

Better Traffic, Better City

Summary

For Requirement 1, this paper analyzes the impact of the Francis Scott Key Bridge collapse on Baltimore's transportation system. Using a directed graph based on the city's nodes and routes, and applying the **random walk algorithm** with 10,000 simulations, the expected connectivity value rises slightly from **207.79** (post-collapse) to **208.22** (post-reconstruction), showing a minor improvement in overall network connectivity and an increase in key traffic hubs. Next, the paper simulates random disturbances to assess the collapse's effect on transportation stability. The expected connectivity decreases by **2.1%** (from 207.79 to 203.5) after the collapse, while the decrease is only **0.99%** (from 208.22 to 206.81) after reconstruction, indicating a significant role in maintaining network stability. **Monte Carlo simulations** further reveal that the collapse increases traffic pressure on other roads by about **0.8%**, with greater pressure on surrounding roads if the area is narrowed. Based on these models, the paper also explores the impact of the collapse on various stakeholders.

For Requirement 2, This research focuses on Baltimore's public transit system. Using data on bus networks, population density, and traffic conditions, we define a study area in downtown Baltimore to create a **Population-Bus Match Index** and **Population-Congestion Match Index**, assessing the spatial alignment of supply and demand, and utilization and saturation in the bus network. We identify 67 key bus stops in the area that may face significant challenges and where residents have strong incentives to use buses. Based on these findings, we propose a regional customized bus project to address resource allocation issues and optimize bus capacity. We estimate a **31.54%** overall optimization rate, increasing regional bus capacity by **144,747** people. Finally, we evaluate the project's impact on Baltimore's shipping industry and various stakeholders, including residents, commuters, and tourists, with customized buses having a positive overall effect.

For Requirement 3, We recommended a bike-sharing program the one that would best improve the quality of life for residents. Combined with the relevant research data and the analysis of the first and second questions, we summarized the four pain points of the current situation of Baltimore transportation. We recommended the bike-sharing project with the main goal of improving the convenience of residents' life and environmental benefits. Because the environmental benefits are of great benefit to almost all groups, we use the **SWOT** to analyze the impact of the bike-sharing project on residents, stakeholders, other transportation needs and people's lives. The bike-sharing program in our case successfully increases the commuting efficiency by **62%**.

Keywords: Random Walk Algorithm, Monte Carlo Simulations, Spatial Matching Patterns, SWOT Analyze

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1 Introduction

1.1 Background

Recently, with the support of state funds, cities across the United States have developed infrastructure plans aimed at reconnecting cities and revitalizing industries. The city of Baltimore is facing aging transportation infrastructure and limited transportation options that affect residents' daily lives and constrain economic growth. This highlights the importance of evaluating the city's existing transport network as well as developing optimization projects.

1.2 Our work

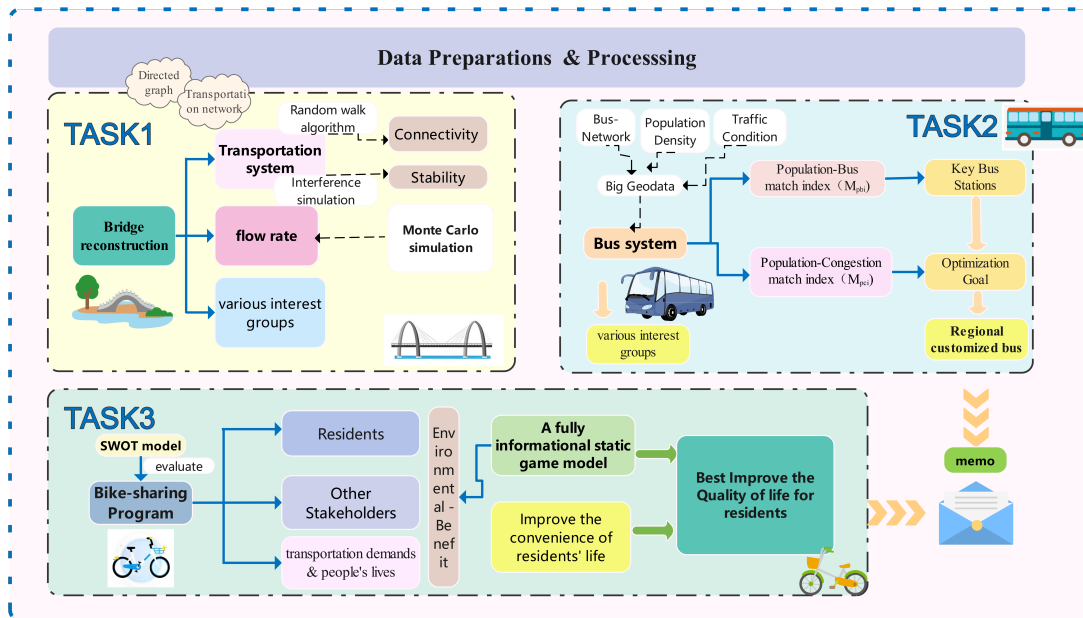


Figure 1: Our Work

In the first part, a directed graph is constructed based on the city's accessible nodes and routes. Using the random walk algorithm, connectivity calculations are performed with and without the bridge to illustrate the traffic system's connectivity in both cases. Then, disturbance simulations are applied to the directed graph, and the connectivity is recalculated to represent the impact on the stability of the transportation system with and without the bridge. Next, based on traffic flow data, the traffic flow index is calculated. Using Monte Carlo simulations, the impact of the bridge on traffic flow is evaluated.

In the next section, the bus network, population density, and traffic conditions of

Baltimore are analyzed. A Population-Bus Match Index and a Population-Congestion Match Index are constructed to assess the supply and demand, and the saturation of the downtown bus system. To address the issue of supply-demand mismatch, a regional customized bus project is introduced, aiming to have a positive impact on the shipping industry in Baltimore and on various stakeholders.

Based on the models from the previous two sections, the final section focuses on improving commuting efficiency and environmental benefits for residents. We recommend a bike-sharing program that best improves the quality of life for residents. The impact of the bike-sharing project on stakeholders, other transportation needs, and people's lives is analyzed in detail using the SWOT model. Combined with data, it is concluded that under ideal conditions, bike-sharing can increase commuting efficiency in the Baltimore area by 62%.

2 Assumption and Justification

Assumption

1. Random walk and community detection methods assume that each node and connection in the network is independent in terms of computation, neglecting the potential complexity of traffic patterns, such as traffic light control, fluctuations in flow, and intersection bottlenecks.
2. Multiple simulations are conducted, and the connectivity changes of the network are recorded after each disturbance. It is assumed that, through repeated simulations, the statistical characteristics of the network under various disturbance conditions, such as the distribution of reachable nodes, can be obtained.
3. In urban bus networks, there exists a significant mismatch between supply and demand, particularly during peak demand periods, where the capacity of the buses does not match the population flow.

Justification

1. The random walk and community detection methods assume that each node and connection in the network are independent in terms of computation, ignoring potential complex traffic patterns, such as traffic light control, flow fluctuations, and intersection bottlenecks.
2. Multiple simulations are conducted, and the connectivity changes of the network are recorded after each disturbance. It is assumed that, through repeated simulations, the statistical characteristics of the network under different disturbance conditions, such as the distribution of reachable nodes, can be obtained.

3. In urban bus networks, there is a significant mismatch between supply and demand, especially during peak demand periods, where the bus capacity does not align well with the population flow.

3 Notation

Symbol	Description
V	Set of traffic network nodes
E	Set of traffic network edges
V'	Set of nodes after disruption
E'	Set of edges after disruption
$N(v_i)$	Set of neighboring nodes of node v_i
$C(v_i)$	Connected component formed by node v_i
W_{sum}	Total weighted traffic flow
W_{total}	Total weight
T_{index}	Traffic flow index
T'_{index}	Simulated traffic flow index
I	Change in traffic flow index
b	Bus capacity
l	Number of bus routes
r	Rated bus capacity
f	Frequency of departure
s	Total number of systems
T	Rush hour
m	Number of route stops
p	Population flow at stations
c	Congestion at stations
M_{pbi}	Population-Bus Match Index
M_{pci}	Population-Congestion Match Index

4 Impact of the Collapse of the Francis Scott Key Bridge

4.1 Impact of Traffic Systems Based on Random Walk Algorithm

4.1.1 Random Walk Algorithm Construction

The random walk algorithm is an effective and reasonable method, especially suitable for large-scale and complex transportation networks. In urban transportation networks, understanding the connectivity between nodes is key to analyzing traffic flow,

assessing network efficiency, and making transportation management decisions. Therefore, in this paper, we use the random walk algorithm to construct a model for calculating traffic connectivity.

(1) **Graph Loading** First, the points and their coordinates in `nodes_drive.csv` are loaded as the nodes of the graph. The data in `edges_drive.csv` is loaded as the edges of the graph. Using this data, a directed graph is constructed, which is treated as a transportation network. The random walk algorithm is then applied to this transportation network.

(2) **Algorithm** For the random walk algorithm, we start with a graph $G = (V, E)$. First, we select an initial node, starting from a node $v_0 \in V$. This node v_0 can be any intersection or road endpoint in the transportation network. Then, we randomly select a neighboring node. Suppose we are at node v_i , and we select an adjacent node v_j as the next step. The probability of walking to node v_j from node v_i is given by:

$$P(v_{i+1} = v_j \mid v_i) = \frac{1}{|N(v_i)|} \quad (1)$$

This process is repeated, where at each step, a node is randomly chosen from the neighboring set of the current node as the next step. The process continues until the predefined number of steps (`num_steps`) is reached or until no further walk can be performed.

4.1.2 Connectivity Calculation and Interference Simulation

(1) **Connectivity Calculation** In a random walk, we record all the visited nodes, which are referred to as the connectivity set. By performing random walks starting from different nodes multiple times, we can obtain the size of the connectivity set for each node.

The expectation is an important statistical measure used to assess the average level of the data distribution. After calculating the size of the connectivity set for each node, we can compute the expected value μ for all nodes, which reflects the connectivity of the transportation system:

$$\mu = \frac{1}{N} \sum_{i=1}^N |C(v_i)| \quad (2)$$

(2) **Interference Simulation** The purpose of interference simulation is to test the impact of node or edge removal on network connectivity, in order to assess the stability of the transportation network. Let the original transportation network be $G = (V, E)$. After removing n nodes, the new graph becomes $G' = (V', E')$. The connectivity is then recalculated for G' . By comparing the interference simulation results before and after the

reconstruction of the Francis Scott Key Bridge, the impact of the bridge on the stability of the transportation network can be estimated.

4.1.3 Impact of the Francis Scott Key Bridge on the Connectivity of the Network

Based on the random walk algorithm, with 1000 steps and 10,000 randomly selected points, we calculated the impact of the Francis Scott Key Bridge on the connectivity of the transportation network. The results are as follows:

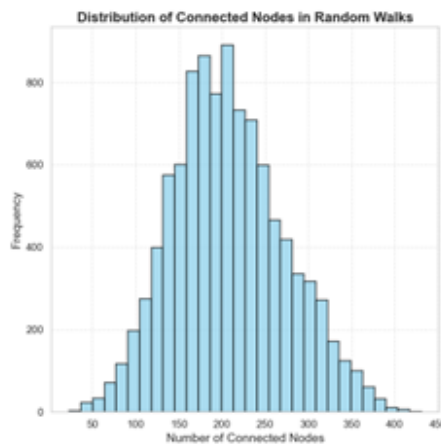


Figure 2: Connectivity Distribution Histogram (Initial State)

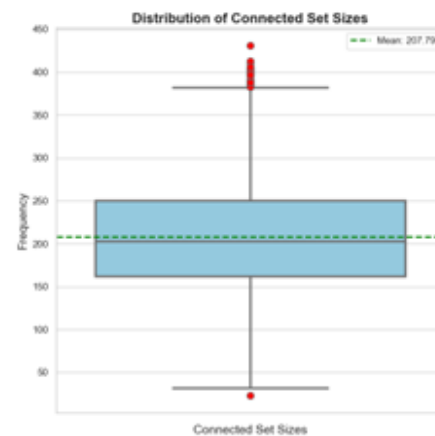


Figure 3: Connectivity Box Plot (Initial State)

According to the algorithm results, when the Francis Scott Key Bridge is collapsed (i.e., no longer in place), the simulation results approximately follow a normal distribution, indicating that the network's structure is relatively uniform. The peak occurs around 200, which means that most nodes have medium connectivity. There are some "hub" nodes whose connectivity is significantly higher than most other nodes. These nodes can connect more nodes and may play a crucial role in the network.

According to the box plot, the median is around 200, meaning that most nodes have a connectivity set size close to 200. The green dashed line in the figure represents the expected value, which is 207.79. The closeness of the mean and median indicates that the data distribution is roughly symmetric, and the overall distribution is not skewed.

In the next simulation of the bridge reconstruction, we simulated the presence of the bridge, connecting the start and end points of the bridge and some surrounding nodes, i.e., the nodes within the circle.

According to the algorithm results, when the Francis Scott Key Bridge is reconstructed, the simulation results again approximately follow a normal distribution, similar to the case when the bridge is collapsed. However, in the box plot, we can observe that the median remains around 200, and the expected value is 208.22. Therefore, the reconstruc-

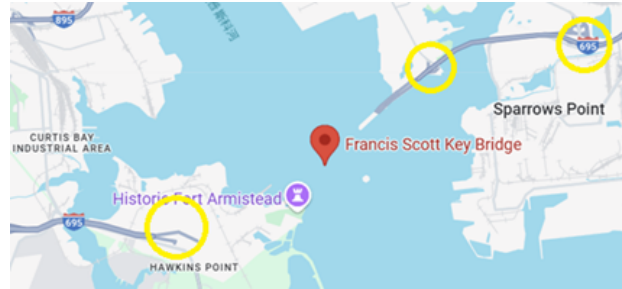


Figure 4: Selected Points in the Simulation of the Bridge Reconstruction

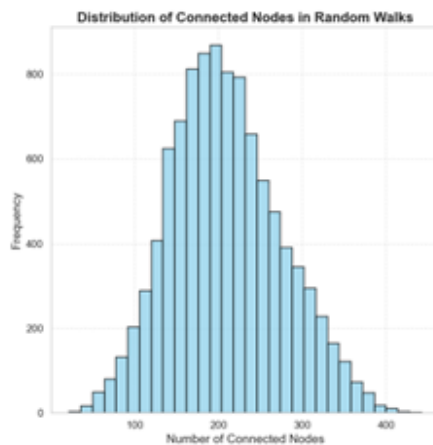


Figure 5: Connectivity Distribution Histogram(After Reconstruction)

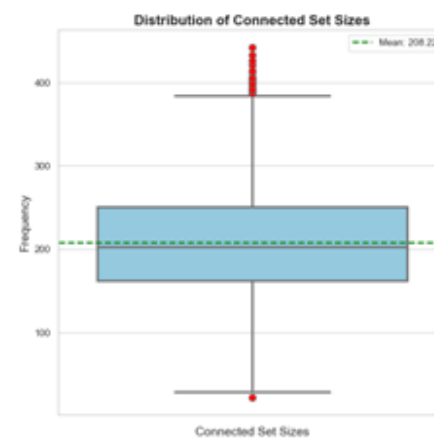


Figure 6: Connectivity Box Plot (After Reconstruction)

tion of the bridge has a slight positive impact on the overall connectivity of Baltimore's transportation network. Additionally, we can observe that after the bridge's reconstruction, the values farther away from the box, represented as red dots in the box plot, have increased. This indicates that the reconstruction of the bridge leads to an increase in the number of core transportation hubs in the city, which has a positive impact on the transportation system.

4.1.4 Impact of the Francis Scott Key Bridge on the Stability of the Network

Through 10,000 iterations of disturbance simulations on the original transportation network, it was observed that the connectivity of most nodes remained concentrated around 200. However, the densest region shifted below 200, showing a slight downward trend compared to the previous random walk results. This shift is mainly due to the influence of random disturbances.

Further analysis of the disturbance simulation results shows that, regardless of whether the Francis Scott Key Bridge exists, the accessibility of the city's transportation network is

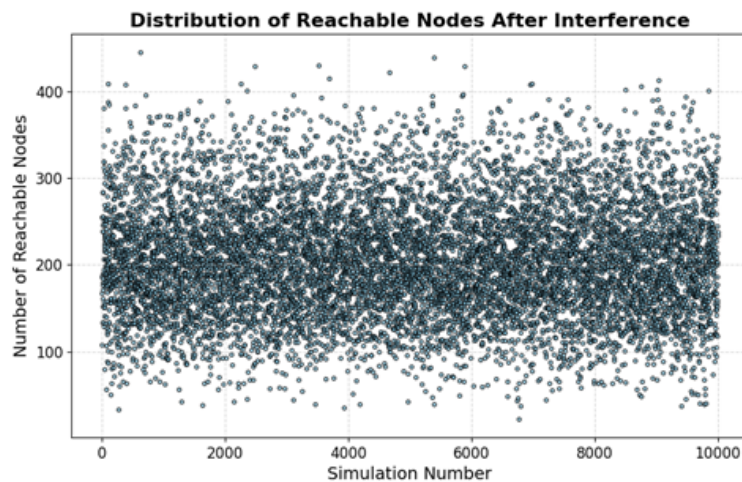


Figure 7: Scatter Plot of Results after Disturbance Simulation

affected. However, a closer comparison reveals that, in the case of the bridge's collapse, the expected connectivity value decreased from 207.79 to 203.5, a decrease of 2.1%. In contrast, when the bridge was reconstructed, the expected connectivity value decreased from 208.22 to 206.81, a decrease of only 0.99%. Therefore, it can be concluded that while the Francis Scott Key Bridge has a limited impact on improving the connectivity of the transportation network, it plays a significant role in the stability of the entire city's transportation network.

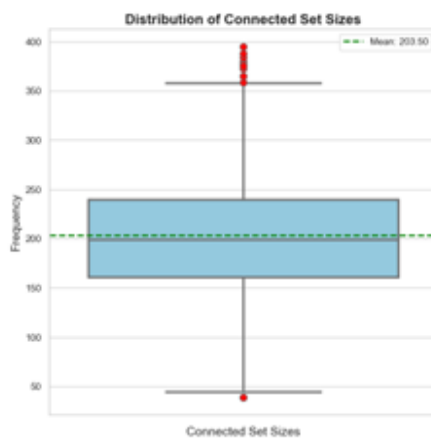


Figure 8: Connectivity Box Plot (After Disturbance)

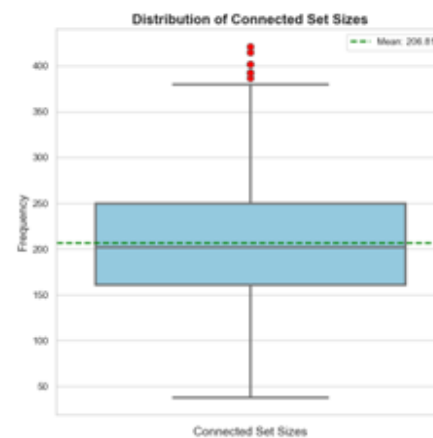


Figure 9: Connectivity Box Plot (After Reconstruction & Disturbance)

4.2 Analysis of Traffic Flow Impact Based on Monte Carlo Simulation

4.2.1 Calculation of Traffic Flow Index

Due to the large number of roads in Baltimore city, it is difficult to identify a representative road for study. Therefore, this study begins with the definition of the traffic flow index, where the weight is derived from the road function and road class. The specific weights are as follows:

Table 2: Road Types and Corresponding Weights for Traffic Flow Index Calculation

Functional Class Code	Road Type	Weight
1	Major Arterial	7
2	Minor Arterial	6
3	Collector	5
4	Local Roads	4
5	Other Principal Arterial	3
6	Secondary Collector	2
7	Local Road / Rural Collector	1

Based on these weights, the total weighted traffic flow for each year is calculated as follows:

$$W_{\text{sum}}(\text{year}) = \sum_i (\text{AADT}_{i,\text{year}} \times \text{Weight}_i) \quad (3)$$

Next, the total weight is calculated, which reflects the importance of all roads in the traffic network:

$$W_{\text{total}} = \sum_i \text{Weight}_i \quad (4)$$

Based on the total weighted flow and total weight, the traffic flow index is calculated as:

$$T_{\text{index}}(\text{year}) = \frac{W_{\text{sum}}(\text{year})}{W_{\text{total}}} \quad (5)$$

The traffic flow index for Baltimore city from 2014 to 2022 is as follows:

Table 3: Annual Traffic Flow Index

Traffic Index	2014	2015	2016	2017	2018	2019	2020	2021	2022
Index	15547	15986	16347	16537	16153	16098	13091	14661	14776

4.2.2 Monte Carlo Simulation

After calculating the traffic flow index, Monte Carlo simulation is used to quantitatively analyze the impact of a specific road on the overall flow index. Monte Carlo simulation is a numerical method based on random sampling, used to evaluate the behavior of complex systems. By randomly deleting roads and recalculating the flow index, the impact of each road's absence on the network flow can be simulated. Through multiple simulations, the average impact of each road's absence on the traffic flow index is obtained, allowing us to analyze which roads have a significant effect on the network flow:

$$I = \sum_i |T_{\text{index}} - T'_{\text{index}}| \quad (6)$$

4.2.3 Impact of Francis Scott Key Bridge on Traffic Flow

In this section, Monte Carlo simulation was conducted 10,000 times, According to the simulation results, the average impact of roads on the traffic flow index is 57.22, with a standard deviation of 116.30. Due to the large standard deviation, it can be concluded that the impact of different roads on traffic flow varies significantly. Therefore, in this study, we calculate the impact of roads on the traffic index based on the road class defined by the Functional Class Code.

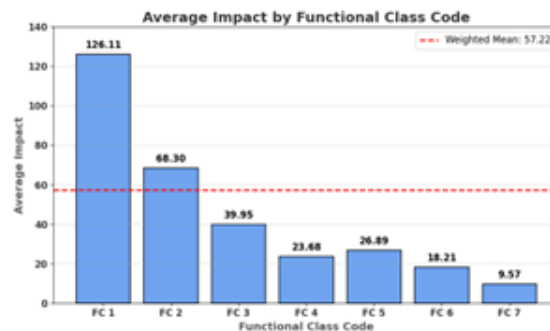


Figure 10: Average Impact of Different Roads on Traffic Flow Index

Based on the results, Major Arterial roads have the largest impact on the traffic flow index in Baltimore city. As the Francis Scott Key Bridge is located on a section of Interstate 695, with a Functional Class Code of 1, it can be concluded that the collapse of the Francis Scott Key Bridge would lead to an approximate 126.11 impact on the city's traffic flow index, or around 0.8%. This can be interpreted as the collapse of the bridge causing about a 0.8% additional pressure on other roads in the city. If the area is narrowed, the pressure on surrounding roads would be even greater.

4.3 Impact on Various Stakeholders

Impact on City Residents: The collapse of the Francis Scott Key Bridge has a limited impact on city residents. Located in the suburbs, the bridge's failure has minimal effects on downtown Baltimore, where most residents' activities occur.

Impact on Merchants: While the collapse would make businesses near the bridge less accessible, alternative routes would see increased traffic and foot traffic, benefiting merchants farther away. However, reduced road connectivity and increased traffic volume could make it harder for businesses requiring frequent shipments, negatively impacting their operations.

Impact on Suburban Residents and Commuters: For suburban residents and commuters, the collapse of the Francis Scott Key Bridge is extremely negative. It has led to an increase in commuting time from 10 minutes to nearly 60 minutes. For residents on both sides of the bridge, this adds an hour to their commute time. Additionally, the collapse has forced residents to use more limited routes, further increasing the traffic pressure and safety risks on alternative routes.

Impact on Tourists: Based on the random walk algorithm and Monte Carlo simulation, the collapse of the Francis Scott Key Bridge has led to a reduction in road connectivity and stability while increasing traffic volume. For tourists, this has a negative impact, as it results in longer travel times between attractions. The increased traffic also detracts from the visitor experience, and the absence of the Francis Scott Key Bridge itself, a noteworthy attraction, also reduces the overall appeal for tourists.

5 Optimizing urban bus network based on spatial matching patterns

5.1 Study area and data

5.1.1 Study on the Public Transportation System of Baltimore City

Following previous research on Baltimore City's transportation system, this section focuses on a small-area and community-level study of its public transportation. As the largest city in Maryland and a key Atlantic port, Baltimore has significant variations in passenger demand across communities. Residential areas may have high population mobility, while commercial zones may experience concentrated demand at specific times. Baltimore faces challenges with aging infrastructure and limited transport options, making the improvement of public transport essential for sustainable development.

To address these issues, lessons from other cities can guide the optimization of Balti-

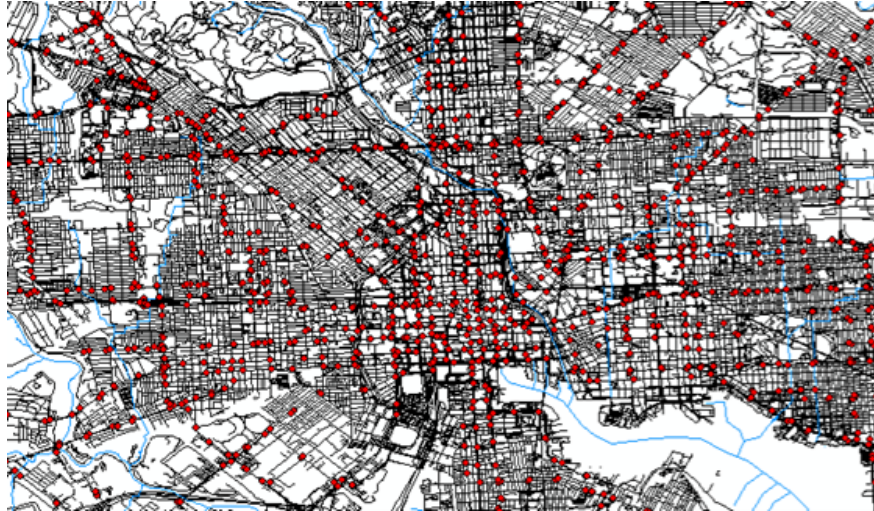


Figure 11: Schematic Diagram of Baltimore City Bus Stops (Part)

more's bus network. By tailoring improvements to local needs, small-scale optimizations can yield significant social, economic, and environmental benefits. This regional research method is adaptable to other areas and communities, offering more accurate optimization results and strategies.

Using Baltimore's road map data, we focus on the downtown area, known for its high commerce, population mobility, and cyclical demand peaks. This area, surrounded by an expressway and key highways, is an ideal subject for studying bus stop distribution and overall road regulation.

5.1.2 Preparation of data

Bus Network Data: The bus network dataset used in this analysis includes 2654 bus stops and 66 bus routes in Baltimore, which were merged to obtain 121 unique bus stops and their corresponding routes. Data on departure times, intervals, and station information were obtained from OpenStreetMap, allowing estimation of bus capacity and representation of the bus network supply side.

Population Density Data: Population density data for Baltimore was sourced from the LandScan Global dataset. The population density heat map categorizes areas into seven levels, ranging from light yellow (low density) to red (high density), helping assess bus network demand and road utilization.

Traffic Situation Data: Real-time traffic data from Google Maps during rush hour in downtown Baltimore was used. Traffic conditions were categorized into four levels (dark red, red, orange, green) representing varying congestion, with corresponding values (4, 3, 2, 1) to assess road saturation and bus stop allocation.

5.2 Optimizing urban bus network based on spatial matching patterns

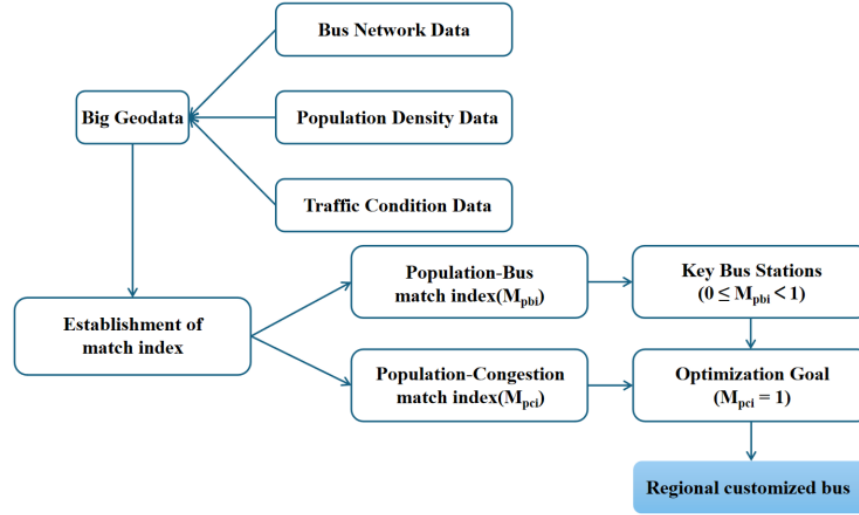


Figure 12: A framework for bus capacity optimization based on spatial matching patterns

5.2.1 Population-Bus Match Index

This study establishes an index to quantify the degree of matching between supply and demand at each bus stop to account for spatial differences within the local area. From a supply perspective, we estimate the bus capacity at each bus stop in the city center during peak periods using bus network data, considering three attributes: bus departure frequency, bus capacity rating, and the total number of bus stops per line. From the perspective of demand, we use population density data, combined with the average cumulative population flow of the city during peak periods, to quantitatively analyze the flow of people at each bus stop.

$$b_i = \sum_{j=1}^l \frac{Tr_j}{s_j f_j} \quad (7)$$

$$Mpbi = \frac{\frac{\sum_{i=1}^m p_i}{b_i}}{\sum_{i=1}^m b_i} \quad (8)$$

Where b_i is the bus capacity at bus stop i , that is, the number of passengers carried by the bus during the period from the entrance to the exit; l is the number of routes passed from bus stop i to j ; f_j is the departure frequency (trips/min) of bus number j ; r_j is the rated bus capacity of each bus number j ; s_j is the total number of stops of bus number j . T is the peak time in minutes, m is the number of bus stops in the bus network, and p_i is the

population flow at bus stop i . M_{pbi} measures whether the population flow at bus station i efficiently allocates the corresponding share of bus capacity. If $M_{pbi} = 1$, then the share of population flow at bus station i equals the share of bus capacity, indicating a perfect matching of supply and demand. If $M_{pbi} > 1$, the population flow share exceeds the bus capacity share at bus station i . A higher value means that the bus stop is underallocated. Conversely, if $0 < M_{pbi} < 1$, it means that the proportion of population flow at bus stop i is lower than the proportion of bus capacity. A low value implies an over-allocation of that bus stop.

5.2.2 Population-Congestion Match Index

We also build an index to quantify the degree of spatial matching between utilization and saturation at each bus stop. From the utilization point of view, we use population density data to measure the utilization of each bus stop by the cumulative population flow. From the saturation point of view, we use the accumulated traffic condition data during the peak period to determine the degree of traffic congestion in the surrounding area of each bus stop, thus characterizing the saturation of road resources.

$$M_{pci} = \frac{\frac{p_i}{\sum_{i=1}^m p_i}}{\frac{c_i}{\sum_{i=1}^m c_i}} \quad (9)$$

Where m is the number of bus stops in the bus network, p_i is the population flow at bus stop i , c_i is the traffic congestion at bus stop i , and M_{pci} measures whether the population flow at bus stop i is effectively allocated to the corresponding traffic congestion share. If $M_{pci} = 1$, the share of population flow at bus stop i is equal to the share of traffic congestion. If $M_{pci} > 1$, the population flow share exceeds the traffic congestion share. Conversely, if $0 < M_{pci} < 1$, the share of population flow is lower than the share of traffic congestion.

5.2.3 Bus Capacity Optimization: Regional Customized Bus Project

These two indexes assess the degree of spatial fit between population flows and bus capacity, and between population flows and traffic congestion. These indicators can identify bus stops with mismatched resource allocation, enabling them to effectively adjust bus capacity and provide more informed decision-making strategies for optimization. Considering the limited resource allocation constraints, this study argues that bus stops ($0 < M_{pci} < 1$) may face more pressing problems, such as severe traffic congestion and urgent population mobility. Therefore, prioritizing these stations can lead to more targeted strategies to address the areas most in need of improvement and ultimately more effectively improve the overall efficiency of the bus network.

Based on this premise, we explore an extreme scenario, assuming that all residents choose buses and that the bus capacity share at each bus stop perfectly matches the pop-

ulation flow share. For this scenario, we introduce a regional customized bus project to improve the efficiency of the bus network.

Regional customized bus project is designed to provide flexible and customized bus services based on the actual needs of specific regions or communities. Different from the traditional bus system with fixed routes and schedules, regional customized buses are adjusted according to the needs of passengers, aiming to provide more personalized and efficient public transport services. Regional customized buses usually provide more flexible travel options by dynamically adjusting routes and shifts according to users' travel needs and flows through an intelligent scheduling system. The system can adjust the number and departure time of buses in real time according to changes in demand, avoiding oversupply or waste of resources.

The project is dedicated to achieving the desired $M_{pbi} = 1$ for all critical bus stops with mismatched resource allocation. The project has no limit on the current bus capacity of the network and dynamically adjusts the average capacity of buses per shift. The optimization objective is still to ensure that the share of population flow at each bus stop perfectly matches the share of bus capacity.

$$b'_i = \lim_{M_{pbi} \rightarrow 1} \frac{p_i \sum_{i=1}^m b'_i}{M_{pbi} \sum_{i=1}^m p_i} \quad (10)$$

5.3 Model application: Baltimore Bus System optimization

5.3.1 Analysis of the Population-Bus Matching Pattern

Next, we calculate the Population-Bus Match Index for each bus stop within the downtown area of Baltimore City based on our proposed method. The figure below shows the spatial distribution of the Population-Bus Match Index (M_{pbi}), where the size of the points indicates the size of the M_{pbi} value at each bus stop. Yellow dots indicate $M_{pbi} > 1$, indicating that a larger proportion of population flows exceed bus capacity. Dark blue dots indicate $M_{pbi} < 1$, indicating a low share of population flows compared to bus capacity.

Based on the analysis of the M_{pbi} during peak hours (Figure 13 and Table 4), approximately 74.38% of bus stops have $M_{pbi} > 1$, indicating insufficient bus capacity for most population flows. M_{pbi} values range from 0.17 at MADISON ST & GUILFORD AVE wb (green circles) to 81.48 at EUTAW ST & SARATOGA ST sb (red circles). Both stops are on the area's outer ring, but the latter, closer to a community with limited bus lines, experiences demand far exceeding capacity, posing challenges for commuters.

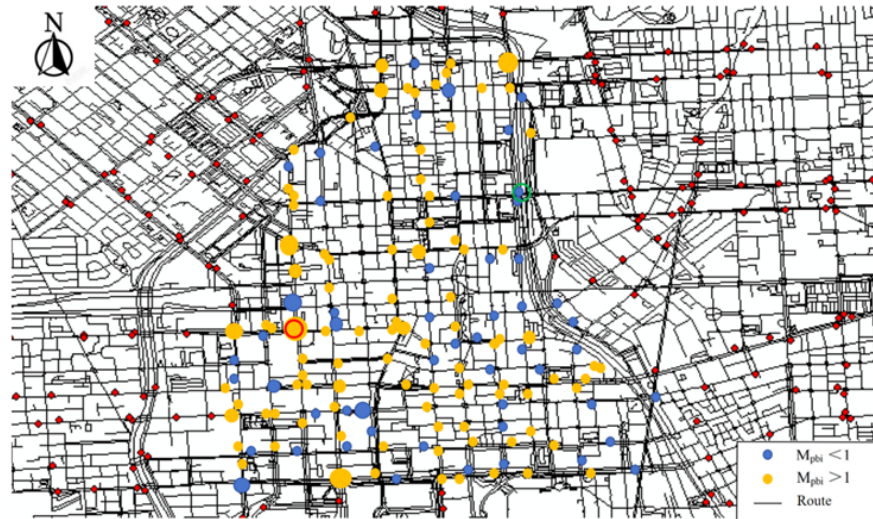


Figure 13: Spatial distribution of Population-Bus Match Index (1:2500 scale)

Table 4: Statistical Data for M_{pbi}

M _{pbi} > 1	M _{pbi} < 1	Total	Mean	Std. Deviation	Max/Min
90 (74.38%)	31 (25.62%)	121	3.28	4.73	81.48 / 0.17

5.3.2 Analysis of the Population-Congestion Matching Pattern

We calculated the Population-Congestion Match Index (M_{pci}) for each bus stop in downtown Baltimore. Figure shows the spatial distribution of M_{pci} during peak hours: green points ($M_{pci} > 1$) indicate smooth traffic and lower bus demand, while light blue points ($M_{pci} < 1$) suggest higher congestion, potentially motivating residents to choose buses.

From the M_{pci} data, we observe that 63.63% of bus stops experience more traffic congestion than population flow ($0 \leq M_{pci} < 1$). These stops, mainly located on the ring road and south of the city center, face significant congestion that increases travel time, parking costs, and fuel taxes. This makes buses a more attractive alternative. Therefore, optimizing bus capacity at these stops is a priority to meet high demand and alleviate congestion. The M_{pci} values range from 0.21 to 2.56, with low variation, indicating a stable relationship between traffic congestion and population flow, which aids in optimizing bus network resource allocation.

5.3.3 Regional customized bus project based on matching analysis

The two matching patterns help assess the bus network's current situation, particularly identifying key bus stops with resource mismatches ($0 \leq M_{pci} < 1$). By targeting these areas, we can improve network efficiency, reduce traffic congestion, and enhance

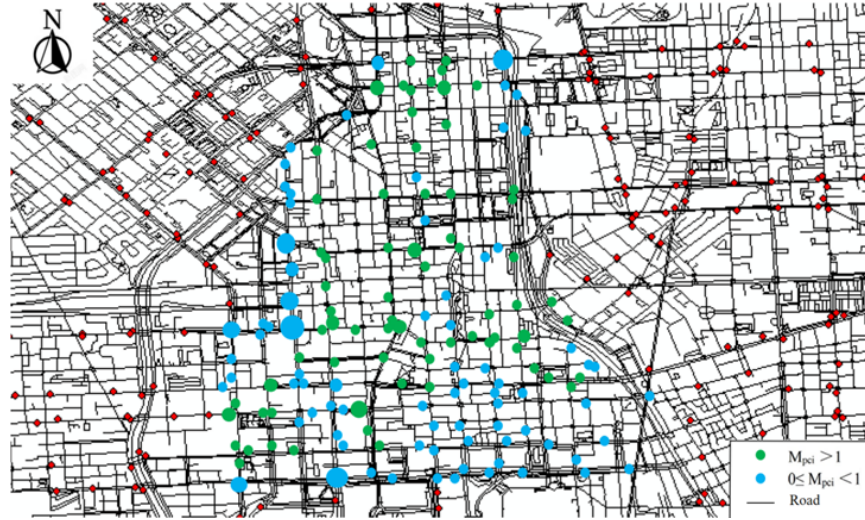


Figure 14: Spatial distribution of Population-Congestion Match Index (1:2500 scale)

Table 5: Statistical Data for Mpci

Mpci > 1	Mpci < 1	Total	Mean	Std. Deviation	Max/Min
44 (36.37%)	77 (63.63%)	121	1.12	0.41	2.56 / 0.21

residents' commuting speeds. To address the mismatch between population flow and bus capacity at key bus stations, we introduce regional customized bus planning, allowing the total bus system capacity to vary and adding key stops to the regional customized bus.

We identified 67 key bus stops, primarily in the southern downtown area of Baltimore, served by routes like BL, OR, 22, and 54. We created new customized bus routes in a loop, adjusting the bus capacity at these stops to perfectly match population flow ($M_{pci} = 1$). As a result, 83.58% of these stops will see capacity improvements, while 16.42% will redistribute excess capacity to regional customized buses, increasing the total capacity by 144,747 people. This also connects the Port of Baltimore to nearby communities, supporting local shipping industry development.

With the ideal optimization ($M_{pci} = 1$ for all stops), the system's overall efficiency improves by 31.54%. The need for more stops indicates a significant capacity gap, underscoring the importance of investing in regional customized buses in densely populated, congested areas. These buses, with dedicated lanes and closely connected service stations, offer a cost-effective solution to traffic problems in these communities.

5.4 Impact of Regional Customized Bus on All Relevant Parties

Community Residents and Commuters: Baltimore's traditional bus service is inefficient and lacks capacity. Customized buses can reduce operational strain and alleviate travel pressure during peak hours. They help decrease private car usage in high-demand areas, improving residents' travel experience and reducing congestion costs. Customized buses can also be scheduled based on commuter needs, optimizing routes for flexibility and efficiency.

Tourists: Customized buses offer flexible routes connecting key attractions, hotels, dining areas, and transportation hubs. Tourists can select routes based on their needs, bypassing the limitations of traditional bus services. These buses also provide private transport from airports and stations to tourist sites, facilitating easier trip planning, boosting tourism, and enhancing Baltimore's urban development.

Baltimore Shipping: Traditional transport infrastructure disrupts access to the Port of Baltimore. Customized buses can improve connectivity for port workers and residents, speed up cargo handling, reduce transit times, and minimize traffic disruptions. By enhancing transportation links, customized buses support the growth of the shipping industry, boosting the competitiveness of the Port of Baltimore and contributing to the city's economic revival.

6 Bike-Sharing Recommendations Based on the SWOT Model

6.1 Recommendation for Bike-Sharing in Baltimore

We recommend bike-sharing as the best transportation solution to improve the quality of life for Baltimore's residents.

Unlike cities with dense populations and superior rail systems, U.S. cities require careful planning of access points, walking distances, and travel times. In urban areas, private vehicle use dominates, causing congestion, economic losses, and environmental damage. A survey found that one-fifth of Baltimore residents experience traffic-related inconvenience, with 43% of Black residents reporting transportation insecurity. In areas like Brooklyn, around 30% of households do not own cars, and for some, car ownership is a financial burden.

The inadequacy of public rail systems, such as MARC and light rail, is evident. These systems mainly serve the suburbs and are insufficient to meet the transportation needs of residents. Rail transport is not extensive enough, and downtown free buses primarily serve tourists. While rail is efficient in dense areas, it struggles to serve dispersed populations. Therefore, bike-sharing programs are a promising solution, inspired by successful systems in cities like Beijing and Nanjing. These programs reduce travel costs, lower emissions, and improve air quality.

Based on the analysis, the transportation system in Baltimore faces several issues:

- Demand-responsive bus services cannot meet the "last mile" travel needs.
- During peak times, buses suffer from low efficiency due to detours.
- Bus services are constrained by road conditions and infrastructure.
- The heavy reliance on private vehicles leads to congestion, economic losses, and environmental harm.

Given these issues, bike-sharing offers clear environmental benefits and can be a key part of a low-carbon transportation strategy. We propose using a static game model to explore the integration of bike-sharing into the urban transport network.

6.2 The Benefits of Bike-Sharing Projects for Residents

"Last mile issue" is resolved. The bike-sharing project addresses the current demand for "last mile" travel services, allowing "door-to-door service" and making transportation or connections more convenient. Commuters can easily reach transportation stations, thus increasing the attractiveness of rail transport.

Transport efficiency is improved. During peak times and in high-density areas, demand-responsive buses suffer from detours and low transport efficiency. The implementation of bike-sharing projects enhances station accessibility, making it easier for people to travel and improving transport efficiency.

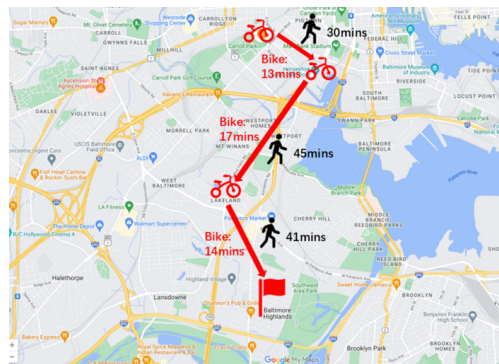


Figure 15: Comparison of Walking and Bike-Sharing Efficiency

Low infrastructure and cost requirements. Transitioning to zero-emission rail transport requires large-scale infrastructure upgrades, which are costly and complex to implement. However, the bike-sharing project does not require significant infrastructure upgrades, alleviating pressure and potential issues related to funding and conflicts of interest.

6.3 Impact on Various Stakeholders Based on the SWOT Model

For other stakeholders, the situation is complex because of the benefits and disadvantages, so we use the SWOT analysis model to explain it clearly.

Obviously, for business owners, bike-sharing provides a more convenient way for customers to get around, especially for those who are far away, and cyclists may find new business opportunities during the ride, thus increasing their spending in nearby stores.



Figure 16: Impact of Bike-Sharing on Business Owners

For suburban residents who don't have a private car or don't want to drive, bike-sharing offers an alternative way to get to the city center or other destinations. Bike-sharing also provides a "last mile" solution for commuters, allowing them to get from public transport to their final destination.

Table 6: SWOT Analysis of the Shared Bicycle Project

Strengths	Weaknesses
Environmental protection and green travel Convenience Low cost	Vehicle management issues Unregulated user behavior Resource waste
Opportunities	Threats
Market demand growth Policy support Technological innovation	User experience issues Substitute transportation methods Social recognition risks

6.4 Impact of Bike-Sharing on Other Transportation Needs and People's Lives

6.4.1 Disruptions to Other Transportation Demand

Reduced investment in other transportation modes. Securing sufficient funding for transportation projects, particularly rail, is challenging due to budget constraints and competing priorities. As cities allocate resources to bike-sharing, it may divert funds from other crucial infrastructure projects, hindering the development of alternative transportation systems.

Disruption to public transportation. Large-scale bike-sharing could reduce public transit ridership, especially for the "last mile" connections, as passengers may prefer bikes over rail, affecting public transport efficiency and revenue.

Disruption to motor vehicle traffic. Increased bike-sharing could slow vehicle flow, especially on roads without bike lanes. Mixing bikes with motor vehicles during peak hours may worsen congestion, while improperly parked bikes could block lanes, further impeding traffic.

6.4.2 Disruptions to People's Lives

Disruption to residents' lives. Improper bike parking can block public spaces, disrupt pedestrian pathways, and inconvenience residents, especially in older areas. Additionally, the large-scale introduction of bike-sharing may cause noise and visual pollution.

Disruption to business activities. Improper bike parking in commercial areas can block customer access, harm the area's image, and inconvenience business owners. It may also damage the aesthetic appeal of commercial districts.

Disruption to the urban environment. Bike-sharing can cause visual clutter and occupy public spaces, affecting aesthetics, especially in historic or scenic areas. It may also limit the availability of resources like parking and sidewalks, hindering other transport modes and residents' use.

Disruption to social order. Bike-sharing may increase management costs, disrupt traffic flow, and pose safety risks. Improper parking requires more regulation, while cyclist behavior (e.g., running red lights) can lead to accidents. Additionally, bike quality issues can compromise safety.

7 Advantages and Disadvantages

Advantages:

1. **Practical applicability:** By simulating the impact of the Francis Scott Key Bridge collapse and reconstruction on traffic connectivity, stability, and traffic flow, the model has strong practical value, especially in transportation planning and decision-making, offering valuable data support to city managers.

2. **Multiple simulations and data support:** Through extensive simulations (such as 10,000 random disturbances, Monte Carlo simulations, etc.), the model accurately reflects the performance of the transportation system under different conditions, yielding highly reliable results.

3. **Use of a regional research approach:** The index evaluation method captures more accurate spatial matching features while offering good transferability.

4. **Multidimensional consideration:** The research not only focuses on the supply-demand matching in the bus system but also takes into account traffic congestion. This multi-dimensional consideration makes the research results more comprehensive.

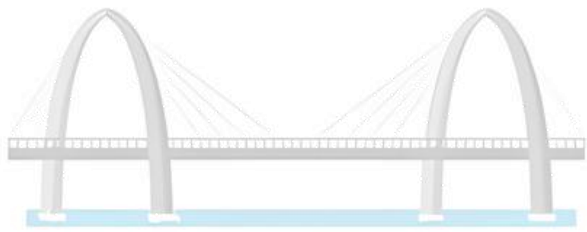
Disadvantages:

1. The model is based on several assumptions, such as traffic flow, road disturbances, and bridge reconstruction assumptions, which may introduce biases in real-world applications. Particularly in complex traffic environments, some assumptions may not fully align with reality.

3. Although the model considers the connectivity and stability of the transportation network, it may overlook some external factors, such as weather changes, sudden events, or policy shifts that can impact the transportation system.

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Memorandum

To: Mayor's office

From: Team #2502911

Subject: Introduction of regional customized bus and bike-sharing -- an optimized solution for Baltimore's transportation system

Date: January 27, 2025

Dear Mr. Mayor,

We are thrilled to share with you our recommendations from network simulation analysis, spatial matching models, and SWOT analysis to optimize Baltimore's transportation network and improve the overall efficiency of urban transportation through the introduction of regionally customized bus and bike-sharing programs. The city of Baltimore has long suffered from aging infrastructure and limited transportation options, which not only affect the lives of community residents, but also hinder the city's economic development. We regret the collapse of the Francis Scott Key Bridge, which not only increased the pressure on the existing road network around the bridge, but also had an impact on the stability of the entire city's transportation network. Our study analyzes the entire transportation network of Baltimore City, aiming to optimize urban transportation and promote urban development through accurate analysis and appropriate measures.

Regional customized bus can provide customized public transport services for citizens. Using spatial matching patterns to analyze downtown bus stops and routes, as well as to quantify the matching degree of population with transit and congestion, we find that there is a large capacity gap in the Baltimore City bus network. Regional customized buses can effectively connect communities and stations in urgent need of improvement, and improve citizens' public transport travel experience. This project will encourage more citizens to choose public transportation, improve the travel experience of commuters and tourists, and enhance the brand image of bus companies to maintain long-term competitiveness. In addition, customized buses will connect the Port of Baltimore to downtown, boosting the shipping industry, creating jobs and increasing transportation capacity. The project will also help reduce congestion and safety hazards for private cars and improve traffic safety.

In order to improve residents' life, we suggest the introduction of bike-sharing projects. Through SWOT analysis, we found that bike-sharing can significantly improve the accessibility and attractiveness of rail transit and enhance urban transportation efficiency, with low infrastructure requirements and significant environmental benefits. Although there may be some disruption to urban traffic due to competition and management issues, we still believe that the advantages of bike-sharing far outweigh the disadvantages.

We believe that this memo provides you with a clear and feasible project optimization plan. The implementation of these two projects can effectively improve the operation capacity of urban transportation network, which is significant for the economic development and sustainable transportation construction of the city.

Looking forward to seeing these projects help in your city's development planning.

Yours Sincerely,
Team #2502911

