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.

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

Section 1: Background and introduction

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

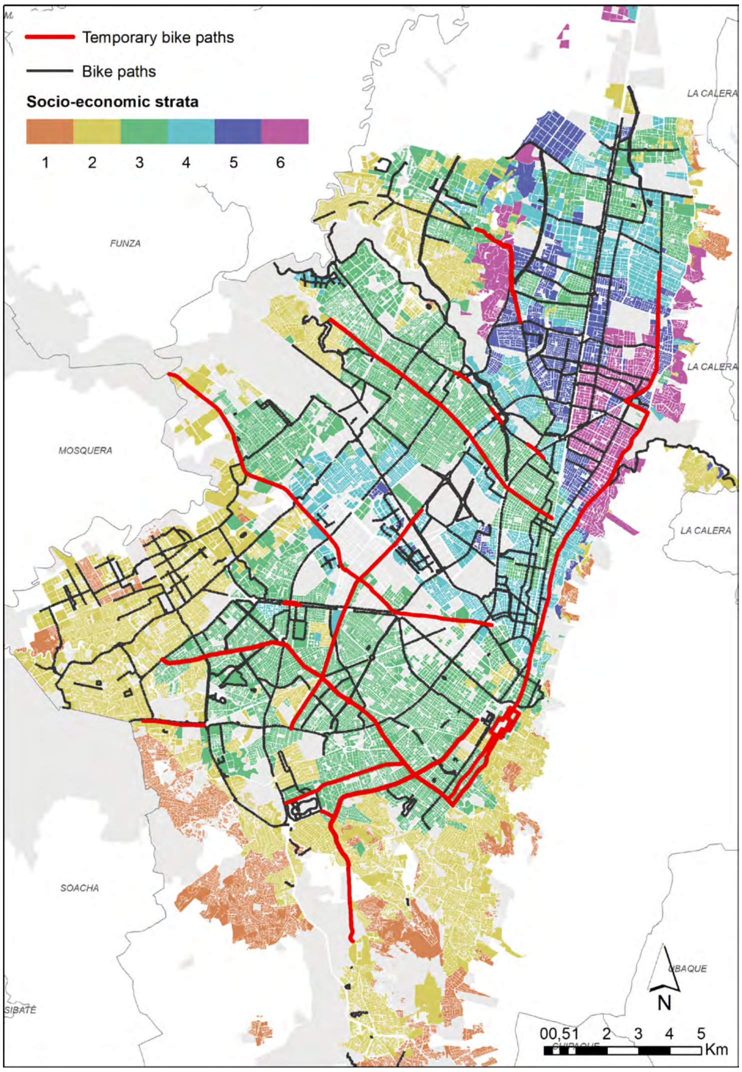
On 20 March 2020, the city of Bogotá (Colombia) entered a strict lockdown. The Mobility Secretariat, the public agency in charge of urban transport, looked for innovative ways to guarantee mobility throughout the city, while reducing the agglomeration of the public transport system, to meet the physical distancing measures recommended to decrease SARS-CoV-2 transmission [1]. Just before the pandemic, 34% of the daily trips generated in Bogotá were made using public transport, the most used mode of transport in the city [2]. The public transport system was considered a public service with a high risk of transmission. Based on the established bike culture in the city, the bicycle was targeted as the primary solution.

As a solution, temporary bike paths were created covering 84 km of the city road network [3]. The initiative was a coordinated action between the Mobility Secretariat, the Recreation and Sports Institute of Bogotá (acronym in Spanish is IDRD), 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 (**Figure 1**). 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, 21km of the temporary bike paths were transformed into permanent bike paths and 28km of temporary bike paths are still in place.

The case of Bogotá has also served as an example for implementing bike paths in other cities around 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 [4]. 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 [5]. Thus, the fast provision of new bike infrastructure during the COVID-19 pandemic in a city like Bogotá, from a middle-income country, is a suitable policy to assess its safety and health potential impacts.

In this context, the aims of the case study are to:

- 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



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 denotes the socio-economic 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.

analytics (henceforth referred as to systems analytics);

- Evaluate the potential impact of policy decisions on the bicycle system in terms of safety, health, efficiency and flexibility; and
- Provide evidence of the potential impact that an emerging transport system could have on preventing SARS-CoV-2 transmission.

Bogotá's bicycle transport system

In Bogotá's bicycle transport 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 performance is the result of the dynamic interaction of a physical infrastructure, a set of rules for using the infrastructure, and decisions made by regulators that enforce the correct use of the system and can modify the infrastructure and its rules. Through its use and regulation, different stakeholders seek to satisfy the needs of bicycle users and improve their conditions to generate more trips in this mode. Appendix A shows the description of the system´s missional activities through the TASCOI tool [6].

For this case study, we analyse the bicycle transport system of Bogotá in 2019 and 2020. We consider the year 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 (**Figure 1**).

Section 2: Analysis and insights

System analytics and 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 the system's metrics (i.e., indicators) and predict changes in the system via statistical and machine learning models. 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 2 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 co-created with the stakeholders (boxes 1 and 2). Box 3 shows an Agent-Based Model (ABM) [7] that simulates different scenarios for the system and estimates 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 policy's 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 (e.g., street level). These two KPIs proved significant when modelling 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) [8] 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 boxes 7, 8, 9) feed the ABM (inputs to box 3). Appendix B describes the methodology for each box.

Application of the systems analytics methodology to Bogotá's bicycle transport system

We applied the systems analytics methodology to Bogotá's bicycle transport system. Through a Group Model Building (GMB) with stakeholders we created a Causal Loop Diagram (CLD) with the main variables that describe the systems behaviour. These variables can be grouped into six domains:

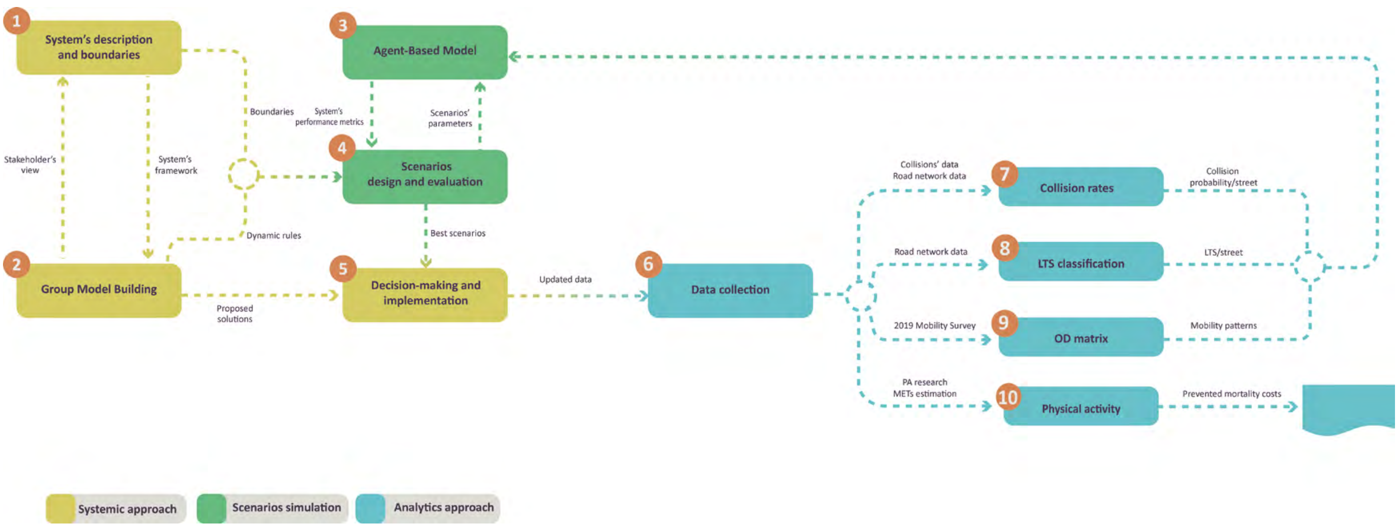


Figure 2. Systems analytics methodology (PA: physical activity; LTS: level of traffic stress; OD: Origin-Destination matrix).

civic culture, cycling motivation, substitute transport modes, quality of life, infrastructure for bicycle use and citizen participation (**Figure 3** and Appendix C). After understanding the different perspectives of the stakeholders, we described the system's complexity, following the University of York's framework [9].

Figure 4 describes the bicycle transport system in Bogotá as a complex system, following the University of York's framework [9]. 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 4** 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

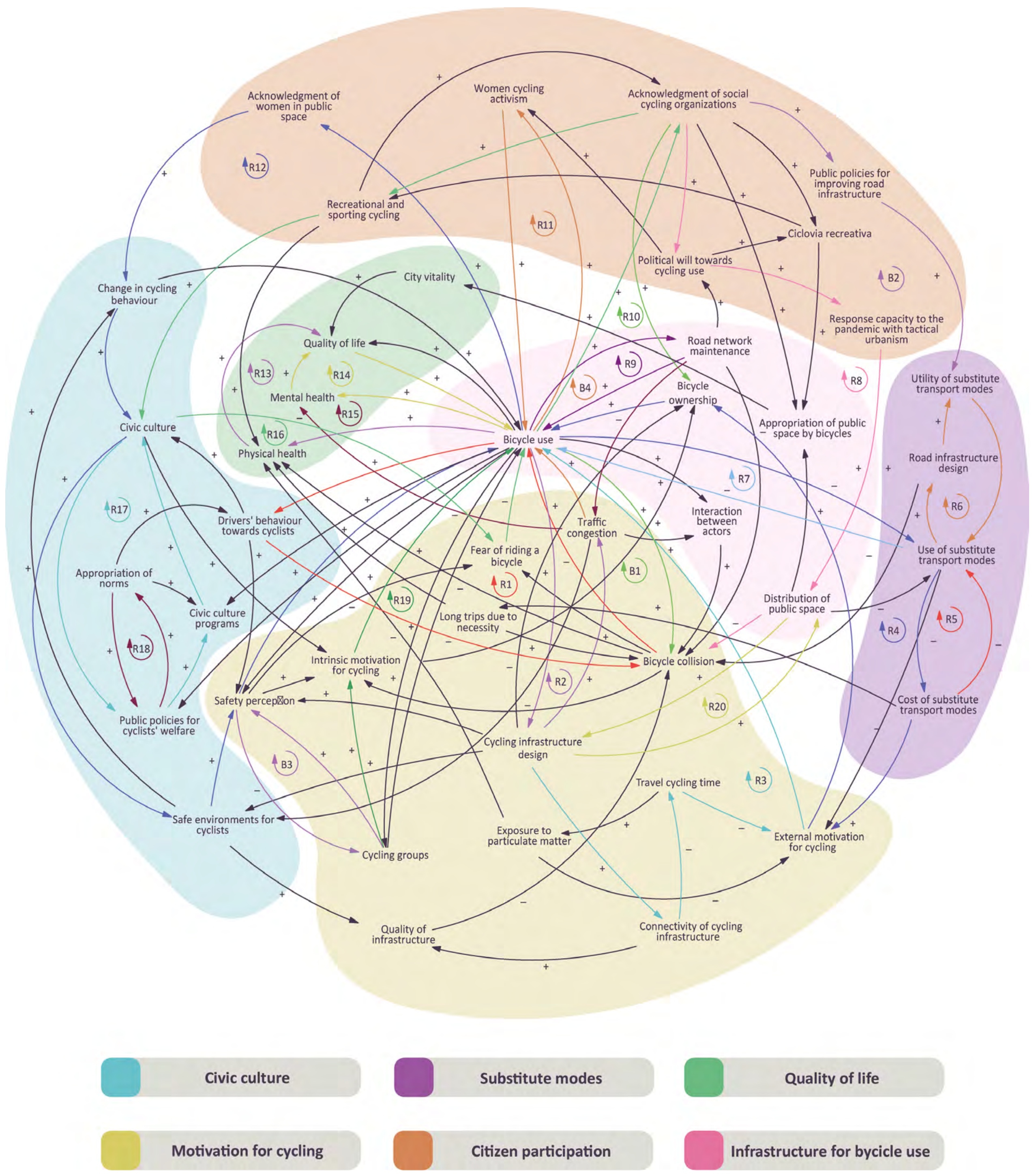


Figure 3. Causal loop diagram of Bogotá's bicycle transport system

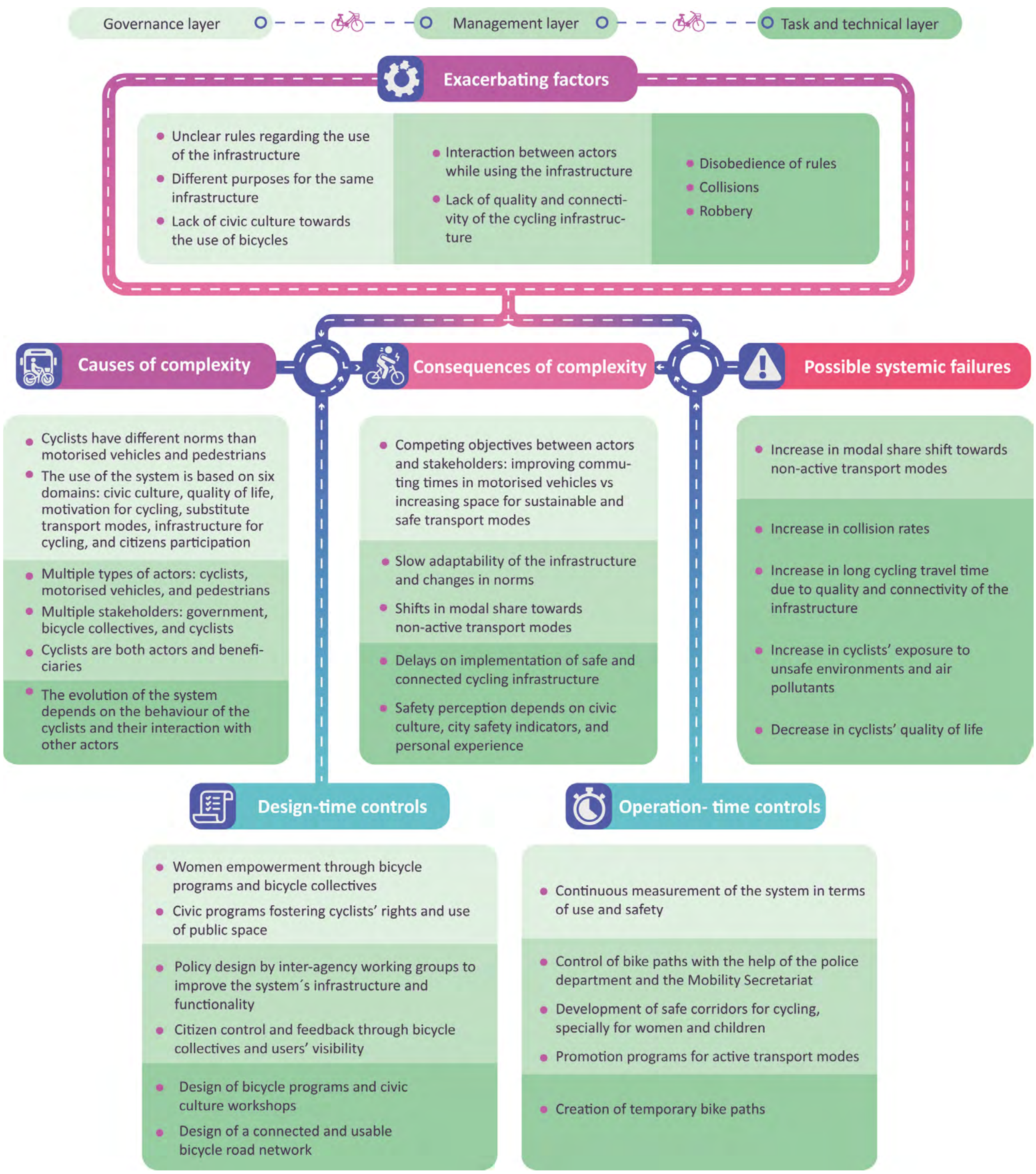


Figure 4. Complex system description via the Complex Systems Framework by the University of York

that relies on the same actors, specifically on the interaction among bicycle users with the infrastructure and other 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 mode 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 empowerment and programmes to promote bicycle use are critical design-time controls that affect the system's behaviour.

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 non-active transport modes to bicycle users' safety. Two of the most critical possible systemic failures are an increase in collision rates among bicycle users and a decrease in quality of life due to 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. 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 simulation model, 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.

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

Scenarios

After describing the complexity of Bogotá's bicycle transport system, we assessed the KPIs for 2019 and 2020 and 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); 2) 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).

Level of traffic stress

As for the LTS, our first KPI of the system, **Figure 5**, shows the classified segments for a) 2019 and b) 2020. 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 in the overall LTS of the city. We partially attribute these changes to the temporary bike paths, which took over a lane of the road for bicycles and changed these segments' speed, congestion, density and flow.

Collision analysis

As for our second KPI, the mean monthly collision rate for 2019 was 1.37 per 1,000 cyclists, while the mean collision rate for 2020 was 0.97. These rates show a significant reduction of 29.73% between 2019 and 2020.

In the same way, the median collision rate per ZAT (acronym in Spanish for Transport Analysis Zone) 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 significant reduction of 43% between 2019 and 2020. **Figure 6** shows the monthly collision rate per 100 million VKmT for each ZAT in a) 2019 and b) 2020.

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 to 38.94, which shows that there was a significant reduction of 45% in the collision rate per ZAT.

Agent-based model (ABM)

The ABM combines the two previously described KPIs to estimate the bicycle transport system's performance. 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 scenario without temporary bike paths. Regarding LTS distribution per travelled meter, scenario 2 LTS Low increased by 6.22%, while the other LTS were reduced by 2% on average, compared to scenarios 1 and 3.

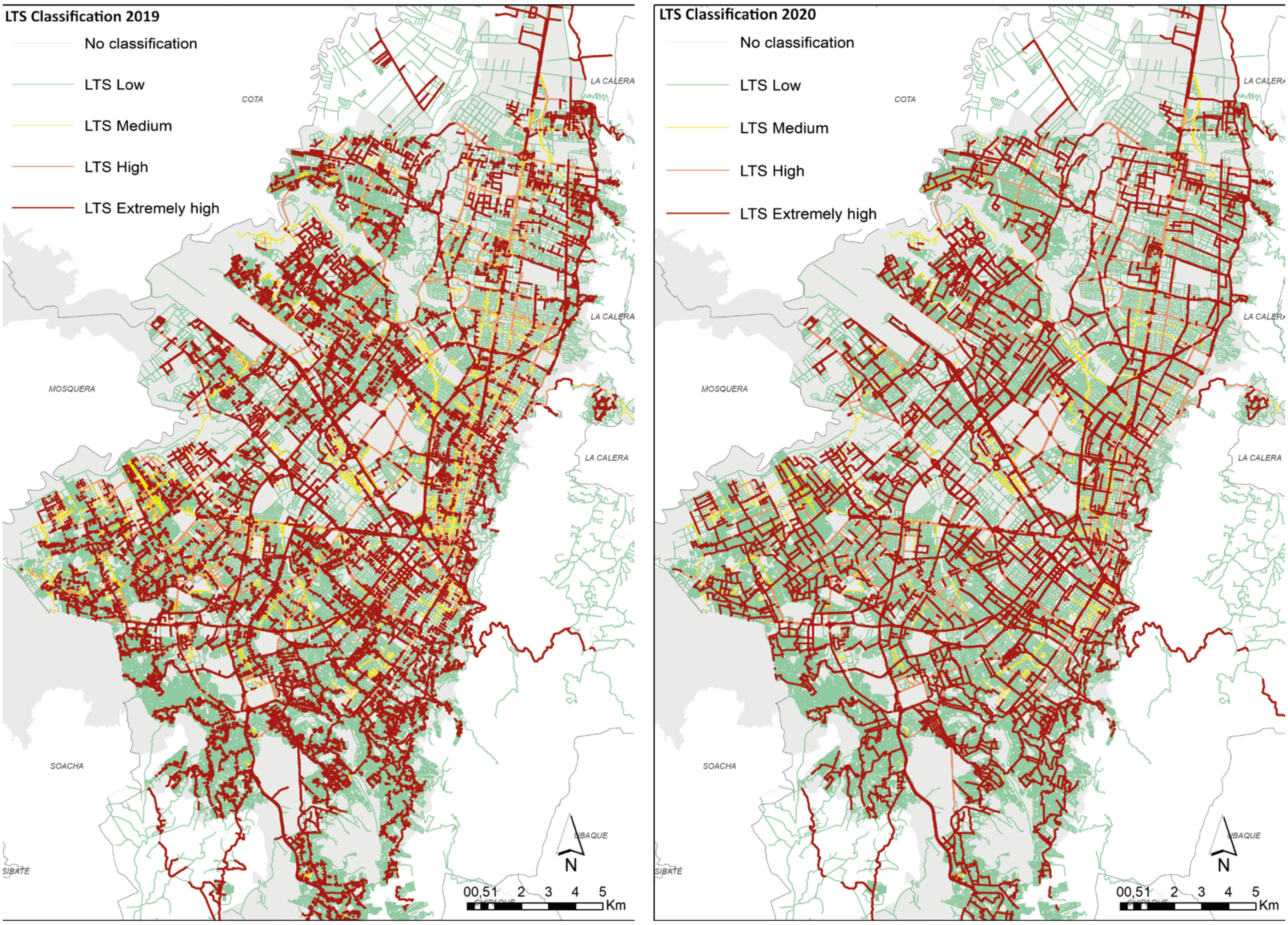
Physical activity

The third KPI measured for the system was physical activity. The average METs per trip for 2019 and 2020 are 236.27. The average METs for bicycle users per person per day are 506.54. 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 a bicycle as a transport mode in 2019 are 126.46 million, while in 2020 they are 93.58 million. Therefore, the reduction in METs for 2020 depends only on the reduction of daily trips by bicycle. This reduction could have been up to 60% if the number of trips per day had remained constant [10], and 34% if the bicycle transport system had followed the same level of activity as the city [11].

Furthermore, we estimated the health and economic value of the bicycle transport system of Bogotá. The analysis using the HEAT tool shows that in 2019 the prevented premature deaths were 199 with an economic value of 224 million euros. In 2020, the prevented premature deaths were 145 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.

Stakeholder's perspective

We held a meeting with the system's primary stakeholders to gather their feedback on our results. At the meeting, staff from the Mobility Secretariat discussed the study results and possible



2019 (scenarios 1 and 3)

2020 (scenario 2)

Figure 5. Maps with road segments classified by LTS levels for (a) 2019 (scenarios 1 and 3) and (b) 2020 (scenario 2)

ways the study could support decision making.

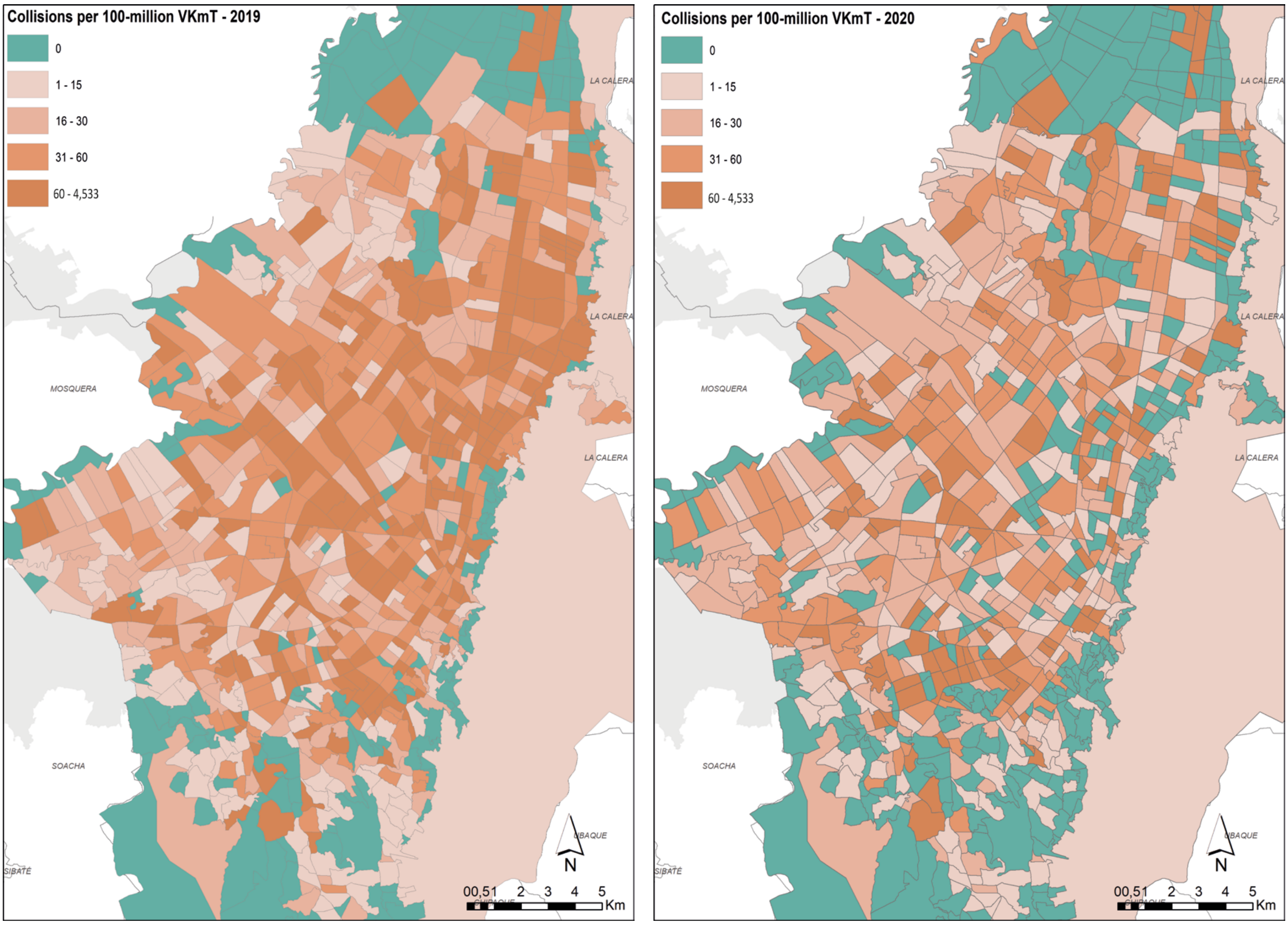
Stakeholders reported that the case study results could be used to diagnose the system and the impact of the intervention. In addition, the study is essential for the city's Mobility Master Plan and Land Use Master Plan, where more bike paths will be supported. Finally, the Bicycle Manager for Bogotá stated: "We consider it 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."

The stakeholders also reported that the findings of the CLD reinforce the idea of developing social infrastructure in the city. Along this line, the Mobility Secretariat is currently working 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 citizens. Our project could certainly support this initiative.

Finally, in terms of follow-up studies for the city, next steps could consider emissions of air pollutants; how bicycles impact these emissions; and estimate 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.

Section 3: Discussion and transferable learnings

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 collision rates, increase the meters of segments with low levels of traffic stress and continue promoting physical activity, which



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

Figure 6. Maps of mean monthly collision rates per 100 million VKmT per ZAT for (a) 2019 (scenarios 1 and 3) and (b) 2020 (scenario 2)

in turn is associated with yearly prevented premature deaths. Local stakeholders recognised the importance of this study in supporting the Mobility Master Plan, the Land Use Master Plan 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 road space. By July 2020, at least 94 cities in 20 countries created or expanded bike paths. In many of these cities, the implementation of temporary bikeways has involved legal disputes [12] and ongoing discussions about the right to use the space [12,13]. 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 United States, United Kingdom, Germany, Spain and Canada, motor vehicle fatality rates, injury accidents and speeding violations have increased and remained elevated when traffic levels began returning to pre-pandemic conditions [14] [15]. Specifically, in Colombia, the total death rate for cyclists also increased from 0.84 to 0.87 per 100,000 inhabitants in 2020 [15]. Our study shows that bicycle collisions decreased during the COVID-19 pandemic and collisions 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 number of kilometres of permanent bike paths could be the basis of a similar study to compare their results with ours as the proposed methodology is based on a local perspective. In conjunction with political and community support, these results could serve to advocate for the implementation of a 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.

The response of the city towards the imminent threat of a pandemic served as an excellent operation-time control. In addition to reducing 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.

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 in understanding the system's complexity, including 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 local governments.

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, the delimitation of paths for the exclusive use of bicycles improves safety for 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 agent-based model where data and the individual behaviour of the agents empower and complement the predictive power of the models.

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 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.

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.

Appendix A. TASCOI tool

Figure 7 shows the system's four missional activities (transformations). The first activity, commuting, is carried out by cyclists whose purpose is to mobilise throughout the city. In this activity, the system's performance depends directly on the decisions cyclists make while they use the infrastructure and their interaction with other actors. These decisions can be affected by the level of stress of each segment, the security and connectivity of the route and the perception of risk of collision of each segment. Government agencies collaborate with cyclists to facilitate 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 by several government agencies in coordination, which adjust and implement new policies based on the system's performance measurements with the aim of improving the actors' wellbeing. Specific policies could negatively affect 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

Missional activities	Commuting	Infrastructure changes	Policy development	System measurement
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 7. Stakeholders and main missional activities of Bogotá's bicycle transport system

collect and report statistics that assess collision rates, the volume of cyclists and perception of safety, among other outcomes.

Appendix B. Description of the main components of the system's analytics methodology

1. Group Model Building

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 via Zoom with Mural as the virtual blackboard, where participants developed the group activities. The whole session was recorded to facilitate the compilation and validation of the CLD. The workshop involved 17 participants representing the Health Secretariat, Planning Secretariat, Mobility Secretariat, Women 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. Agent-Based Model

The Agent-Based Model (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 meter. 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 is 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 [17] and Portland (Oregon, USA) [18], where cyclists are classified by the potential risk that 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 choosing 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 8** 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 meter 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,

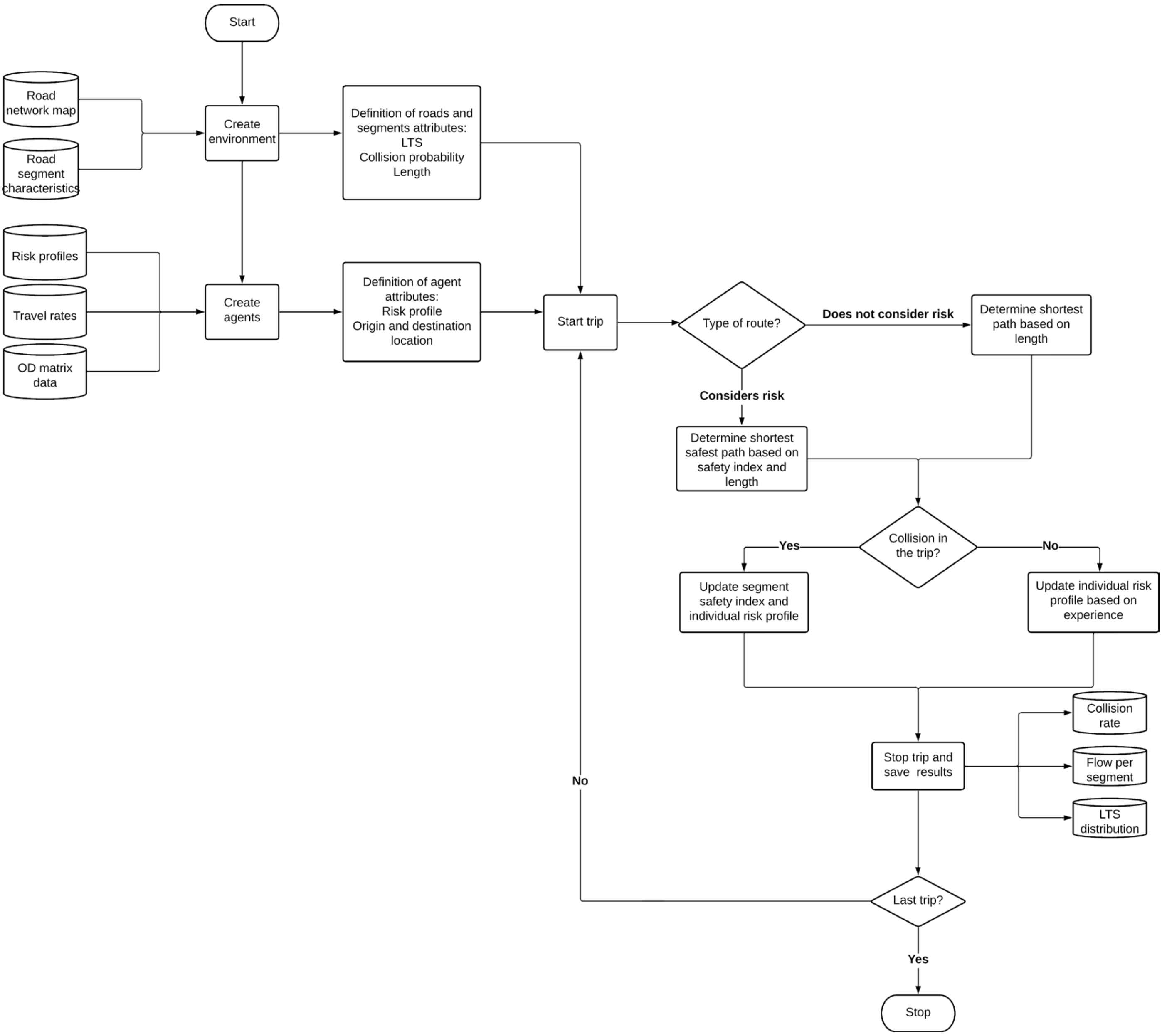


Figure 8. Flow diagram of the ABM

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 [19].

3. OD-matrix and cycling paths

Origin-Destination (OD) matrices describe the spatial distribution of daily trips. Although these matrices are usually generated for motorised vehicles, an OD matrix for bicycles is essential for decision makers to allocate resources effectively [20]. 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. [21] 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.

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 [22–24]. The Level of Traffic Stress (LTS) is a proxy of the potential stress experienced by cyclists due to road network attributes [25,26]. 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. [27] 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 with different typologies 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 [28], 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-used 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 due to data access limitations to the Google API engine, yet the traffic behaviour consistently captures the pre-and follow-up COVID scenarios.

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 non-fatal) registered in that zone. Thus, collision rates allow us to assess road safety and how it changes by year.

Carvajal et al. [29] 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 in Bogotá per million cyclists and per ZAT per 100 million VKmT using the collision 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 [30]. 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; and the dependent variable is the number of collisions per year for each segment. Then, 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 [31] and its packages tidyverse [32] and sf [33]. We used QGIS for spatial data visualisation [34].

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 non-communicable diseases, such as cardiovascular diseases, cancer, hypertension and diabetes [35] and reduces symptoms of depression and anxiety [36]. 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 [38]. 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) [39]. HEAT is a tool developed by the WHO designed to conduct economic assessments of the health impacts of cycling [39]. 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 [8]. The HEAT tool is designated to be used by 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 members of 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.

Appendix C. Causal Loop Diagram description and feedback loops description

Table 1 describes the feedback loops of the resulting CLD of the system. 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-used road network and bike paths and political power to react towards a pandemic with tactical urban health.

Table 1. Feedback loops description for CLD

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 increases the use of the 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
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 – Acknowledgment of social cycling organisations – Public policies for improving road infrastructure – Utility of substitute transport modes – Use of substitute transport modes

Feedback loops	Description	Variables
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 – Acknowledgment 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 – Acknowledgment of women in public space – Change in cycling behaviours – Civic culture – Safe environments for cyclists – Safety perception
R13	Increase in the quality 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
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

Feedback loops	Description	Variables
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

Two of the most relevant feedback loops are reinforcement loops 3 and 12. Reinforcement loop 3 shows that the rise in bicycle use leads to a better design and increase in cycling infrastructure and improves connectivity. With these improvements, cycling travel time reduces, motivating more cycling trips. This motivation leads to a rise in bicycle ownership, increasing bicycle use. The reinforcement loop 12 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.

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