Optimal Place for New Bus Stop in Columbus, Ohio

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1. Introduction/Motivation

Public transportation accessibility is a cornerstone of equitable urban development, ensuring residents can reach jobs, education, and essential services. In Franklin County, the recent passage of Issue 47 provides the Central Ohio Transit Authority (COTA) with a significant influx of tax dollars to address long standing challenges in service and infrastructure. This creates a critical opportunity to strategically improve public transportation by identifying underserved neighborhoods and maximizing the impact of new developments.

Columbus, as a growing metropolitan area, faces increasing demands for efficient and accessible transit. However, gaps remain in the current bus stop network. Our goal is to leverage this unique moment of financial support to develop a data-driven approach for optimizing new bus stop placements. By balancing current stop placement, population coverage and cost, this project seeks to ensure that the additional resources from Issue 47 are used effectively to enhance accessibility and equity for all residents.

2. Problem Statement

The placement of new bus stops in Columbus presents a significant challenge in addressing the needs of underserved neighborhoods while adhering to budgetary limitations. The decision-making process must balance some critical objectives: maximizing population coverage, minimizing placement redundancy, and ensuring cost-effectiveness.

Key considerations include identifying neighborhoods that are underserved based on current bus stop locations and population density, and determining how to prioritize high-density, high-need areas within the constraints of a fixed budget. An effective solution must strategically allocate resources to enhance public transportation accessibility and equity across Columbus.

3. Objective

To address the challenge of optimizing public transportation accessibility in Columbus, we propose developing a Mixed-Integer Linear Programming – Facility Location Problem — model that strategically determines the placement of new bus stops. The model aims to maximize weighted efficiency by prioritizing locations based on the population served per dollar spent, while accounting for the number of existing stops in each area. By incorporating population density, implementation costs, and existing infrastructure, the model will identify neighborhoods that offer the highest impact for new bus stops. Additionally, it will adhere to a defined budget constraint, ensuring solutions are both effective and financially viable in a real-world context.

4. Data Collection and Sources

Data Used:

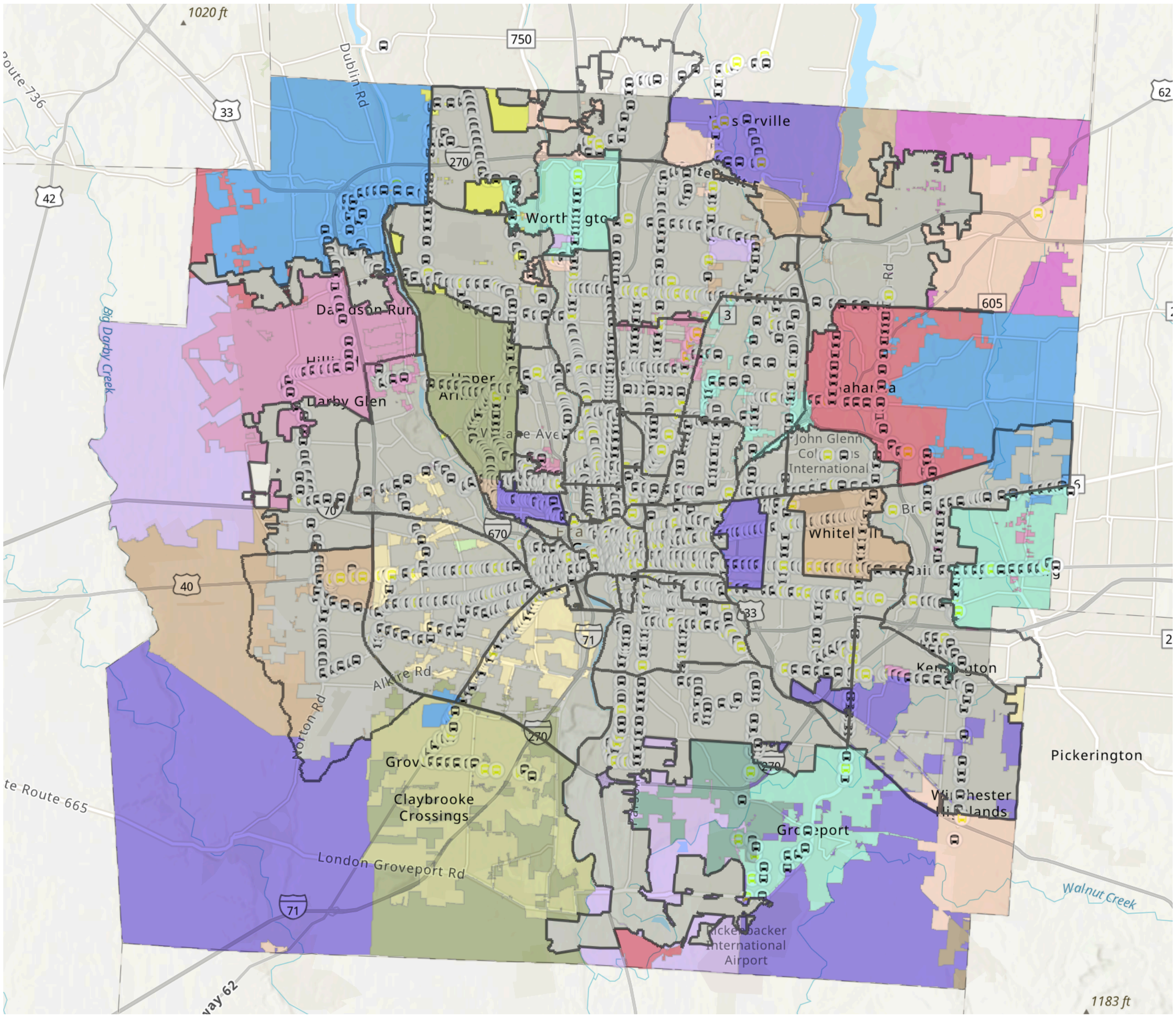
Current Bus Stops:
Source: COTA GIS Open Data Portal
Variables: Stop ID, Location, Onboardings/Alightings, Lines Served, Jurisdiction

Population Densities:
Source: City of Columbus Department of Development for neighborhoods within Columbus, Census Reporter for other Franklin County municipalities

Budget Information:
Transit Stop Improvement Program: Allocated $250,000 for new developments in 2024.
Estimated stop costs: $15,000–$20,000 per stop; urban stops cost 30–50% more.

Combined Excel file with neighborhoods, corresponding densities, and amount of stops

To collect the number of stops in each area, we used ArcGIS to overlay a map of all bus stops in the COTA network on the neighborhoods of Columbus and municipalities of Franklin County, and used the "Summarize Within" tool to count the stops in each subdivision. Here is the link to this ArcGIS project.



5. Decision Variables/Formulation:

Decision Variables:

- x_i: Binary variable (1 if a stop is placed at location i, 0 otherwise).

Objective Function:

$$Max\ Z = \frac{P_i}{C_i(S_i+1)} \times x_i$$

P_i: Population density at location i

C_i: Cost of placing a stop at i (Base Cost + Scaling Factor × P_i)

S_i: Number of existing stops near i

Constraints:

1. **Single Stop Constraint**: $x_i \leq 1$
2. **Budget Constraint**: $\sum_i C_i \times x_i \leq Budget$
3. **Population Density Threshold**: $P_i \geq P_{min}, \forall i$
4. **Min and Max Stops:** $3 \leq \sum_i x_i \leq 5$

6. Assumptions

- All stops have similar construction requirements, with costs varying only by population density
- Budget constraints are strictly enforced
- Existing stops near a location decrease the priority for a new stop
- Population figures from 2021 are sufficient enough for analysis
- The boundaries of the neighborhoods and Franklin County municipalities have not significantly shifted since 2022 (the year the data is sourced from)
- Density in each area is uniformly distributed throughout it (that is, there aren't parts of a neighborhood with a much higher concentration of people than others)
- Existing bus stops in the data set from COTA Open GIS are accurately placed and operational
- We are able to connect these optimal new stops to existing bus routes in the COTA system
- Bus stop usage patterns don't significantly affect the outcome of where the new stops should be
- Future population growth in the Columbus metropolitan area has little bearing on where the new stops should be (we want to serve people *today*)
- There is significant enough demand in each of these underserved areas to warrant building bus stops there

7. **Code:**

```
import pandas as pd
import numpy as np
import cvxpy as cp

# Load the dataset from a CSV or Excel file
file_path = r"C:\Users\arjun\Downloads\final_cota_stop_density_counts.csv"
df = pd.read_csv(file_path)
```

```
# Extract relevant data from the dataframe
places = df['neighborhood'].tolist()
population_density = df['density'].values  # Population density
nearby_stops = df['stop_count'].values  # Existing bus stops

# Define base cost, budget, and scaling factor
base_cost = 15000  # Base cost per stop
scaling_factor = 10  # Cost increases by $10 per unit of density
budget = 250000  # Total budget

# Compute costs based on population density with a gradual scaling factor
cost = base_cost + scaling_factor * population_density

# Define the max and min number of stops
max_stops = 5  # Maximum number of stops to place
min_stops = 3  # Minimum number of stops to place

# Decision variable: x[i] = 1 if a bus stop is placed at location i
num_locations = len(places)
x = cp.Variable(num_locations, boolean=True)

# Objective: Maximize population served per dollar, weighted by existing
stops
objective = cp.Maximize(cp.sum(population_density / (cost * (nearby_stops +
1)) * x))

# Constraints
constraints = [
    cp.sum(x) <= max_stops,  # Maximum number of stops
    cp.sum(x) >= min_stops,  # Minimum number of stops
    cp.sum(cost * x) <= budget,  # Budget constraint
]

# Add the minimum population density threshold constraint
P_min = 500  # Example threshold for minimum population density
for i in range(num_locations):
    if population_density[i] < P_min:
        constraints.append(x[i] == 0)  # Prevent selection if density is
below threshold

# Solve the problem
problem = cp.Problem(objective, constraints)
```

```python
result = problem.solve(solver=cp.GUROBI)

# Check the solution feasibility and interpret the result
solution = x.value

if solution is not None:  # Check if a solution was found
    selected_places = [places[i] for i, val in enumerate(solution) if val >
0.5]
    print("Optimal Solution Found:")
    for i, val in enumerate(solution):
        print(f"{places[i]}: {'Place Stop' if val > 0.5 else 'No Stop'}")
    print(f"Objective Value (Total Weighted Efficiency): {problem.value}")
    print(f"The best places to add bus stops are: {',
'.join(selected_places)}")
else:
    print("No feasible solution found. Check constraints or budget.")
```

Optimal Solution Found:
Far South: No Stop
Livingston Ave: No Stop
Southwest: No Stop
University District: No Stop
Westland: No Stop
South Linden: No Stop
Milo-Grogan: No Stop
Far East: No Stop
West Scioto: No Stop
Fifth by Northwest: No Stop
Greater Hilltop: No Stop
Near East: No Stop
North Central: No Stop
North Linden: No Stop
Franklinton: No Stop
Northeast: No Stop
Clintonville: No Stop
South East: No Stop
Northland: No Stop
Downtown: No Stop
Italian Village: No Stop
Brewery District: No Stop
German Village: No Stop
Victorian Village: No Stop
Far Northwest: No Stop
Northwest: No Stop
Far North: No Stop

East Columbus: No Stop
Mid East: No Stop
Hayden Run: No Stop
Far West: No Stop
Airport: No Stop
Rocky Fork-Blacklick: No Stop
Olentangy West: No Stop
Harrison West: No Stop
Harmon Road Corridor: No Stop
Wolfe Park: No Stop
Dublin Road Corridor: No Stop
Fort Hayes: No Stop
South Side: No Stop
Blendon Township: No Stop
Brown Township: No Stop
Clinton Township: No Stop
Franklin Township: No Stop
Hamilton Township: No Stop
Jefferson Township: No Stop
Perry Township: No Stop
Pleasant Township: No Stop
Prairie Township: No Stop
Bexley: No Stop
Brice: No Stop
Canal Winchester: No Stop
Dublin: No Stop
Gahanna: No Stop
Grandview Heights: No Stop
Grove City: No Stop
Groveport: No Stop
Harrisburg: Place Stop
Hilliard: No Stop
Lithopolis: No Stop
Lockbourne: No Stop
Marble Cliff: No Stop
Minerva Park: Place Stop
New Albany: No Stop
Obetz: No Stop
Pickerington: Place Stop
Reynoldsburg: No Stop
Riverlea: Place Stop
Upper Arlington: No Stop
Urbancrest: No Stop
Valleyview: Place Stop
Westerville: No Stop
Whitehall: No Stop
Worthington: No Stop
Objective Value (Total Weighted Efficiency): 0.33038391508194653
The best places to add bus stops are: Harrisburg, Minerva Park, Pickerington, Riverlea, Valleyview

8. Post-Optimality Analysis

Limitations:

- Model does not account for future growth in population density.
- Simplistic assumptions about costs being linearly related to density without considering external factors like land availability or traffic infrastructure.
- Model doesn't take into account the need for bus stops versus car/bike usage

Potential extensions:

- Consider multiple stops at each location instead of a single stop.
- Incorporate additional factors like traffic flow, specific location, land-availability
- Possibly have alternative objectives, possibly focusing on minimizing costs or reducing disparities for underserved neighborhoods

9. Appendix

Github: https://github.com/arjunnarang24/ISE-3230-Project.git

YouTube: https://www.youtube.com/watch?v=gtFzXrgH_e4

Team Contributions:

- Arjun: MILP Problem Formulation, Report Writing, Constraint Formulation, Powerpoint

- Tate: Proposal Idea, ArcGIS Data Collection, Assumptions, Coding, Constraint Formulation

- Adi: Budget Data Collection and Market Research, Coding, Constraint Formulation, Report Writing