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Optimization of Trunk Public Transport Routes in Guadalajara

Rafael Aldo Hernández Luna

[1] University Center of Exact Sciences and Engineering (CUCEI),
[2] University of Guadalajara, Guadalajara, Mexico
`Project Report - Intelligent Systems`

Abstract. This report presents the development of an intelligent system for the optimization of urban bus routes using genetic algorithms and graph theory. The problem is addressed by modeling the city as a network of nodes and edges, seeking to minimize a hybrid cost function that weighs both the service provider's operational costs and the users' travel time. A simulation was implemented using a passenger demand matrix, identifying **hotspots** or high-traffic points. The results demonstrate the algorithm's capability to generate routes that reduce passenger time, although the complexities of implementation in a real urban environment due to legal and zoning factors are highlighted.

Keywords: Genetic Algorithms · Route Optimization · Public Transport · Graph Theory · Guadalajara.

1 Introduction

Public transportation systems serve as the backbone of sustainable urban development, facilitating economic growth and social equity by providing essential mobility to the population. As cities expand, the challenge of maintaining an efficient, accessible, and sustainable transport network becomes increasingly complex. Global studies emphasize that effective public transport must not only reduce reliance on private vehicles to lower emissions but also ensure equitable access to opportunities for all socioeconomic groups [1]. However, in many developing metropolitan areas, these systems struggle to meet the dual goals of sustainability and efficiency. Reviews of sustainable transportation concepts highlight that despite the clear environmental and social benefits of public transit, the practical implementation often faces significant hurdles related to planning, funding, and adapting to rapid urban sprawl [1].

In the context of Mexico, and specifically the Guadalajara Metropolitan Area (GMA), these challenges are acute. The public transport system, including the main bus lines and the SITEUR (Sistema de Tren Eléctrico Urbano) network, plays a critical role in the daily lives of millions. However, recent analyses indicate that the current infrastructure is often insufficient to cover the "transport social needs" of the population effectively. For instance, studies targeting Sustainable Development Goal 11.2 in Guadalajara have found that approximately 50.3%

of inhabitants reside in areas with very high social transport needs, yet the coverage remains uneven [2]. Furthermore, historical reviews of public transport in Guadalajara from 1960 to 2020 reveal that the system's efficiency has been hampered by issues related to ownership structure, fare policies, and a lack of focus on social justice in route planning [3]. The result is a system often characterized by slow transportation times, poor accessibility, and insufficient coverage, which directly diminishes the quality of life for a significant percentage of inhabitants [3].

Existing literature has extensively documented the sustainability deficits [1] and social exclusion caused by the current transport layout in Guadalajara [2][3], there is a lack of research focusing on the dynamic and data-driven optimization of these specific routes that this research aims to tackle. The primary objective is to utilize bio-inspired optimization algorithms and graph theory to simulate the passenger flow (affluence) through the city's transport network. By modeling the city as a graph where nodes represent stops and edges represent routes, this research aims to determine if the current network configuration is fit to cover the mobility demand and to demonstrate how rearranging routes can improve efficiency, accessibility, and ultimately, the quality of life for users.

2 Methodology

2.1 Network Modeling and Representation

To model the complex street network of the Guadalajara Metropolitan Area, this study utilizes graph theory, specifically representing the city as a Weighted Directed Multigraph. The foundational graph was extracted from real-world OpenStreetMap (OSM) data. In this model, nodes represent street intersections or specific locations (such as transit stops), while directed edges represent the navigable street segments connecting them.

A critical component of this network is the assignment of weights to the edges, which symbolize the travel time (impedance) required to traverse a segment. Travel time is calculated as a function of the street segment length and an estimated traversal speed. To better reflect real-world urban dynamics, a dynamic traffic noise multiplier was introduced to the edge weights, simulating variable congestion patterns across the network.

Simultaneously, passenger affluence is modeled using a demand matrix. This matrix maps the origin-destination (O-D) flow of passengers across the network. To represent urban focal points—such as commercial centers, universities, and historical districts—specific high-traffic nodes were designated as "hotspots". The demand matrix artificially inflates the passenger volume traveling to and from these hotspots, providing a realistic baseline of public transport demand.

2.2 Cost Function Formulation

In order to assess alternative public bus routes that enhance time efficiency and accessibility, a compound cost function was formulated. This function evaluates both the operational expenses of the transit provider and the travel time incurred by users traversing from various origins (A) to destinations (B) within the multigraph. The objective function J is defined to be minimized:

$$J = (C_{operator} \cdot \beta) + (C_{user} \cdot \alpha)$$

The operator cost ($C_{operator}$) is determined by the total temporal duration of the proposed routes and an associated operational expense rate (e.g., maintenance, fuel, and wages). It is approximated as:

$$C_{operator} \approx \text{Route Duration} \times \text{Cost per minute}$$

Conversely, the user cost (C_{user}) quantifies the total time investment of the passengers. It is calculated by aggregating the travel time of all passengers across their respective route segments:

$$C_{user} = \sum(\text{Passengers in segment} \times \text{Travel time})$$

The parameters α and β serve as scaling factors to steer the algorithm's optimization tendency:

- Prioritizing β: Favors shorter routes with lower operational costs, potentially at the expense of network coverage.

- Prioritizing α: Favors longer, more comprehensive routes that provide high coverage and reduce user travel time.

The computational evaluation of this fitness function requires calculating the shortest paths for all passengers using the proposed transit network. Below is the pseudo-code illustrating the evaluation process:

2.3 Cost Function

2.4 Simulation Parameters

To ensure a faithful representation of the metropolitan area's reality, the following parameters were used:

Table 1. System Parameters

Parameter	Value / Description
Walking Speed	5 km/h
Bus Speed	23 km/h (Average per MIDE Jalisco)
Time Multiplier	$T_{bus} = T_{walking}/T_{bus\_speed}$
Base Operation Cost	1 unit/minute
Existing Trunk Routes	21 (Reference)
Generations	50
Routes in Simulation	10

Algorithm 1 Compound Cost Function Evaluation

Require: Candidate routes (R), City Graph (G), Passenger Demand Matrix (D), Hotspots (H)
Ensure: Total Cost (J)

```
OperatorCost ← 0
UserCost ← 0
TransitGraph ← Copy(G)
// Step 1: Calculate Operator Cost & Update Transit Graph
for all route in R do
    for all segment (u, v) in route do
        TravelTime ← GetEdgeWeight(G, u, v)
        OperatorCost ← OperatorCost + (TravelTime × BusSpeedMultiplier) × CostPerMinute
        UpdateEdgeWeight(TransitGraph, u, v, TravelTime × BusSpeedMultiplier)
    end for
end for
// Step 2: Calculate User Cost via Shortest Paths
for all source in H do
    if source has departing passengers in D then
        ShortestPaths ← Dijkstra(TransitGraph, source)
        for all destination, passenger_count in D[source] do
            if destination is reachable in ShortestPaths then
                UserCost ← UserCost + (passenger_count × ShortestPaths[destination])
            else
                UserCost ← UserCost + (passenger_count × UnservedPenalty)
            end if
        end for
    end if
end for
// Step 3: Apply Tendency Parameters
J ← (OperatorCost × β) + (UserCost × α)
return J
```

3 Results

The simulation was executed on a graph representing an approximation of the city (due to the computational complexity of processing the full network with OSMnx).

3.1 Algorithm Evolution

The behavior of the algorithm across generations is shown below.

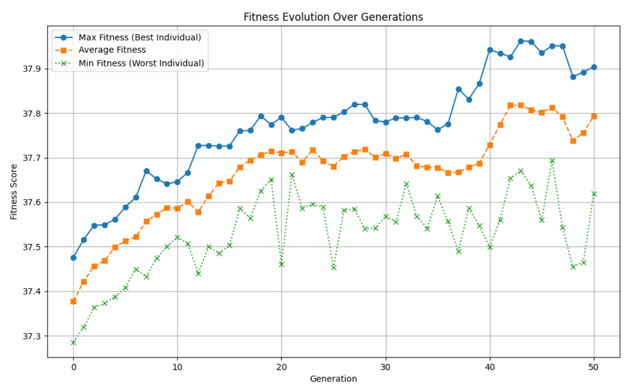

Fig. 1. Fitness Evolution over 50 generations. An improvement in the cost function is observed, stabilizing near generation 43.

The algorithm demonstrated convergence capability. In generation 43, a *Current Fitness* above 37.9 was reached, after which a plateau in fitness values can be seen, indicating that the genetic algorithm successfully explored the non-differentiable search space.

3.2 Route Visualization

The resulting routes showed an interesting tendency to overlap with existing infrastructure lines (Light Rail and Macrobús).

4 Conclusions

The genetic algorithm proves to function adequately in finding routes that minimize time costs for passengers. However, transitioning this theoretical model to a real urban development presents additional challenges that cannot be ignored. Although mathematically optimal under the current cost function, the viability of these routes cannot be ensured without considering:

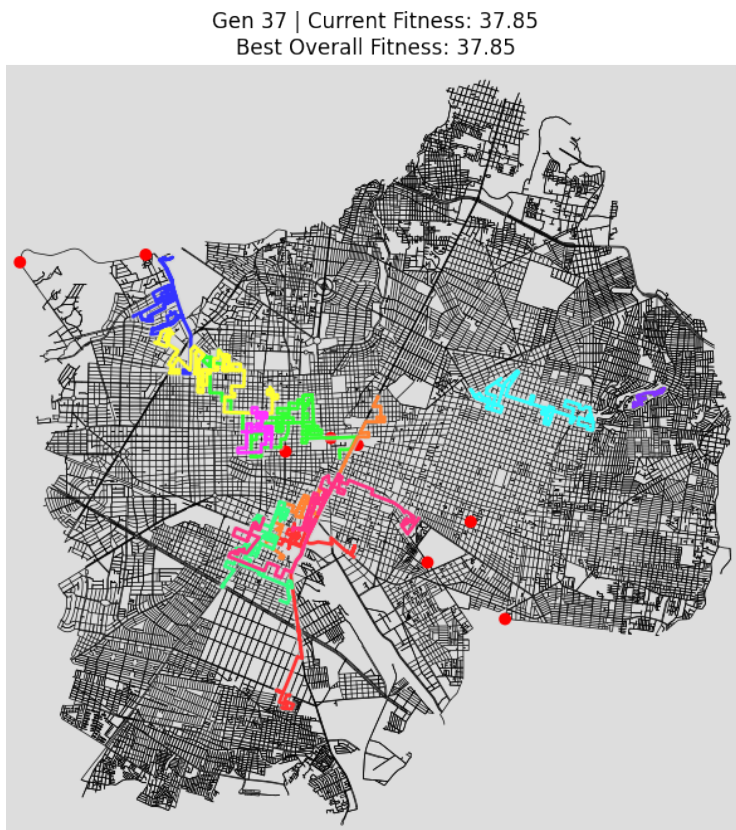

Fig. 2. Visualization of the 10 optimized routes on the city graph.

1. **Legal and Traffic Framework:** Turn restrictions, street directions, and public transport regulations.
2. **Zoning:** The distribution of commercial versus residential zones affects peak hours, something a static demand matrix does not fully capture.
3. **Population Density:** Factors specific to Guadalajara that would add greater complexity to modeling edge weights.

As future work, it is proposed to revisit the objective function to optimize the processing of full graphs using tools like OSMnx and to refine edge weights with real-time traffic data.

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