ownership
R4	Increase in external motivation for cycling due to the rise in the cost of substitute transport modes. The increase in the use of bicycles reduces the use of substitute transport modes, which increases the cost of those transport modes. Thus, the increase in the cost leads to more external motivation for cycling, which raises the use of bicycle.	Bicycle use – Use of substitute transport modes – Cost of substitute transport modes – External motivation for cycling – Bicycle ownership
R5	Decrease in the use of substitute transport modes due to the increase in their costs.	Use of substitute transport modes – Cost of substitute transport modes
R6	Decrease in the use of substitute transport modes due to their quality. The reduction in the use of substitute transport modes reduces the road infrastructure design, reducing the utility of substitute modes of transport. This reduction leads to a reduction in the use of substitute transport modes.	Utility of substitute transport modes – Use of substitute transport modes- Road infrastructure design
R7	Increase in bicycle use due to the reduction in the use of substitute transport modes.	Bicycle use – Use of substitute transport modes
R8	Increase in bicycle use due to response capacity. The increase in the use of the bicycle generates a broader acknowledgement of social cycling organisations. This acknowledgement increases the political will towards cycling, which allows a better capacity to respond to a pandemic with tactical urban planning. In addition, this capacity favours the distribution of public space, which reduces bicycle collision rates and increases bicycle use.	Bicycle use – Acknowledge of social cycling organisations – Political will towards cycling – Response capacity to the pandemic with tactical urban planning – Distribution of public space – Bicycle collision rate

Feedback loops	Description	Variables
B3	Reduction in bicycle use due to public policies for improving road infrastructure. The increase in bicycle use generates a broader acknowledgement of social cycling organisations. This acknowledgement promotes public policies for improving the road infrastructure, which enhances the utility of substitute transport modes, reducing bicycle use.	Bicycle use – Acknowledgement of social cycling organisations – Public policies for improving road infrastructure – Utility of substitute transport modes – Use of substitute transport modes
R9	Increase in bicycle use due to improvement in road network maintenance.	Bicycle use – Road network maintenance
R10	Increase in bicycle ownership due to the acknowledgement of social cycling organisations. The increase in bicycle use raises the acknowledgement of social cycling organisations, which impulses bicycle ownership, increasing the use of the bicycle.	Bicycle use – Acknowledgement of social cycling organisations – Bicycle ownership
R11	Increase of bicycle use due to women cycling activism.	Bicycle use – Women cycling activism
R12	Increase in safety perception due to safer environments and civic culture. The increase in bicycle use foments the acknowledgement of women in public spaces, which promotes changes in cycling behaviours. These changes improve civic culture, increasing safe environments for cyclists, and improving safety perception. This safety perception increases the use of the bicycle.	Bicycle use – Acknowledgement of women in public space – Change in cycling behaviours – Civic culture – Safe environments for cyclists – Safety perception
R13	Increase in the utility of life due to physical health. The increase in bicycle use promotes the improvement in physical health through physical activity, increasing the quality of life of cyclists and the use of the bicycle.	Bicycle use – physical health – Quality of life
R14	Increase in quality of life due to mental health. The increase in bicycle use improves mental health, increasing the quality of life of cyclists and the use of the bicycle.	Bicycle use – Mental health– Quality of life
R15	Increase in mental health due to the reduction of traffic congestion. The increment in bicycle use promotes road network maintenance. The maintenance of the road network decreases traffic congestion, which improves mental health and bicycle use.	Bicycle use – Road network maintenance – Traffic congestion – Mental health
R16	Increase in bicycle use due to reduction in fear of using bicycles. The increase in bicycle use promotes the acknowledgement of social cycling organisations. This acknowledgement increases recreational and sporting cycling, which incentivises civic culture. Civic culture reduces the fear of using bicycles, which increases the use of the bicycle.	Bicycle use – Acknowledgement of social cycling organisations – Recreational and sporting cycling– Civic culture – Fear of using bicycles
R17	Improvement of civic culture due to public policies and culture programmes. The improvement of public policies for cyclists' welfare increases civic culture programmes, which improve civic culture.	Civic culture – Public policies for cyclists' welfare – Civic culture programmes
R18	Increase in norm appropriation due to development of public policies for cyclists' welfare.	Public policies for cyclists' welfare – Norm appropriation
B2	Improvement in safety perception due to cycling groups accompaniment.	Safety perception – Cycling groups accompaniment

Feedback loops	Description	Variables
R19	Increase in intrinsic motivation for cycling due to cycling groups accompaniment. The increase in bicycle use increases the cycling groups' accompaniment to other cyclists, which improves the intrinsic motivation for cycling and increases the use of the bicycle.	Bicycle use – Cycling groups accompaniment – Intrinsic motivation for cycling
R20	Increase in the distribution of public space due to road network design.	Road network design – Distribution of public space
B4	Reduction in bicycle use due to reduction in traffic congestion. The increase in bicycle use leads to better road network maintenance. This maintenance reduces traffic congestion, which reduces the use of bicycles.	Bicycle use – Road network maintenance – Traffic congestion

Appendix C. ABM main components under the ODD + D protocol

Outline (à template)		Guiding questions	ODD+D Model description
I) Overview	**I.i Purpose**	I.i.a What is the purpose of the study?	The model evaluates the collision dynamics for the bicycle users and the LTS according to changes in bicycle infrastructure and cyclists' behaviour.
		I.ii.b For whom is the model designed?	Decision-makers and stakeholders of Bogotá's bicycle transport system
	I.ii Entities, state variables, and scales	I.ii.a What kinds of entities are in the model?	The main agents in this model are the bicycle users in Bogotá. Moreover, the spatial units represent the road network in the city used by cyclists. This network is divided into transport analysis zones (from now on ZAT for its acronym in Spanish)
		I.ii.b By what attributes (that is state variables and parameters) are these entities characterised?	Of Agents: origin's ZAT, destination ZAT (from Origin-Destination matrixes), origin's point based on ZAT, destination point based on ZAT and risk probability (probability associated with each cyclist's profile that determines their willingness to take safer routes)
			Of environment (Road network): the probability of occurrence of a collision (probability of a cyclist collision in the road) and safety index (cyclists' perception of safety on the road)
		I.ii.c What are the exogenous factors / drivers of the model?	Available bicycle infrastructure
		I.ii.d If applicable, how is space included in the model?	In the model, the space is represented by the bicycle road network and the ZATs. The ZATs are presented by polygons which contains line segments representing the road network.
		I.ii.e What are the temporary and spatial resolutions and extents of the model?	One time step represents about 1 hour (time in which a cyclist can make two trips if it matches the work and comes back hours: one to work and one back home), and the simulations were run for one year (8760 steps)
	I.iii Process overview and scheduling	I.iii.a What entity does what, and in what order?	Processes in the model: 1. Agents and environment initialisation - External data - Definition of agents and environment attributes 2. Simulation dynamics - Selection of type of movement: determine the shortest or safest route - Collisions' rate. - Update individual risk probability - Update unsafety index for segments 3. Validation of the model - Calibration of parameters based on comparison with current collision rates data.

Outline (à template)		Guiding questions	ODD+D Model description
II) Design Concepts	**II.i Theoretical and Empirical Background**	II.i.a Which general concepts, theories or hypotheses are underlying the model's design at the system level or the level(s) of the submodel(s) (apart from the decision model)? What are the link to the complexity and the purpose of the model?	The model is guided by the premise that Bogotá's bicycle transport system is complex and social since multiple actors and decisions affect its performance. Similarly, the model integrates analytical methodologies to characterise the dynamics of cyclists, specifically those related to collisions, which is the model's objective.
		II.i.b On what assumptions is/are the agents' decision model(s) based?	The agent's decisions are based on a combination of the theory of cyclist behaviour and real-world observations. Thereby, the bicycle users decide their route considering their risk preferences: "High risk," "Moderate risk," and "Low risk."
		II.i.c Why is a/are certain decision model(s) chosen?	The decisions are based on data availability (Origen and Destination matrixes) by referencing other studies and theoretical considerations.
		II.i.d If the model / a submodel (for example the decision model) is based on empirical data, where does the data come from?	The data used in this model came from historical data estimated based on reports and surveys made by public entities related to bicycle transport
		II.i.e At which level of aggregation were the data available?	Geographical data (origin and destination of cyclists) are at an individual level of aggregation, while their risk classification is at a group level of aggregation.
	II.ii Individual Decision-making	II.ii.a What are the subjects and objects of decision-making? On which level of aggregation is decision-making modelled? Are multiple levels of decision-making included?	Subjects: Bogotá's bicycle users
			Objects of decision-making: route to transport from origin to destination (shortest or safest route).
		II.ii.b What is the basic rationality behind agents' decision-making in the model? Do agents pursue an explicit objective or have other success criteria?	Agents follow a rational choice, specifically utility maximisation. Its utility function is based on the minimum distance they travel.
		II.ii.c How do agents make their decisions?	Utility function minimising the distance
		II.ii.d Do the agents adapt their behaviour to changing endogenous and exogenous state variables? And if yes, how?	Bicycle users adapt their route's preferences based on the past road collisions they experienced.
		II.ii.e Do social norms or cultural values play a role in the decision-making process?	Cultural values: risk tendency
		II.ii.f Do spatial aspects play a role in the decision process?	Cyclists' decision process involves spatial aspects since an origin gives their initial conditions and destination location, and the cyclist wants to minimise distance.
		II.ii.g Do temporary aspects play a role in the decision process?	Although the simulation periods include the cyclist's daily travels, the temporary aspect does not influence the decision-making process of the cyclists.
		II.ii.h To which extent and how is uncertainty included in the agents' decision rules?	Uncertainty affects the number of collisions that occur on the routes since these are generated randomly. Later, these collisions affect the cyclist's decisions. Agents decide to follow the shortest or safest route based on their risk profile and random numbers generated in each step.

Outline (à template)		Guiding questions	ODD+D Model description
II) Design Concepts	II.iii Learning	II.iii.a Is individual learning included in the decision process? How do individuals change their decision rules over time as consequence of their experience?	Agents change their decisions over time as of the collisions they experienced in their past routes; however, their decisions rules do not change over time, i. e., each period they will select their route based on their risk classification.
		II.iii.b Is collective learning implemented in the model?	Collective learning does not apply in this model since each cyclist makes the decisions.
	II.iv Individual Sensing	II.iv.a What endogenous and exogenous state variables are individuals assumed to sense and consider in their decisions? Is the sensing process erroneous?	Agents consider their risk classification as part of their decision-making process
		II.iv.b What state variables of which other individuals can an individual perceive? Is the sensing process erroneous?	The behaviour or actions of other cyclists does not influence the route decision of the agents
		II.iv.c What is the spatial scale of sensing?	Bogotá's bicycle road network
		II.iv.d Are the mechanisms by which agents obtain information modelled explicitly, or are individuals simply assumed to know these variables?	Cyclists simply assumed to know the variables related to the decision-making process: risk classification and collisions in the routes they used
		II.iv.e Are costs for cognition and costs for gathering information included in the model?	Costs are not included in this model
	II.v Individual Prediction	II.v.a Which data uses the agent to predict future conditions?	Extrapolation from experience (past collisions)
		II.v.b What internal models are agents assumed to use to estimate future conditions or consequences of their decisions?	Does not apply
		II.v.c Might agents be erroneous in the prediction process, and how is it implemented?	(External) uncertainty
	II.vi Interaction	II.vi.a Are interactions among agents and entities assumed as direct or indirect?	Cyclists interact directly with their environment, that is, with the bicycle road network. There is no interaction between cyclists.
		II.vi.b On what do the interactions depend?	Does not apply
		II.vi.c If the interactions involve communication, how are such communications represented?	Does not apply
		II.vi.d If a coordination network exists, how does it affect the agent behaviour? Is the structure of the network imposed or emergent?	Does not apply
	II.vii Collectives	II.vii.a Do the individuals form or belong to aggregations that affect, and are affected by, the individuals? Are these aggregations imposed by the modeller, or do they emerge during the simulation?	In this model, the individuals do not generate aggregations or collectives directly. However, later, the cyclist will be analysed as a collective social group in the analysis and results.
		II.vii.b How are collectives represented?	Does not apply

Outline (à template)		Guiding questions	ODD+D Model description
II) Design Concepts	**II.viii Heterogeneity**	II.viii.a Are the agents heterogeneous? If yes, which state variables and/or processes differ between the agents?	The agents are heterogeneous, their risk classification is not the same, and the exposure to different places varies depending on their origin and destination.
		II.viii.b Are the agents heterogeneous in their decision-making? If yes, which decision models or decision objects differ between the agents?	Cyclists are not heterogeneous in their decision-making. They all rely on the same parameters to make their decisions.
	II.ix Stochasticity	II.ix.a What processes (including initialisation) are modelled by assuming they are random or partly random?	Initialisation of random location within the administrative unit. Collision rates. Selection of the route they follow.
	II.x Observation	II.x.a What data are collected from the ABM for testing, understanding, and analysing it, and how and when are they collected?	The following data are required for the initialisation: - Secondary data from Bogotá's cyclists - Origin-destination matrix data - Road network data
		II.x.b What key results, outputs, or characteristics of the model are emerging from the individuals? (Emergence)	Collision's rate of cyclists, mean LTS per trip, segment flow.
III) Details	**II.i Implementation Details**	III.i.a How has the model been implemented?	The ABM is generated in JavaScript using the GAMMA 1.8 platform
		III.i.b. Is the model accessible, and if so, where?	
	III.ii Initialisation	III.ii.a What is the initial state of the model world, that is at time t=0 of a simulation run?	The initial attributes for cyclists are origin and destination administrative unit location (x, y) and risk profile. The initial attributes of the roads and segments are length, collision probability, LTS, and safety index.
		III.ii.b Is initialisation always the same, or is it allowed to vary among simulations?	The initialisation is always the same. However, the seed in each initialisation varies to generate randomness in the point generation.
		III.ii.c Are the initial values chosen arbitrarily or based on data?	The initial values are based on data.
	III.iii Input Data	III.iii.a Does the model use input from external sources such as data files or other models to represent processes that change over time?	External models required for Initialisation: OD matrix, collision probabilities, LTS, cyclists risk profiles, travel rates.
	III.iv Submodels	III.iv.a What, in detail, are the submodels that represent the processes listed in 'Process overview and scheduling?	The main steps in the model are the following: 1. Agents and environment initialisation - External data - Definition of agents' attributes 2. Simulation dynamics - Selection of type of path: shortest path or safest shortest - Collision check - Update individual risk probability - Update unsafety index for segments - Save results 3. Validation of the model - Calibration of parameters - Comparison with current collision rates data.

<table>
<tr><th colspan="2">Outline (à template)</th><th>Guiding questions</th><th>ODD+D Model description</th></tr>
<tr><td rowspan="2">III) Details</td><td rowspan="2">III.iv Submodels</td><td>III.iv.b What are the model parameters, their dimensions, and reference values?</td><td>
<table>
<tr><th>Parameters</th><th>Dimensions</th><th>Reference values</th></tr>
<tr><td>Origin administrative unit location</td><td>(x, y)</td><td>OD matrixes data</td></tr>
<tr><td>Destination administrative unit location</td><td>(x, y)</td><td>OD matrixes data</td></tr>
<tr><td>Risk profile</td><td>Percentage</td><td>Rozas-Satizabal et al. [12]</td></tr>
<tr><td>Collision probability</td><td>Proportion rate</td><td>Analysis via CPM</td></tr>
<tr><td>Safety index</td><td>Proportion rate</td><td></td></tr>
<tr><td>LTS</td><td>Discrete numeric</td><td>Analysis in the case study</td></tr>
</table>
</td></tr>
<tr><td>III.iv.c How were submodels designed or chosen, and how were they parameterised and then tested?</td><td></td></tr>
</table>

Appendix D. Parameters for HEAT tool

Parameter	2019	2020
Population	Health Secretariat [40]	Health Secretariat [40]
Number of bicycle users	2019 Mobility Survey	Estimated with the percentage of change in daily trips.
Mean travel time per trip	2019 Mobility Survey	2019 Mobility Survey
Number of trips per person	2019 Mobility Survey	2019 Mobility Survey
Percentage of trips in bicycle	2019 Mobility Survey	2019 Mobility Survey