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## Navigating the Future: Transformative Traffic Solution for Baltimore

“Our city is not among the safest places to drive. not by a long shot.” quote taken from *America's Best Drivers 2016 report* by Allstate Insurance. The **Baltimore's transportation network** currently has significant problems due to aging infrastructure and other reasons. Especially after the collapse of the Francis Scott Key Bridge, people's mobility and socio-economic development have been hit hard. In order to improve the development of the area, we modeled the distribution of the assisted transportation network to achieve the optimal balance between satisfying the various stakeholders.

Several models are established: Model I: Bridge-Collapsed Effect Model; Model II: Bus Stop Optimization Model ; Model III: Kruskal-Edmonds Traffic Revitalization Model , etc.

Before building all the models, we cull the redundant data and visualize the data that contributes more, through which we can do better analysis. In addition, we use a variety of **visualization** methods to make the results more intuitive.

For Model I: The **BPR** algorithm was used to simulate the traffic flow and determine the relationship between road capacity and road width based on **Kilby coefficient**, thus determining the direction of optimization with the objective of reducing the commuting time of residents. The shortest travel time between any two nodes before and after the bridge collapse is simulated using **Dijkstra's algorithm** and simulated using **Python** to get the impact of bridge collapse/reconstruction on the stakeholders, Due to the diversity of the result, it will be shown in section 5.3.

For Model II: The **Haversine formula** is used to convert latitude and longitude to distance for subsequent calculations. We continue to use **Dijkstra** to simulate the shortest paths between the current transportation nodes, and then add a certain bus stop to simulate the geographic location of the station using the **Particle Swarm Optimization (PSO)** algorithm, combined with the traffic flow optimization function to keep the traffic flow at an average level at all nodes, to prevent the social problems caused by the excessive or insufficient passenger flow. At the same time, we use **K-mean** clustering method to divide Baltimore into three neighborhoods based on the distribution of bus stops, and control the variance of the distance of bus stops in each neighborhood, so as to ensure that the distribution of bus stops is more balanced in each area of Baltimore.

For Model III: We establish a Multi-Objective Optimization function . **Minimum Spanning Tree (MST)** is used to optimize the connectivity between traffic nodes, while the **Edmonds-Karp** algorithm is used to optimize the distribution of traffic on each side, avoiding excessive concentration of traffic on certain roads or intersections. This project can significantly improve the mobility of the stakeholders and increase the mobility efficiency while reducing the safety problems caused by traffic.

In addition, since the above model can generate different project results by changing the nodes, our model is **generalizable**.

Finally, **sensitivity analysis** of the parameters in BPR shows that our model is not sensitive to changes in  $\alpha$  and  $\beta$ , it can be assumed that our model is stable, that is , it can be applied to various types of transportation hubs.

**Keywords:** BPR; Dijkstra's algorithm; Particle Swarm Optimization(PSO); Multi-Objective Optimization; Minimum Spanning Tree (MST)

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# 1 Introduction

## 1.1 Problem Background

“Without transportation ..... You can't get to work, you can't get to the hospital or primary care provider, you can't choose fresh food. You can't even go home.” So says one Baltimore resident.

Road planning is an extremely important task for a city. The urban transportation system may have both positive and negative effects on the development of the city and the quality of life of the residents, and different stakeholders have different needs and priorities for urban roads, so the planning of the urban transportation system needs to take into account factors such as geographic conditions, soil composition, and weather conditions, in order to satisfy the maximization of benefits for most stakeholders.

With its busy port and shipping center, Baltimore is an important transportation hub city. The recent collapse of a major bridge in Baltimore, Maryland, USA, has hampered the lives of the city's residents and the city's economic development. “It really boils down to equitable distribution of transit resources, and really who needs it,” said Porter to WYPR. Staggered highways and railroad hubs also impede or disrupt city streets and neighborhoods, causing nuisance to residents.



### Figure 1: Baltimore Geographic System Map

Therefore, it is important to carefully consider all factors, plan for new transportation hubs, and try to reconnect Baltimore City's neighborhoods in order to create more sustainable neighborhoods, add more green space, and improve the living experience for residents.

## 1.2 Restatement of the Problem

Proper transportation planning is vital for cities. Considering the background information and restricted conditions identified in the problem statement, we need to solve the following problems:

- Build a mathematical model to analyze the impact of the collapse and/or reconstruction of the Francis Scott Key Bridge on stakeholders in and around Baltimore.
- Select a project or potential project that affects Baltimore's bus or sidewalk system

and specifically analyze the project's impact on stakeholders in Baltimore and the surrounding area.

- Select a project for Baltimore's transportation network that would best improve the lives of residents and analyze: the benefits of the project for residents; the impact of the project on other stakeholders; and explain in what ways the project interferes with other transportation needs and people's lives.
- Using the transportation system to effectively address safety in Baltimore.

### 1.3 Literature Review

This problem is mainly related to urban traffic road planning and design strategy. In recent years, the research on traffic road planning strategy is very hot, and the existing model research mainly focuses on the following parts: **Dijkstra Algorithm Based Vehicle Travel-Path Optimization Model**, **TOD Based Public Transportation Model** and **Improved Four-Stage Traffic Forecast Model**.

this section mainly discuss the models that have be proposed:

- ✧ In[1] Wu et al., in the path optimization model based on **Dijkstra's algorithm** in graph theory, calculate the comprehensive shortest path after setting constraints by establishing a road arc segment-node topological network model, the path solving ability of this algorithm is stronger, but it is affected by the number of nodes and the computational efficiency is low;
- ✧ In the model of public transportation planning method based on the **TOD** (Transit-Oriented Development) model, Huang et al.[2] carried out station construction and transportation planning through high-density mixed circle development around the city center and bus station domains in large and medium-sized cities. The model can promote compact urban development and create public space in the city, but in the actual implementation of the coordination between various government departments is difficult, and the problem of conflict of interest will lead to the failure of the idea;
- ✧ In the improved **Four-Stage** traffic forecasting model, Wang et al.[3] predict the traffic distribution in the coming years on the basis of the OD survey to determine the current OD of highway traffic, and accordingly allocate the predicted OD flow to the road network through a calibration model to realize the traffic volume prediction. The model can systematically analyze and predict traffic demand, but with the increasing complexity of urban traffic problems, the feedback mechanism between the various steps of the model is not perfect, and the accuracy of the results is therefore affected;

In summary, the strengths and weaknesses of the previous models can be visually presented and is shown below:

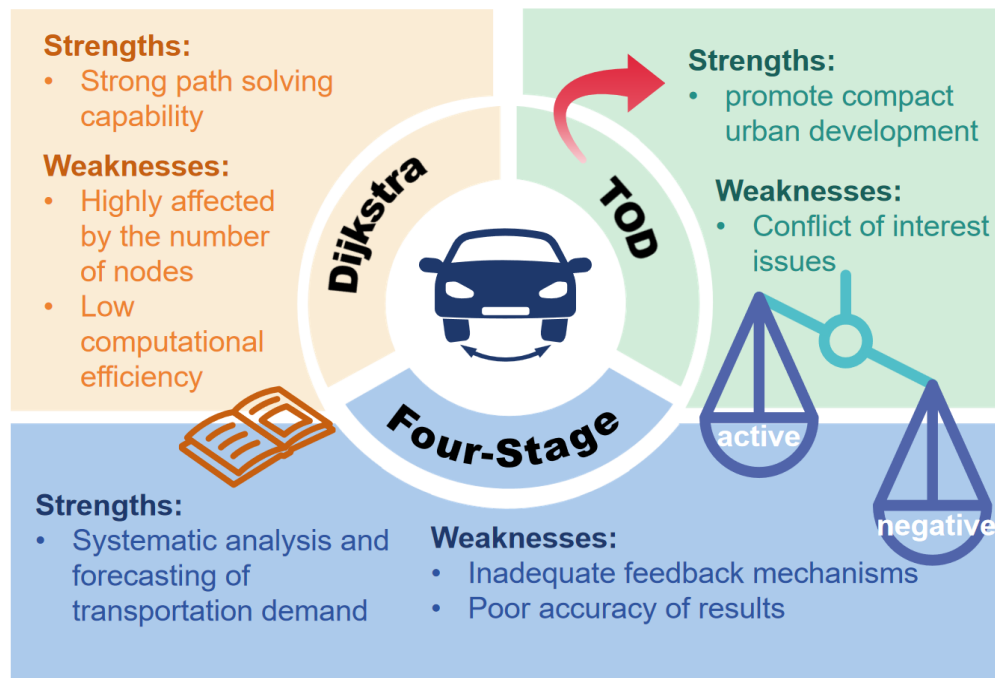


Figure 2: Literature Review Framework

## 1.4 Our work

This topic requires us to redesign the transportation network in the Baltimore region based on Baltimore area transportation data and analyze the impacts on stakeholders. Our work mainly includes the following:

- 1) Based on the data of Baltimore's traffic, analyze the impact on stakeholders before and after the bridge collapse
- 2) Choose a project that affects buses in Baltimore and analyze the impact of this project on stakeholders
- 3) Select a project that would best improve the lives of Baltimore residents and analyze it accordingly

In order to avoid complicated description, intuitively reflect our work process, the flow chart is shown in Figure 3:

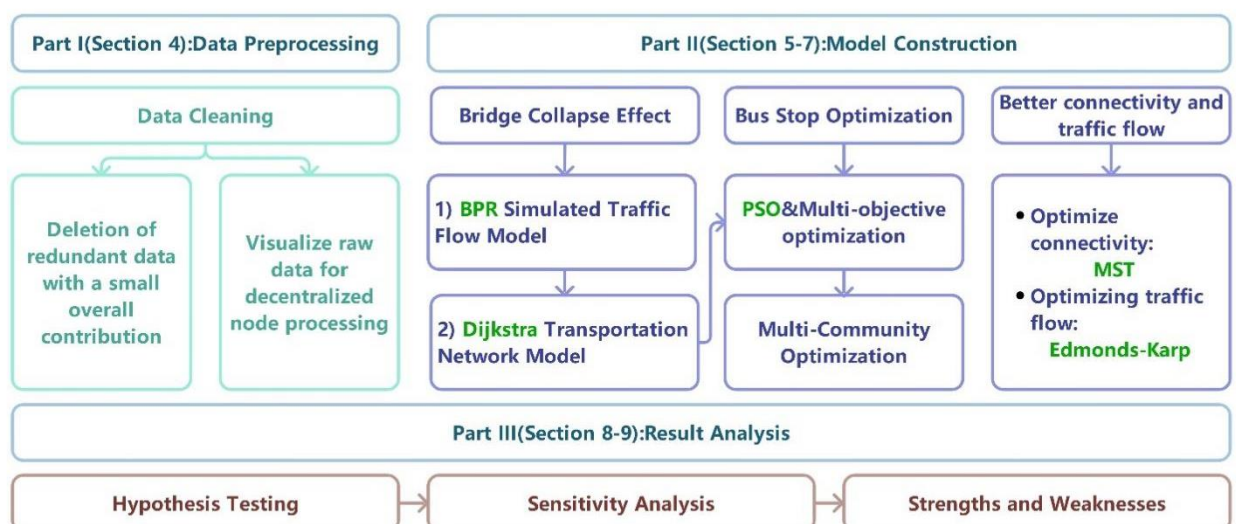


Figure 3: The Flow Chart of Our Work

## 2 Assumptions and Justifications

To simplify the problem, we make the following basic assumptions, each of which is properly justified.

- **Assumption 1:** Assume the entire Baltimore area has uniform altitude with nearly zero altitude difference, simplifying terrain to an ideal plane and removing slope - resistance interference

**Justification:** Baltimore's highest altitude is 90 meters. Relative to the transportation network, the altitude difference is negligible, and terrain undulations minimally impact the transportation system. Simplifying terrain reduces modeling difficulty and focuses on core planning.

- **Assumption 2:** Set a unified legal maximum speed threshold for the same road type in Baltimore, standardizing vehicle speed control.

**Justification:** Local regulations have clear speed limits for different road types. Emergency vehicle speeding is rare and short - lived, minimally affecting the traffic flow model. Unifying speed limits helps accurately quantify transportation efficiency.

- **Assumption 3:** Baltimore road traffic flow is in dynamic equilibrium and doesn't change much over time, separating the time variable for static flow analysis.

**Justification:** Research data isn't time - continuous, unable to support a complex time - varying traffic flow model. Also, the local government has no short - term plans to change traffic flow significantly. Given data and policy stability, assuming a steady traffic flow helps build a basic road network capacity assessment model.

## 3 Notations

The key mathematical notations used in this paper are listed in Table 1.

**Table 1: Notations used in this paper**

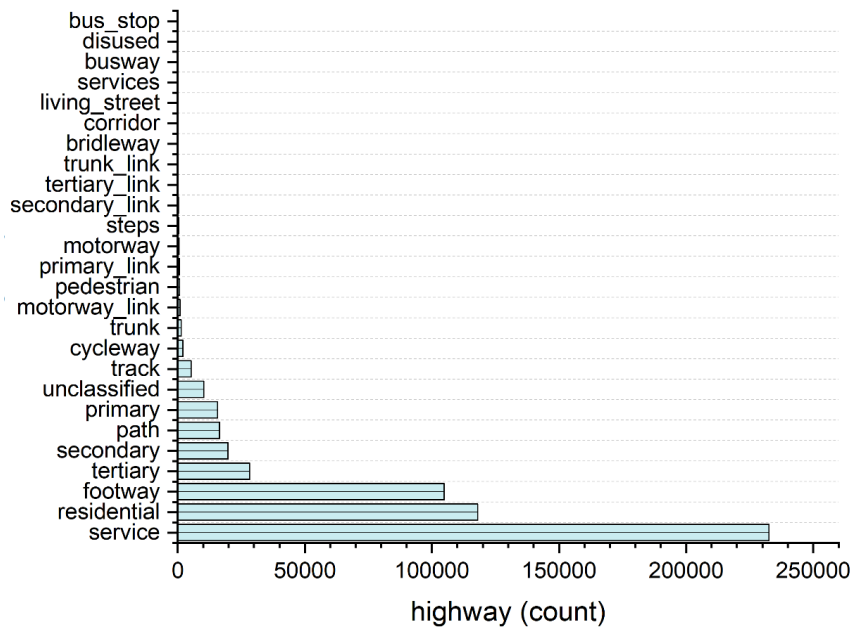
Symbol	Description	Unit
$V_{ij}$	Traffic volume between road $i$ & $j(i,j=1,2,3,\dots,n)$	/
$C_{ij}$	Road capacity between road $i$ & $j(i,j=1,2,3,\dots,n)$	veh/H
$T_{ij}$	Commuting time of residents between road $i$ & $j(i,j=1,2,3,\dots,n)$	s
$x$	Starting point	/
$y$	Destination	/
$v_i^{(t)}$	The velocity of particle $i$ at moment $t$	/
$x_i^{(t)}$	The position of particle $i$ at moment $t$	/

## 4 Data Preprocessing

Since the amount of data is large and not intuitive, we directly visualize some of the data for display.

- After analyzing the data in table **edges\_all.csv**, it is not difficult to find that there are 25 road hubs in the HIGHWAY column, and the number of data sets for each road hub is shown below:

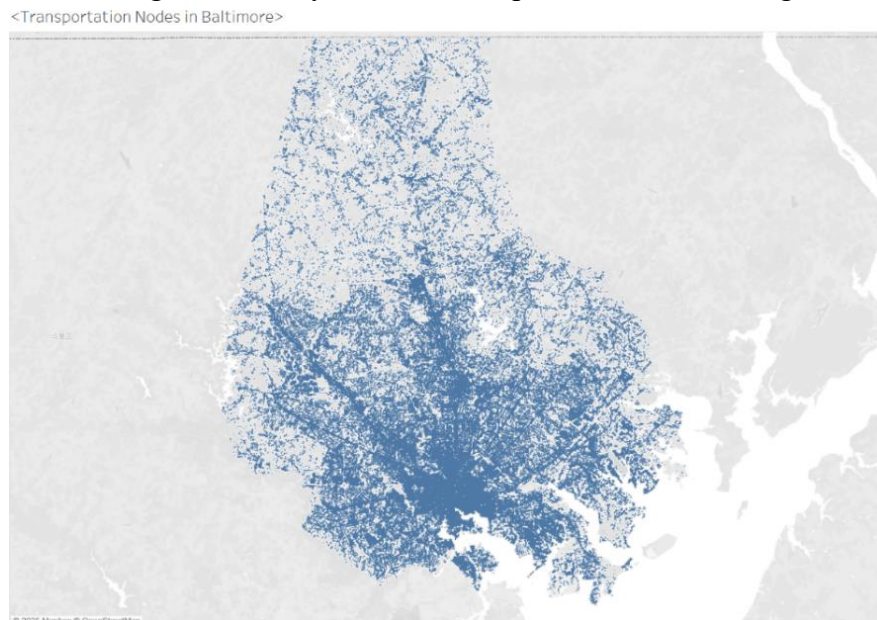




**Figure 4: Number of road groups**

The data that accounted for too little contributed less to the overall analysis, but still needed to consume computational resources and time in the process of data processing and analysis, so we deleted the data that accounted for too little ( $<1\%$ ) to avoid their interference in the analysis results, so that the analysis was based on more representative data, which resulted in more accurate and reliable conclusions, and improved the quality and credibility of the analysis results.

- Based on the nodes\_all.csv data provided by the MCM organizing committee, we performed the following visual analysis of the transportation nodes in Figure 5:



**Figure 5: Transportation Nodes Around Baltimore**

The graph shows the number of streets (or roads) connected to a particular node. It can represent intersections or endpoints, and it is clear that the nodes in the city of Baltimore are more densely populated than those in neighboring cities, so in order to simplify the calculations

and make the final results more relevant, we will further analyze the remaining nodes in Model I using Dijkstra's algorithm.

## 5 Model I: Bridge-Collapsed Effect Model

The collapse of the Francis Scott Key Bridge had significant impacts on Baltimore's transportation system, such as regional economic impacts and residential commuting impacts, to name a few, and impacted different stakeholders differently. In this section, a transportation network model is developed to analyze the impact of the Francis Scott Key Bridge collapse on Baltimore's traffic flow by applying the **Dijkstra's Algorithm**.

### 5.1 BPR Simulated Traffic Flow Model

Baltimore's assemblage of residents is undoubtedly the largest stakeholder, so we began by analyzing changes in residents' commute times to quantify the impact of the Francis Scott Key Bridge collapse on Baltimore's transportation system. We used the **BPR (Bureau of Public Roads) Model** to simulate changes in traffic flow and adjusted the flow and travel times of major roadways to account for changes in traffic flow.

Therefore, the commuting time between nodes  $i$  and  $j$  can be expressed as:

$$T_{ij} = T_0 [1 + \alpha (\frac{V_{ij}}{C_{ij}})^\beta] \quad (1)$$

Where,  $\alpha$  is a parameter with values in  $[0.1, 0.5]$ ,  $\beta$  is a parameter with values in  $[3, 4]$ . We will later analyze the sensitivity of these two parameters.  $T_0$  is the base passing time when there is no other traffic on the roadway, which can be expressed as:

$$T_0 = \frac{length}{maxspeed} \quad (2)$$

$length$  and  $maxspeed$  can be retrieved in Table **edges\_all.csv**.

Based on assumption 1, road capacity  $C$  is proportional to the width of the road, we introduce the **Kilby coefficient**  $k$  to quantify the relationship between width and capacity:

$$C = k \times width \quad (3)$$

### 5.2 Dijkstra Transportation Network Model

Based on the data **nodes\_all.csv**, we selected transportation nodes within the city of Baltimore, and the weight between any two nodes is the commuting time of the residents, and if there is no passable path between the two nodes, the weight is  $+\infty$ .

This gives us the adjacency matrix is:

$$W = \begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} \cdots a_{1n} \\ a_{21} & a_{22} & a_{23} & a_{24} \cdots a_{2n} \\ a_{31} & a_{32} & a_{33} & a_{34} \cdots a_{3n} \\ a_{41} & a_{42} & a_{43} & a_{44} \cdots a_{4n} \\ \vdots & \vdots & \vdots & \vdots \\ a_{n1} & a_{n2} & a_{n3} & a_{n4} \cdots a_{nn} \end{bmatrix} \quad (4)$$

Among them :



$$a_{ij} = \begin{cases} T_{ij}, & i, j \text{ are connected} \\ +\infty, & i, j \text{ are not connected} \end{cases} \quad (5)$$

**Dijkstra's algorithm** is used to calculate the minimum time for residents to commute, and the implementation of the algorithm is presented in pseudo-code as follows:

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**Algorithm 1:** The process of minimize commuting time:

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**Input:**  $x, y$

**Output:**  $d(x, y)$

**for**  $i = 1$  to  $n$  **do**

    Nodes that minimize  $d(i)$  but have not yet been visited;

    Record  $i$  has been accessed;

**for**  $j = 1$  to  $n$  **do**

**if**  $j$  has not been visited && The shortest path  $d(x, y)$  from  $x$  to  $y$  is made better by using  $i$  as an intermediary point:

            Optimize  $d(x, y)$ ;

            Suppose the previous node of  $y$  is  $x$ ;

**end**

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The following figure briefly shows the shortest path between two nodes derived by Dijkstra's algorithm:

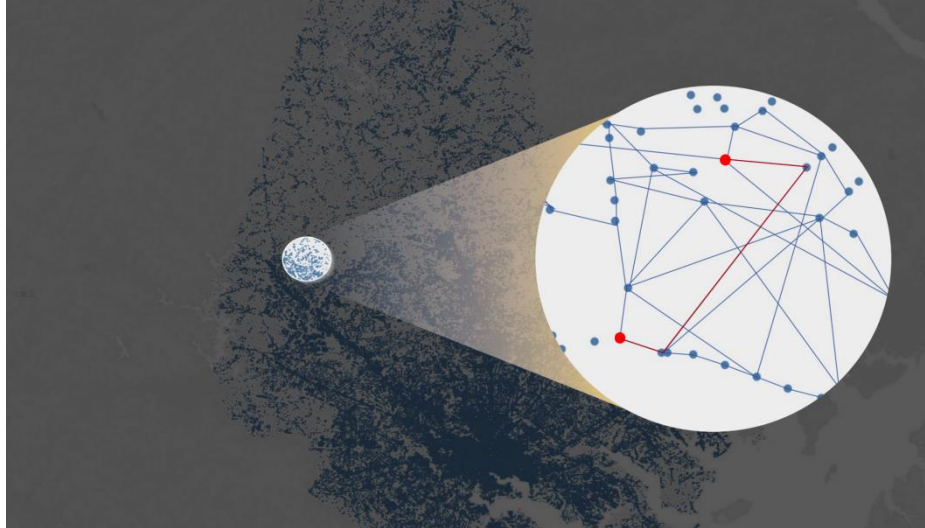


Figure 6: Simplified graphical representation of Dijkstra's algorithm

## 5.3 Results and Analysis

The results and analyses of Model I are as follows :

### 5.3.1 Results Visualization

According to the algorithm in 4.2, we use **Python** for simulation and obtain the shortest travel times between each traffic node before and after the collapse of the Francis Scott Key Bridge. Figure 7 directly shows the results of the comparison between the shortest distances before and after the bridge collapse:

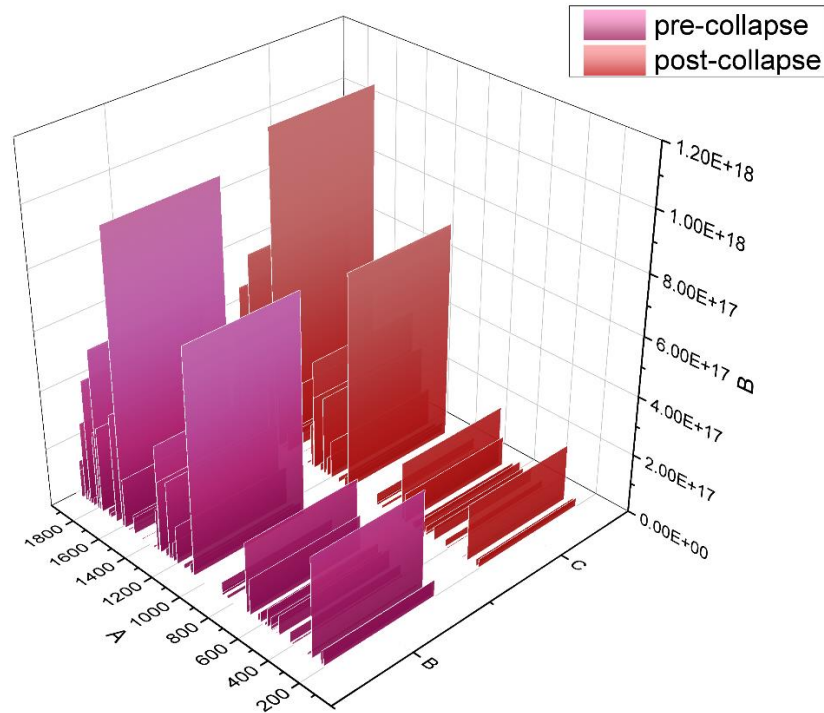


Figure 7: Comparison of Shortest Distances

### 5.3.2 Hypothesis Testing

Figure 5 shows that there are certain fluctuations in the travel time between any two nodes before and after the bridge collapse. Next, we will analyze whether this change will increase the commuting time of citizens:

**a) Determine the null hypothesis & alternative hypothesis**

$H_0$ : The mean commuting times before and after the bridge collapse are equal,  
i.e.,  $\mu_1 = \mu_2$

$H_1$ : The commuting time before the bridge collapse is less than that after the collapse,  
i.e.,  $\mu_1 < \mu_2$

**b) Determine the significance level  $\alpha = 0.05$**

**c) Z-test**

Since the sample size is large enough, according to the **Central Limit Theory (CLT)**, a normal - distribution test is adopted:

$$Z = \frac{\bar{X}_1 - \bar{X}_2}{\sqrt{\frac{\sigma_1^2}{n_1} + \frac{\sigma_2^2}{n_2}}} \quad (6)$$

Where  $\bar{X}_1$  and  $\bar{X}_2$  are the average commuting times of citizens before and after the bridge collapse in the selected samples, respectively;  $\sigma_1$  and  $\sigma_2$  are the population standard deviations of the two groups of data, respectively;  $n_1$  and  $n_2$  are the sample sizes of the two groups, respectively.

**d) Results**

Through calculation,  $z = 1.843 > 1.64$ . There is sufficient evidence that the commuting time before the bridge collapse is less than the commuting time after the collapse, that is, the bridge collapse will greatly increase the commuting time of citizens.

### 5.3.3 Multi-Stakeholder Impact Analysis

The collapse of the Francis Scott Key Bridge didn't just have an impact on local Baltimore residents, but also on other stakeholders in large and small ways, and we'll explain each of the impacts on individual representative stakeholders next:

#### a) Government

- **After the collapse of the bridge:** the government needs to bear the upfront costs of emergency rescue and cleanup; if the bridge is not rebuilt, although it will save a large amount of construction costs in the short term, in the long term, it will hinder the economic communication within and outside of the Baltimore region, which will inevitably lead to a gradual decline in the GDP of Baltimore, and ultimately lead to the long-term economic downturn.
- **After the bridge is rebuilt:** in the short term, there will be a need to pay for the huge cost of the restoration work, which will put greater pressure on the local budget, and at the same time, it may be necessary to seek financial support from the federal government, which will affect the allocation of financial resources and the advancement of other public projects. Of course, although the collapse of the bridge will have a short-term impact on the local economy, in the long run, if the reconstructed bridge can improve the transportation situation, it will promote economic development and enhance the state economy and national GDP.

#### b) Environmentalist

- **After the collapse of the bridge:** The collapse of the bridge will generate a large amount of construction debris and construction dust and other pollutants, which will cause some damage to the surrounding environment, which is contrary to the concept of sustainable development advocated by environmentalists. However, if the bridge is not rebuilt after the collapse, vehicle emissions will be greatly reduced compared to before the bridge collapsed.
- **After the bridge is rebuilt:** a lot of construction pollution will be created during the reconstruction of the bridge, and a lot of carbon emission pollution will be created after the reconstruction is completed and opened to traffic, which does not fit in with the concept of environmentalists and will have a negative impact on them.

#### c) Commercial Operator

- **After the collapse of the bridge:** the collapse of the bridge will inevitably lead to traffic congestion, increase the cost of transportation of goods, affect the normal development of commercial activities, some enterprises may face problems such as the untimely supply of goods and difficulty in the transportation of fresh food, which will affect customer satisfaction and lead to a reduction in customer traffic and economic losses.
- **After the bridge is reconstructed:** the improved traffic conditions will facilitate the resumption and development of commercial activities, attract more consumers and investments, and enhance economic returns. However, some disruption to neighboring commercial activities may continue to occur during the reconstruction period.

Therefore, the collapse of the bridge has a certain degree of negative impact on all stakeholders. The bridge reconstruction has almost no negative impact on citizens; it has a short-term negative impact on the government but a continuous long-term positive impact; and the negative impacts on environmentalists are significantly more than the positive ones.

## 6 Model II: Bus Stop Optimization Model

Many residents of Baltimore City travel on foot or by bus, but there are many potential problems with the transit system, and we will use this model to improve Baltimore's transit

system and increase the well-being of its citizens and the stability of the community. Our goal is to achieve the relative balance of passenger flow at bus stops through Model II, to minimize the situation of too many or too few passengers at the same bus stop, and to equalize the flow of people at each bus stop as much as possible.

## 6.1 Latitude and Longitude to Distance Conversion

The Haversine formula is a useful formula in spherical trigonometry. It is used to calculate the great - circle distance between two points on a sphere given their longitudes and latitudes[4], seen in the equation:

$$D = 2R \arcsin \left( \sqrt{\sin^2 \left( \frac{\varphi_2 - \varphi_1}{2} \right) + \cos(\varphi_1) \cos(\varphi_2) \sin^2 \left( \frac{\lambda_2 - \lambda_1}{2} \right)} \right) \quad (7)$$

Where R represents the radius of the earth,  $\varphi_1$  and  $\varphi_2$  indicates the latitude of the two nodes,  $\lambda_2$  and  $\lambda_1$  express the longitude of them. We define the weight of the line connecting two nodes as the relative distance between the nodes  $d$ :

$$d = \arcsin \left( \sqrt{\sin^2 \left( \frac{\varphi_2 - \varphi_1}{2} \right) + \cos(\varphi_1) \cos(\varphi_2) \sin^2 \left( \frac{\lambda_2 - \lambda_1}{2} \right)} \right) \quad (8)$$

## 6.2 Multi-objective optimization based on graph optimization

In this model, we hope that by adding new bus stops, we can make the flow of people at each stop as balanced as possible.

### 6.2.1 Extension of Dijkstra's algorithm

We extended and adapted the model of Dijkstra's algorithm in **Model I** by adopting the data in **Bus\_Stop.csv**, where each bus stop is defined as a node, and the relative distance  $d$  between every two nodes according to the formula in **6.1** is defined as the weight between node links, thus obtaining the initial weight matrix (i.e., the matrix of the relative shortest paths) between all nodes:

**Table2: Initial node weight results**

Node	1	2	3	4	...	2654
1	0	0.2636	0.4055	0.5014	...	8.5966
2	0.2636	0	0.1655	0.6912	...	8.8232
3	0.4055	0.1655	0	0.8565	...	8.9867
4	0.5014	0.6912	0.8565	0	...	8.1353
...	...	...	...	...	...	...
2654	8.5966	8.8232	8.9867	8.1353	...	0

### 6.2.2 Particle Swarm Optimization (PSO)

Since citizens always choose the shortest path when traveling, which we have calculated in **Table 2**, we will use **Particle Swarm Optimization (PSO)** to simulate the geographic location of the new bus stops:

- Each newly added bus stop is treated as a massless “particle” that solves for the layout of the bus stop and the location of the new stop.

- Each particle update depends on  $pbest_i$  &  $gbest$ :  
 $pbest_i$ :Optimal position of the current position of the self-particle  
 $gbest$ :Optimal position in group particles
- Each particle will update its position based on the current solution and the historical optimal solution to finally find the optimal solution.

Each particle updates its position and velocity according to the following rules:

$$v_i^{(t+1)} = w \cdot v_i^{(t)} + c_1 \cdot r_1 \cdot (pbest_i - x_i^{(t)}) + c_2 \cdot r_2 \cdot (gbest - x_i^{(t)}) \quad (9)$$

Where  $w$  is the inertia weight, which is used to control the exploration behavior of the particle.  $c_1$  and  $c_2$  are acceleration constants that control the degree to which the particle is attracted to  $pbest_i$  and  $gbest$ .  $r_1$  and  $r_2$  are two random numbers in the range  $[0,1]$ , which are used to represent the randomness of the search.

### 6.2.3 Composite objective function

We define a composite objective function  $DL$  to represent the differences in passenger - flow volumes among various stations:

$$DL = \sum_{i=1}^N |L_i - \bar{L}|^2 \quad (10)$$

Where  $L_i$  is the passenger - flow volume of bus stop  $i$  ( $i=1,2,3,\dots,N$ ), and  $\bar{L}$  is the average passenger - flow volume of all bus stops. When the value of this objective function is minimized, it means that the differences in passenger - flow volumes among stations are minimized, that is, the overall passenger - flow volume of bus stops reaches a balance.

By running a Python program, the geographical locations of the newly - added bus stops are obtained. The following are the passenger - flow distribution maps before and after optimization:



Figure 8:Passenger flow before optimization



Figure 9:Passenger flow after optimization

The figures display the passenger - flow distribution of each bus stop in Baltimore after the addition and optimization of bus - stop distribution. The darker the color, the higher the unit passenger - flow volume. Obviously, after optimization, the passenger - flow distribution is

more even, reducing extreme situations of excessive or insufficient passenger - flow. The utilization rate of transportation resources is improved, scheduling is smoother, avoiding vehicle empty - loading or over - congestion. Meanwhile, to a certain extent, it reduces the occurrence of safety issues such as stampede accidents.

The following is the overall process of Multi - objective optimization based on graph optimization:

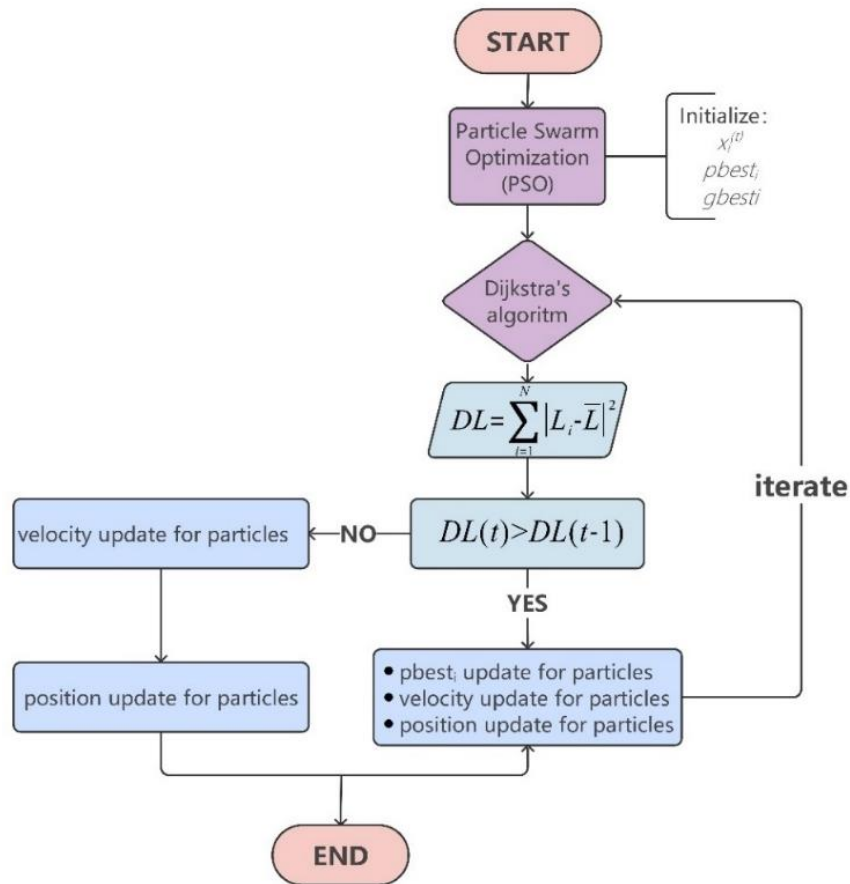


Figure 10: Integrated optimization process

### 6.3 Multi-Community Optimization

Numerous research studies, as clearly pointed out in [5], suggest that urban areas in the Baltimore frequently encounter the thorny problem of inaccessible rail transit stations. Specifically, in areas where the sidewalk infrastructure is in a poor state, with cracks, uneven surfaces, and a lack of proper maintenance, or where feeder traffic such as shuttle buses and local feeder trains is insufficient, this issue becomes even more pronounced. In such situations, citizens have no choice but to rely more on private cars for daily travel. As a result, the roads are filled with a large number of vehicles, leading to serious traffic congestion that wastes commuters' precious time. Additionally, the over - use of private cars significantly increases carbon emissions, posing a major obstacle to the long - term sustainable development of cities.

Moreover, regions with a fragmented transportation system, where different modes of transportation fail to connect smoothly, often experience social instability. The poorly - connected transit areas usually lack proper security measures, like adequate lighting and security patrols, creating an environment that is conducive to criminal activities, thus resulting in a relatively high crime rate. Therefore, in addition to optimizing residents' commute times, which is crucial for improving the quality of urban life, it is essential to address the problem of overly



dispersed transportation stations. By doing so, we can enhance social safety and stability, making cities more livable.

Due to the large area of Baltimore, it is difficult to control the variance of the distances between bus stops. Dividing Baltimore into multiple communities is more conducive to management. Thus, referring to the data in Bus\_Stops.csv, we conduct simulations using Matlab:

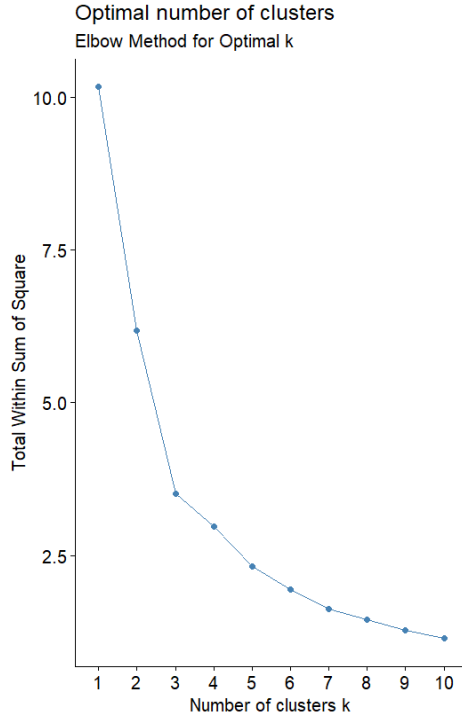


Figure 11:Scree Plot

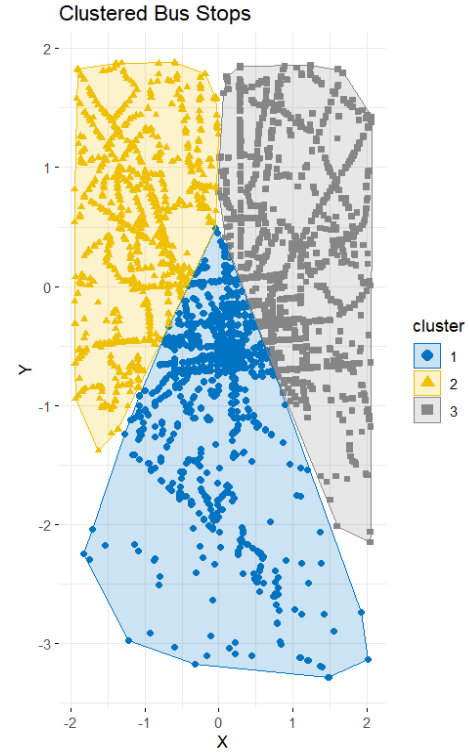


Figure 12:k-means community segmentation map

- Figure 11 presents a **Scree Plot** based on the density analysis of bus stops. It is evident from the figure that the slope of the broken - line becomes significantly gentler when  $k=3$ . Therefore, the number of factors (i.e., the number of community divisions in Baltimore) is determined to be 3.
- Figure 12 shows the specific division plan of Baltimore communities obtained according to the optimal number of factors and the **K - means** clustering method.

In the process of measuring the dispersion degree of bus - station distribution in each community, we introduce the objective function **Intra-Cluster Variance**  $S_k$ , which can measure the density of station distribution within a group. It calculates the average value of the sum of the squared distances from each point to the centroid within the cluster. For the  $k$  - th cluster:

$$S_k = \frac{1}{N_k} \sum_{i=1}^{N_k} \|x_i - \mu_k\|^2 \quad (11)$$

Where  $N_k$  is the number of points in the  $k$  - th cluster,  $x_i$  ( $i=1,2,3,\dots$ ) represents each point in the current cluster,  $\mu_k$  is the centroid of the  $k$  - th cluster, and  $\|x_i - \mu_k\|$  is the Euclidean distance between point  $x_i$  and the center point  $\mu_k$ . A smaller intra - cluster variance indicates that the points within the cluster are more densely packed.

Through simulation, the geographical coordinates of the centroid of each cluster and the intra - cluster variance are obtained, as shown in **Table 3**:

**Table 3: center point and Intra-cluster variance**



Cluster	1	2	3
$\mu_k$	(-76.625350,39.279292)	(-76.671369 , 39.327131)	(-76.576595,39.320633)
$S_k$	0.001152	0.001061	0.001114

In order to make the bus stops in the three communities more compact within a reasonable range, we determine the number of new bus stops to be added in each community according to the proportion of the intra - cluster variances:

$$S_1:S_2:S_3=0.001152 : 0.001061 : 0.001114 \\ \approx 100 : 92 : 97$$

Therefore, 100, 92, and 97 new bus stops are added to cluster 1, cluster 2, and cluster 3 respectively. Using **R Studio** for a new round of particle - swarm optimization simulation, 289 new bus stops are obtained, and the **K - means** clustering results are shown in the following figure:



Figure 13: Updated bus stop distribution clustering

## 6.4 Result

The following graph shows the variance of the station distribution in Baltimore after the addition of bus stops:

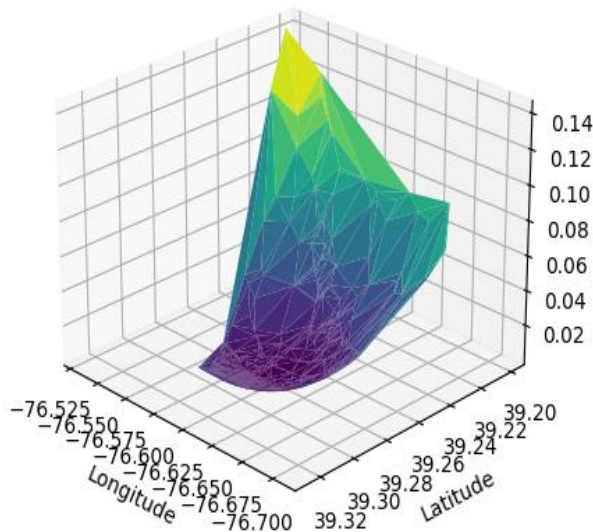


Figure 14: Intra-variants after optimization

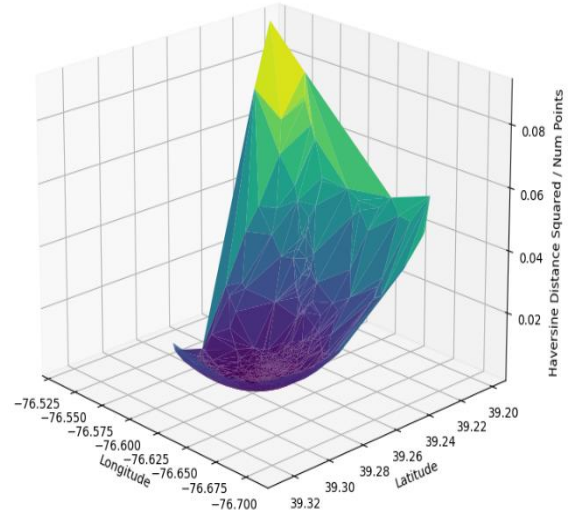


Figure 15: Intra-variants before optimization

It is worth noting that although the two plots appear to be indistinguishable, a closer look at the vertical axis reveals a significant reduction in intra-cluster variance. Which means that Baltimore's bus distribution is more balanced as a result of our program.

## 7 Model III: Kruskal - Edmonds Traffic Revitalization Model

Some research shows that the traffic - accident occurrence rate in Baltimore is relatively high compared to other states in the United States[6], especially on busy urban streets and highways. Due to certain deficiencies in road planning and design, as well as the unreasonable settings of curves, intersections, etc. on some roads, it is difficult to meet the increasing demand for traffic volume, which affects the smooth passage of vehicles, increases traffic congestion. Moreover, due to the collapse of the Francis Scott Key Bridge, the connectivity of part of the public transportation has been disrupted. Therefore, the project we recommend that can most improve the lives of Baltimore residents is as follows:

- Optimize the connectivity of the urban transportation network by connecting the transportation nodes in the city, while minimizing the connection of transportation nodes in high - risk areas.
- Optimize the traffic - volume distribution of vehicles on the major traffic arteries connecting the nodes to reduce traffic congestion and highway over - loading situations.

### 7.1 Kruskal Transit Connect - Pro Model

Our goal is to optimize the overall connectivity of the urban transportation network and reduce the accident - occurrence rate. **Kruskal's algorithm** in **Minimum Spanning Tree (MST)** is used to connect the various transportation nodes in the city, ensuring that the urban transportation network remains connected while minimizing traffic connections in high - risk areas. The following shows the general steps of Kruskal's algorithm:

- Given an undirected connected weighted graph  $G = (V, E)$ , where  $V$  is the set of nodes and  $E$  is the set of edges.

- Each edge  $e \in E$  has a non - negative weight value  $w(e)$ :

$$w(e) = \frac{1}{v_e}$$

- Sort all the edges in graph  $G$  in ascending order of their weight values to obtain an ordered list of edges  $S$ .
- Successively take out the edge  $e = (i, j), (i, j \in V)$  with the smallest weight value from the ordered list of edges  $S$ .
- Check whether nodes  $i$  and  $j$  belong to a connected component and make decisions on the inclusion or exclusion of the connection line.
- Iterate the previous step  $n$  times until the edge set contains  $|V| - 1$  edges, at which point the graph formed by the edge set is the connectivity-optimized transportation network

The following figure shows the pseudo-code of the Kruskal algorithm that implements the minimum spanning tree:

---

**Algorithm 2:** The process of Kruskal algorithm for minimum - spanning - tree:

---

**Input:**  $G = (V, E)$

**Output:**  $T$  (the set of edges of the minimum - spanning - tree)

**Set**  $T = \emptyset$  //Initialize the set of edges of the minimum - spanning – tree;

Sort all edges in  $E$  in ascending order of their weights;

**for** each  $v \in V$  **do**

    Make - Set( $v$ )// Create a separate connected component for each vertex;

**for** each edge  $(i, j)$  **do**

**if** Find - Set( $i$ ) $\neq$ Find - Set( $j$ ) **then:**

$T = T \cup \{(i, j)\};$

            Union ( $i, j$ )

**end if**

**return**  $T$

---

With this algorithm we can stimulate the connectivity-optimal transportation network for Baltimore.

## 7.2 E - K Smart - Flow Traffic Model

After refining the connectivity of the traffic network in Baltimore using the Kruskal algorithm, we also need to optimize the distribution of traffic flow on each road to avoid excessive concentration of buses or private cars on certain roads or intersections. The **Edmonds-Karp** algorithm can be used to regulate the flow of edges to balance the traffic flow in the transportation network and ensure an even distribution of traffic flow. The following are the general steps to implement the E-K algorithm:

- **Determine Source and Sink Nodes:** In the transportation network scenario of Baltimore, the main transportation hubs of the city are treated as **Source Nodes**  $s$  and other transportation nodes are treated as **Sink Nodes**  $t$ .
- **Determine Edge Capacities:** Determine the traffic flow on each edge  $C(i, j)$ :

$$C(i, j) = k \times width$$

Initialize traffic flow for all edges in the traffic flow network  $f(i, j) = 0$

- **Find Augmenting Path:** Create a residual network  $G_f$ , where the residual capacity of the edge  $C_f(i, j) = C(i, j)$ . Use **Breadth-First Search (BFS)** to find an augmenting path from the source node to the sink node in residual network  $G_f$ . Residual capacity of edges in the residual network  $r(i, j) = C(i, j) - f(i, j)$ , if  $r(i, j) > 0$ , then the edge exists in the residual network.
- **Update Flow:** Once an augmenting path is found, calculate the minimum residual capacity on the path  $\Delta(i, j)$ , this value determines the maximum amount of flow that can be added along this path. Update the flow along the augment path, for each edge:
 
$$\Delta(i, j) \begin{cases} \text{increase, } (i, j) \text{ is a forward edge} \\ \text{decrease, } (i, j) \text{ is a reverse edge} \end{cases}$$
- **Output the Result:** Continuously repeat the steps of finding the augmenting path and updating the flow until no augmenting path from  $s$  to  $t$  can be found in the residual network. the total flow leaving the source vertex  $s$  or entering the sink vertex  $t$  is the maximum flow of the network.

## 7.3 Results and Analysis

### 7.3.1 Results

Since the 1921 traffic nodes could not be fully visualized, we intercepted 30 of them to illustrate them:

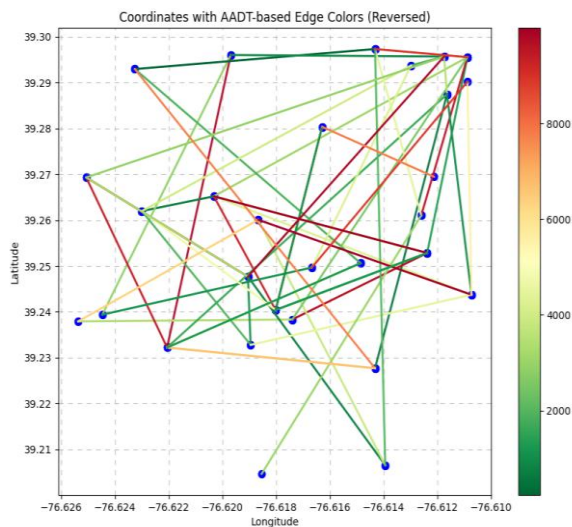


Figure 16: Traffic Flow Before Optimization

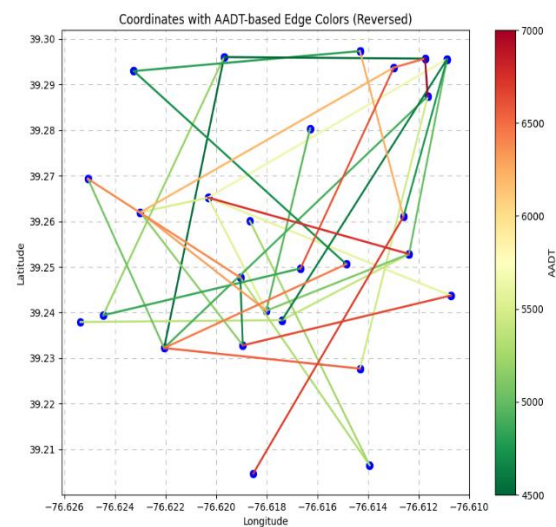


Figure 17: Traffic Flow After Optimization

The two graphs show the traffic flow on the edges connected to the selected nodes after the optimization has been carried out, there is quite a bit of extreme traffic on the edges before the optimization (too small or too large), and after the optimization the traffic on the edges has improved, proving that our project is feasible.

### 7.3.2 Analysis

We have the following analysis of the recommended PROJECT:

- What are the benefits to residents of this project?**

We use Kruskal algorithm to improve the connectivity of the transportation network and Edmonds-karp algorithm to control the traffic flow on the roads in a balanced range, so that Baltimore's highways will be more reasonable and the residents will spend less time on commuting during their daily trips. The reduction in traffic accidents will also improve the well-being and quality of life of the residents in the city.

**b) How does your project impact other stakeholders?**

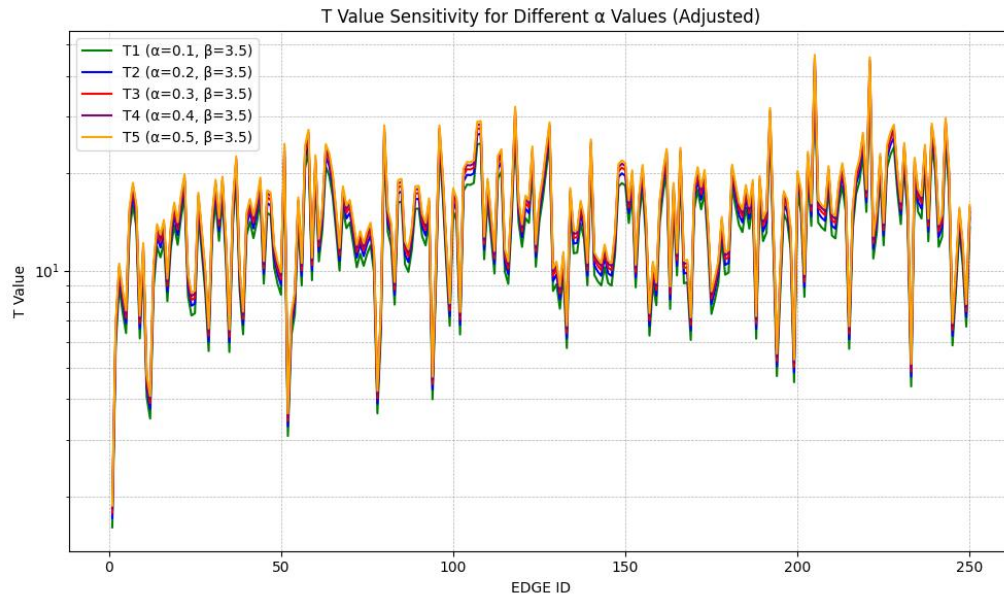
- **Government:** Improvements to urban transportation networks can help enhance the image and competitiveness of cities, attract more investment and talent, and promote long-term urban economic development. However, they require significant investment in project construction and maintenance, may face short-term financial pressure and take time to coordinate.
- **Transportation Operators:** After the optimization of the transportation network, the operational efficiency of public transportation will be improved, which can attract more residents to choose public transportation for travel and increase the income of transportation operating companies. However, during the construction period of the project, the operation order and revenue may be affected due to traffic control, etc. A certain amount of funds will need to be invested in vehicle renewal and personnel training to adapt to the new transportation environment.
- **Tourists:** With the implementation of our recommended programs, tourists have more routes to choose from when planning their trips, and are able to travel to various attractions more conveniently, enhancing the overall travel experience, while tourists are more secure during their trips.

**c) Explain the ways that our project disrupts other transportation needs and people's lives.**

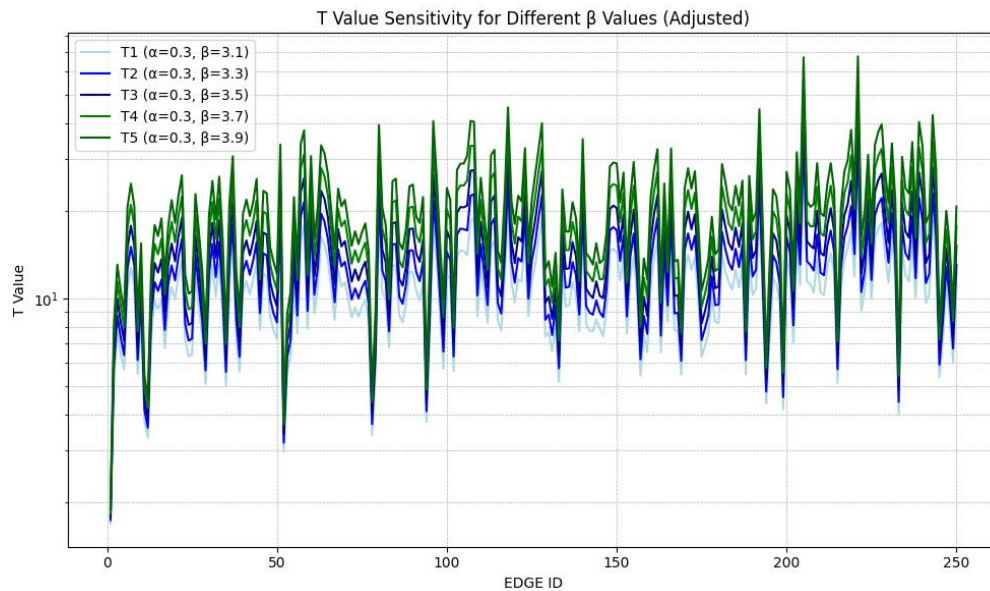
While optimized transportation networks are intended to be more efficient, it takes time for people to adjust to new routes and traffic patterns. Some people may find it difficult to quickly adjust their long-established travel habits, resulting in initial confusion and inconvenience. In addition, changes to the transportation network may create challenges for seniors and people with disabilities. They may have difficulty adjusting to new traffic signals, crossing wider roads, or using new transportation facilities. Special care and guidance will be needed to ensure that their trips are safe and convenient.

## 8 Sensitivity Analysis

In section 5.1, factors  $\alpha$  and  $\beta$  are introduced to estimate the simulate changes in traffic flow. Therefore, by varying the magnitude of this parameter, the relationship between traffic flow and travel time is also subjected to change , so we wish to analyze the sensitivity of the two parameters separately, simulation results are shown in Figure:



**Figure 18: Sensitivity analysis for parameter  $\alpha$**



**Figure 19: Sensitivity analysis for parameter  $\beta$**

Upon examining the aforementioned graphs, it is evident that when  $\alpha$  and  $\beta$  are subjected to specific perturbations, Commuting time of residents fluctuates up and down accordingly. In short, the model effectively captures the relationship between traffic flow and travel time on different roads, so it is logical and reasonable that the curves may change significantly at certain nodes.

## 9 Evaluation of Strengths and Weaknesses

### 9.1 Strength

- The main advantage is that all information on all road nodes, traffic flow, and bus stops are fully considered. At the same time, other algorithms such as Dijkstra's algorithm are used to scientifically and rationally propose improvements for local transportation.
- In this study, multiple optimization objectives are considered in an integrated manner so that the final solution can best satisfy the interests of different local stakeholders.

- The visualization work is well done, for example, the flowcharts in this study clearly and accurately show how these models solve the actual local traffic problems, while the use of shades of dots and road colors in place of the flow of people at the bus stops, which is very intuitive.
- This study is generalizable to other cities, and the traffic optimization strategies for other cities can be obtained simply by obtaining the relevant traffic data for that city.

## **9.2 Weaknesses and Further Improvements**

Our model has the following limitations and related improvements:

- Due to the difficulty of obtaining data related to the topography and hydrology of Baltimore City, its impacts on local transportation were not considered in this study. If relevant data become available in the future, they will be included in the study.
- For the maximum capacity of the lane this study only considered their width, other factors such as local terrain and the number of lanes were not included in the study.



# MEMORANDUM

**Subject:** Proposal for Optimizing Baltimore's Urban Transportation System

**To:** The Mayor of Baltimore

**From:** Team#2502815

**Date:** January 27, 2025

Dear Mayor,

The current transportation situation in Baltimore demands immediate attention to enhance the safety and convenience of our residents. This memo aims to present a comprehensive strategy focusing on optimizing the public transit and road systems as the most cost-effective approach. Compared to investing in extensive railway expansion or other high-cost transportation modes, upgrading the bus and road systems offers a more immediate and affordable solution. The capital expenditure required for building new railway lines is substantial, involving costly land acquisition, complex engineering works, and long construction periods.

The first project provides convenience for residents. New bus stops strategically located in residential areas and near key destinations such as schools, hospitals, and shopping centers will significantly reduce walking distances for commuters. This means residents can access essential services more quickly.

However, there is noise and air pollution. The increased frequency of buses stopping and starting at new stops may generate additional noise. Moreover, buses emit exhaust fumes, contributing to local air pollution. However, modern technologies such as electric buses can mitigate these issues, and proper site selection can minimize the impact on sensitive areas. By improving road connections in project two, we can reduce travel times and congestion. This not only saves time but also reduces stress levels associated with traffic jams, leading to safer driving conditions.

In emergency situations, better-connected roads enable quicker access for ambulances, fire trucks, and police vehicles. When the overall traffic volume remains constant, redistributing traffic evenly across different roads can prevent bottlenecks and gridlocks. This is achieved through intelligent traffic management systems, such as variable message signs and adaptive traffic signals. By guiding drivers to less congested routes, we reduce the likelihood of rear-end collisions and other accidents caused by sudden stops and starts in heavy traffic. It also minimizes wear and tear on specific roads, reducing the need for frequent and costly repairs, which ultimately benefits taxpayers and ensures a safer driving environment. Thank you for your attention!

Best regards,



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## Report on Use of AI

### 1. OpenAI ChatGPT (Nov 5, 2023 version, ChatGPT-4)

Query1:

What negative impact has the collapse of Francis Scott Key Bridge had on local traffic in Baltimore?

Output1:

The collapse of the Francis Scott Key Bridge in Baltimore would have had significant negative impacts on local traffic. Some of the key issues include:

1. **Increased Traffic Congestion:** The bridge is an essential route for connecting key areas of the city. Without it, traffic would likely be diverted to other nearby bridges or roadways, leading to increased congestion on those routes. This could slow down travel times for commuters and create bottlenecks.
2. **Delays for Commuters and Freight Traffic:** The Francis Scott Key Bridge is important not only for daily commuters but also for freight transport. Its closure would disrupt the flow of goods and services, causing delays for businesses that rely on quick transport across the region.
3. **Longer Detours:** With the bridge out of service, drivers would have to take longer detours, potentially adding several miles and additional time to their journeys. This could be particularly challenging for people in a rush, such as those with time-sensitive work or appointments.

### 2. OpenAI ChatGPT (Nov 5, 2023 version, ChatGPT-4)

Query1:

What traffic problems in Baltimore need to be improved?

Output1:

Baltimore faces several traffic-related issues that need improvement. These problems range from congestion to infrastructure challenges and could benefit from targeted solutions. Some key areas for improvement include:

1. **Traffic Congestion:**
  - **Problem:** Baltimore experiences heavy congestion, especially during peak rush hours on major highways like I-695 (the Beltway), I-95, and I-83. Traffic jams can extend travel times, affecting commuters and freight transport.
  - **Solution:** Expanding road capacity, improving public transit options, or implementing more efficient traffic management systems like adaptive traffic signals could help alleviate congestion.
2. **Traffic Safety:**
  - **Problem:** High rates of traffic accidents, particularly in areas with poor lighting, confusing intersections, or high-speed limits, contribute to safety concerns. This also affects vulnerable road users, like pedestrians and cyclists.
  - **Solution:** Implementing safer traffic calming measures (such as speed bumps, more traffic signals, and red-light cameras), improving intersection design, and increasing public awareness about traffic safety could help reduce accidents.