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A Genetic Algorithm Approach to Bicycle Network Design Based on Cyclist Comfort: A Case Study of Pasig City, The Philippines

自転車利用者の快適性を考慮した遺伝的アルゴリズムによる自転車ネットワークデザイン
―フィリピン・パシグ市のケーススタディ―

37-225081　Justine Brylle Pajarin

The COVID-19 pandemic led the Philippine government to expand bicycle networks in major cities, including over 500 km of bike lanes. Despite the infrastructure, challenges persist in cyclist comfort and safety. This study aims to optimize Pasig City's bicycle network, considering factors like existing traffic, road geometry, and operating conditions while adhering to budget constraints. A bi-level optimization method is employed: traffic assignments for cars at the lower level and maximizing cycling comfort using the Bicycle Comfort Index (BCI). The model was tested on the Sioux Falls and Pasig City networks, showing improved comfort on bike lane-equipped links. The impact of bike lanes on traffic and speed was analyzed, and road diet proposals further enhanced cycling conditions, offering insights for traffic-congested urban areas in the Philippines.

1. Introduction

1.1 Background

During the COVID-19 pandemic, active transport gained momentum nationwide, leading to significant government initiatives. Substantial funds were allocated for projects, and design standards for cycling infrastructure were established, with classifications based on traffic volume and speed limits. Government agencies were tasked with promoting active transport, and educational efforts highlighted the rights of vulnerable road users, including cyclists and pedestrians.

From 2020 to 2023, 564 km of bike lanes were built, increasing cyclist numbers but also cycling-related accidents, which rose by 48% from 2019 to 2020[1]. Many bike lanes remain disconnected and are on roads congested by motorized vehicles, especially in Metro Manila, the world's most congested metropolitan area in 2023[2]. Additionally, a survey by the Institute for Climate and Sustainable Cities[3] revealed a significant gender disparity, with over 90% of cyclists being male, highlighting the need for safer, more inclusive cycling infrastructure.

1.2 Research Objective

Given the aforementioned existing issues in the local context, this research aims to optimize bicycle networks in terms of cyclist's comfort given factors such as existing traffic, and road geometry and operating conditions. Road geometry encompasses the allocation of space for cyclists relative to existing traffic, focusing on the width of proposed bike lanes and their impact on current traffic patterns. Operational factors include changes in traffic volume and road speeds resulting from bike lane installation, as well as presence of roadside parking and surrounding land use development.

This study also considers network connectivity while adhering to budget constraints for constructing bike lanes.

2. Review of Related Literature

Designing bicycle networks aims to optimize performance across various aspects, using different approaches. Duthie et al.[4] retrofitted existing roads in Austin, Texas to develop cycling networks, while Caggiani et al.[5] created an optimization framework to improve bikeway access and reduce inequities among population groups. Bi-level optimization addresses two interlinked problems simultaneously, similar to the Stackelberg model, where decisions by a leader affect the follower's outcome[6]. Multi-objective optimization balances conflicting goals[7], such as accessibility, comfort, travel time, and bikeway suitability, considering constraints like budget, connectivity, and traffic. Previous studies applying the aforementioned methods include the study by Zhu and Zhu[8] focusing on commuter cyclists in Singapore, and Mesbah et al.[9] balancing cyclist travel and traffic impact in Australia.

In bicycle network design, global practices were also explored and considered. International benchmarks for cycling infrastructure are primarily from Western countries. CROW[10] from the Netherlands identifies five key elements of cycling-friendly infrastructure (i.e., cohesion, directness, attractiveness, safety and comfort). These elements are consistent across various guidelines found such as the Urban Bikeway Design Guide from the National Association of City Transportation Officials (NACTO) and Transport for London's Cycling Design Standards, among others.

3. Methodology

3.1 Bicycle Compatibility Index

In this research, the concept of BCI, proposed by Harkey et al.[11], was employed and integrated into the optimization framework. The BCI formula consists of parameters that provide an accurate assessment of cyclists' comfort when traveling along roads with existing traffic. BCI is given by Equation (1).

$$BCI = 3.67 - 0.966BL - 0.41BLW - 0.498CLW + 0.002CLV + 0.0004OLV + 0.022SPD + 0.506PKG - 0.264AREA + AF \quad (1)$$

BL indicates bike lane presence; BLW, bike lane width; CLW, curb lane width; CLV, curb lane volume; OLV, other lane volume; SPD, legal speed limit; PKG, presence of a parking lane; AREA, residential classification of a road; and AF, additional factors like truck volume, parking turnover, and right-turn volume. Table-1 shows the ranges of BCI values and their corresponding level of service (LOS) and compatibility levels, indicating that lower BCI values correspond to higher comfort levels for cyclists.

Table-1: BCI range and corresponding LOS and compatibility level

LOS	Compatibility Level	BCI
A	Extremely High	≤ 1.50
B	Very High	1.51 – 2.30
C	Moderately High	2.31 – 3.40
D	Moderately Low	3.41 – 4.40
E	Very Low	4.41 – 5.30
F	Extremely Low	> 5.30

3.2 Bi-level optimization

The study adopts a bi-level optimization method, minimizing BCI, which means maximizing cyclists' comfort at the upper level while conducting traffic assignment for cars at the lower level. User equilibrium traffic assignment for cars was considered given the existing traffic conditions in Metro Manila.

<u>Upper-level: Maximize BCI Improvement</u>

$$Max\ Z = \sum_{a \in A1}(BCI_{0,a} - BCI_{1,a}) \cdot l_a \quad (2)$$

$$BCI_a = 3.67 - 0.966\emptyset_a - 0.41BLW_a - 0.498CLW_a + 0.002CLV_a + 0.0004OLV_a + 0.022SPD_a + 0.506PKG_a - 0.264AREA_a + AF_a \quad (3)$$

Subject to:

$$\sum_{a \in A1} l_a(\sum_{a \in A1} e_a \emptyset_a) \leq bdg \quad (4)$$

$$\varphi_a = 0 \; or \; 1,\ \forall a \in A \quad (5)$$

$G[A_1]$ is connected

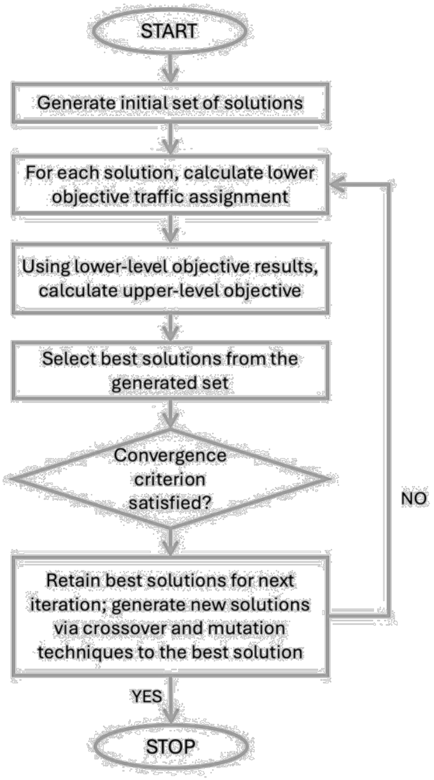

Figure-1: Genetic algorithm flowchart for this research

<u>Lower-level: Traffic Assignment for Cars</u>

$$min\, Y = \sum_{a \in A} \int_0^{x_a} t_a(x)dx \quad (6)$$

Subject to:

$$\sum_k f_k^{rs} = q_{rs}, \ \forall\, r, s \quad (7)$$

$$f_k^{rs} \geq 0, \ \forall\, k, r, s \quad (8)$$

$$x_a = \sum_{rs} \sum_k f_k^{rs}\, \delta_{k,a}^{rs}, \ \forall (i, j) \in A \quad (9)$$

Prioritizing cycling comfort is essential when building bike lanes on selected routes within a network. This approach, which has not been fully explored in previous studies, aims to promote cycling and encourage greater adoption of cycling as a mode of transportation.

3.3 Genetic Algorithm

To solve for the formulated problem, genetic algorithm is employed. This solution algorithm generates an initial set of solutions used to obtain values of the objective functions in the lower and upper levels. Solutions with the optimal value of the objective function will be selected and will undergo crossover and mutation techniques that will generate offspring solutions which are more likely to improve the values of the objective function. This cycle continues until the convergence criterion is satisfied, which will then identify the most optimal solution in this framework[12]. Flowchart of how genetic algorithm works is shown in Figure-1.

4. Application

4.1 Study area – Pasig City

This research is applied to Pasig City, one of the 17 local government units in Metro Manila. The city has been considered one of the frontrunners in promoting cycling and building cycling facilities and infrastructures in earlier and recent years. The city's institutional capacity and commitment to enhancing active transport make it an ideal area for this research. As of 2022, Pasig City has a 57.5 km bike lane network primarily in

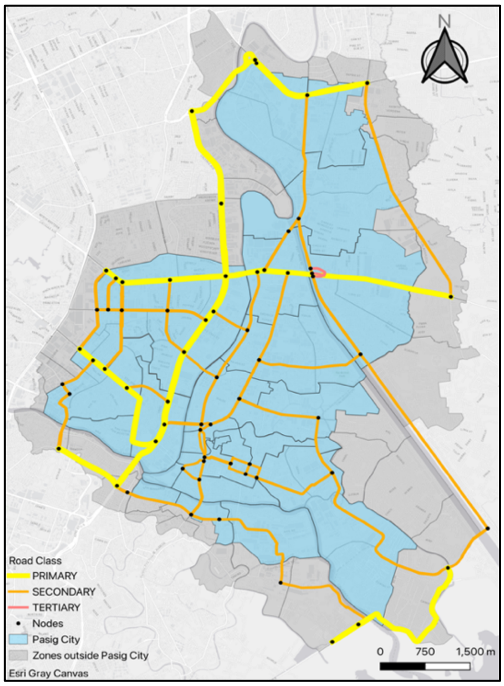

Figure-2: Classes of roads in the network considered in the optimization process the central business district, extending through collector roads to suburban areas. 18.8 km of said network has physically-separated (protected) bike lanes.

4.2 Inputs to the network

Applying the model in the study area aims to: (1) build a bike network where no bike lanes are existing and, (2) provide insights on which road segments can be added into the existing network. Inputs to the study area (shown in Figure-2) include primary, secondary, and some tertiary roads, whose information were derived from existing reports for Metro Manila, Google Maps, OpenStreetMap, and TomTom Move Portal's O-D analysis. These data were used in the traffic assignment level of the model.

4.3 Road space reallocation

One of the road diet solutions being implemented in urban areas of the Philippines involves lane width reduction, as shown in Figure-3, with a cross-section illustrated in Figure-4. This was adopted in this study, with assumed lane widths in all roads measuring 3.35m. With this setup, lane width reduction, which adopted width requirements from NACTO[13] and Japan's Ministry of Land, Infrastructure, Transport and Tourism (MLIT)[14], applies only to roads with two or more lanes, as shown in Table-2.

Table-2: Redesigned roads with baseline widths of 3.35m

No. of lanes	W_{road}	BLW_1	CLW_1
2	6.70	1.20	2.75
3	10.05	1.80	2.75
4	13.40	1.80	2.90
5	16.75	2.25	2.90

5. Results

5.1 Results of the model in the study area (assuming no bike lanes exist)

Incorporating all mentioned processes into the optimization model, and assuming no existing bike lanes in the network as an initial state, the resulting bike network, shown in

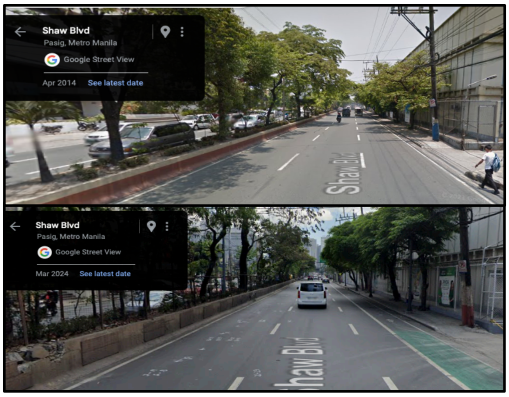

Figure-3: Cross section for lane width reduction as the proposed road diet solution

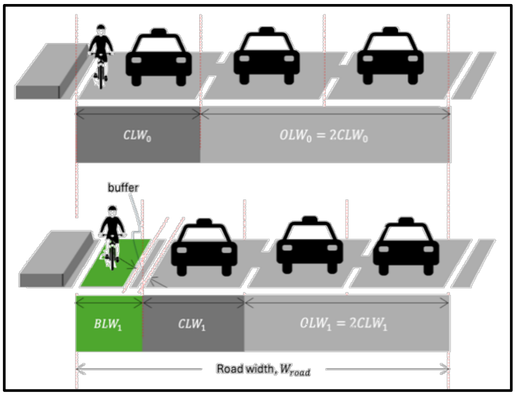

Figure-4: Lane width reduction applied to a road in Pasig City

Figure-5, was obtained. The selected links showed improved cycling comfort levels from LOS F to LOS D as indicated in Table-3. Roads are selected for bike lanes if there's potential to reduce traffic volume. Roads without bike lanes near the solution show increased traffic volume, particularly in red links. Roads with bike lanes have also reduced speeds. This finding is consistent with existing studies showing the impacts of building bike lanes on motor vehicle traffic[15),16)]. Moreover, the presence of a critical link in the solution weakens network connectivity, as its removal violates the connectivity constraint.

From the perspective of transport planners and authorities, adjusting the budget limits in the model can be taken advantage to determine which links should be prioritized to immediately improve cycling comfort.

Table-3: Descriptive statistics of BCI values in roads with bike lanes

	w/o BL	with BL
Minimum	3.12	1.85
1st Quartile	4.45	2.57
Median	5.51	3.34
Mean	6.00	3.52
3rd Quartile	6.97	4.17
Maximum	11.89	6.68
Std. Deviation	2.29	1.23

5.2 Redesigned roads in the existing network

Finally, the proposed road diet solutions were applied to the existing bike network. A field survey was conducted and showed that many roads did not meet the minimum BLW and CLW requirements. The proposed road diet solutions addressed this issue. In addition, the model was applied to the existing network, revealing added new roads with bike lanes in green links as illustrated in Figure-6. Said links have improved cycling comfort levels from LOS F to LOS D as shown in Table-4.

Table-4: Descriptive statistics of BCI values in roads with newly added bike lanes in the network

	w/o BL	with BL
Minimum	3.29	1.96
1st Quartile	3.53	2.35
Median	3.95	2.62
Mean	4.16	2.82
3rd Quartile	4.37	3.10
Maximum	7.00	5.20
Std. Deviation	0.87	0.76

6. Conclusion

This research applied the model to Pasig City, enhancing cycling comfort levels. Traffic volume parameters between the lower and upper levels of optimization significantly impact the selection of roads for bike lanes. Roads with bike lanes show reduced speeds compared to when they had no bike lanes. Additionally, budget constraints can help transport planners/authorities plan their bike network according to their timelines.

While conducting this study, a few limitations were encountered. First, the BCI tool, even though widely accepted, was not

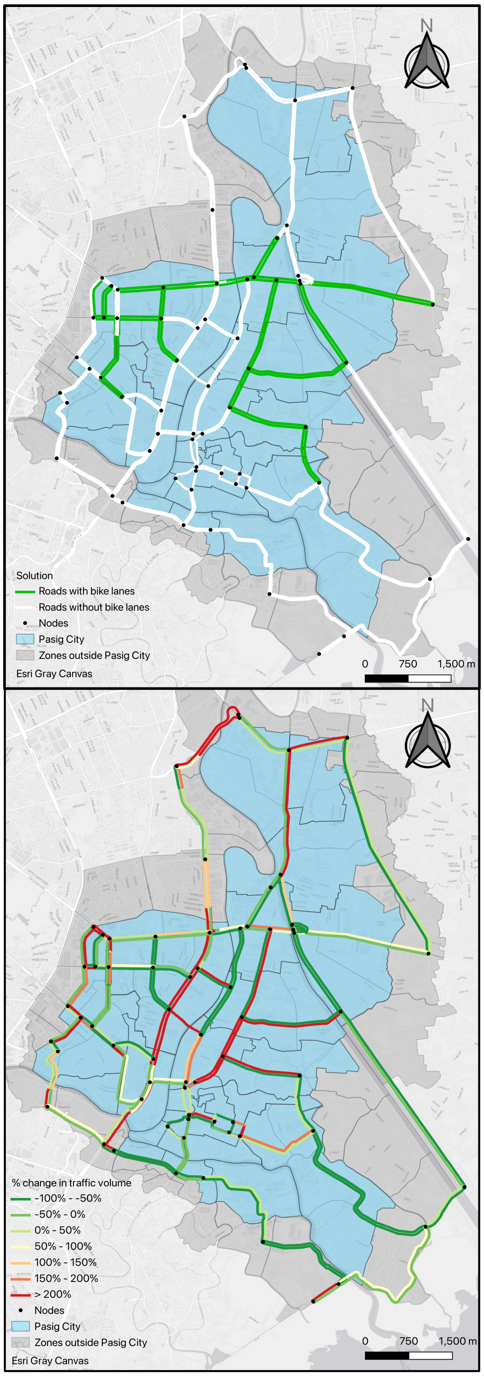

Figure-5: Optimized network given a budget limit of 40km (top) and the corresponding changes in traffic volume before and after bike lanes are introduced in the network (bottom)

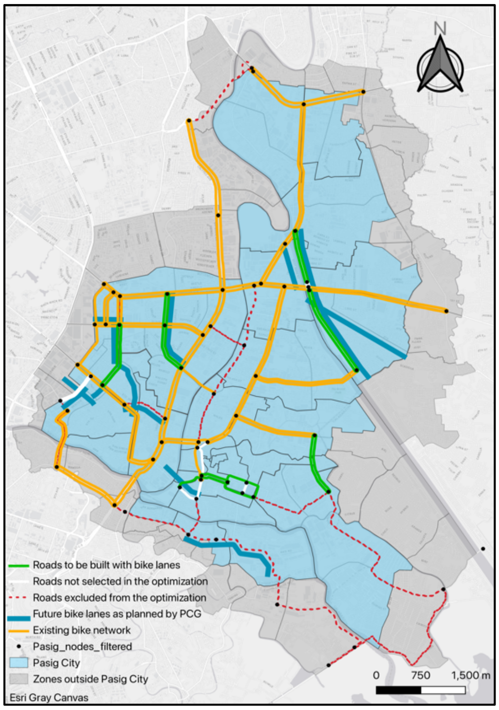

Figure-6: Comparison between the optimization solution and plans of the city for its expanded bike network

locally calibrated due to time constraints. Secondary sources underestimated O-D travel demand on congested roads. While there is a connectivity constraint, it only checked link connectedness. Tertiary roads were also excluded from bike lane construction, based on the input from an officer in the Department of Transportation; however, the city government plans of building bike lanes in selected tertiary roads in the network (shown in blue links in Figure-6). Finally, cyclist demand, which was attempted to be incorporated in the model, was not considered due to a lack of O-D data. This research recommends addressing these limitations to improve results in future relevant studies.

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