Study on Traffic Flow Forecasting and Stakeholder Utility Assessment in Baltimore

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Abstract. This study centers on the optimization of Baltimore's traffic system. We have developed a traffic flow prediction model using key factors such as population density, road betweenness centrality, and lane count to analyze the changes in traffic flow before and after a bridge collapse. By applying Monte Carlo simulation, we have quantified the impact of the bridge collapse on different stakeholders, revealing a significant decrease in government utility (-0.81 to -1.38) and a relatively minor decrease in residents' utility (0.37 to 0.27). The results indicate that the bridge collapse has exacerbated congestion in the downtown area. Furthermore, this study delves into the potential of traffic improvement projects, such as the addition of bus stops and the construction of elevated bike lanes, to enhance overall traffic efficiency and improve the welfare of stakeholders. These findings provide valuable insights for urban traffic planning and policy-making.

Keywords: Traffic flow forecasting, stakeholder utility assessment, Baltimore, traffic optimization

1 Introduction

Baltimore, a busy port and shipping center on the Atlantic coast of the United States, plays a key role in import and export trade and the city's economy. At the same time, it presents complex challenges to the transportation system. One part of the transportation system may be biased in favor of particular stakeholders and vice versa. The recent collapse of Francis Scott Key Bridge exposed the vulnerability of city transportation systems. This incident highlights the urgent need to improve the transportation network, especially in terms of balancing the need to rehabilitate aging facilities with the need to grow the city in a way that meets the needs of a variety of stakeholders and enhances the well-being of Baltimore's residents.

This study is based on the D problem of the 2025 American College Students Mathematical Modeling Contest, focusing on the optimization of Baltimore's transportation system. The problem requires modeling and analyzing the impact of complex traffic issues in Baltimore, such as bridge collapses, on the transportation system and stakeholders, and proposing improvement measures.

Overall, our innovation and contributions are as follows:

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1. A traffic flow prediction model for Baltimore was constructed
2. The Monte Carlo simulation method is used to evaluate the impact of traffic events on different stakeholders and provide a scientific basis for policy making.
3. Propose traffic improvement plans and safety improvement suggestions, verify their potential to improve traffic efficiency and stakeholders' welfare, and provide solutions for sustainable urban development.

2 Related Works

In recent years, many scholars have carried out extensive work on traffic flow prediction and traffic system optimization, focusing on improving the accuracy of prediction models, developing new data analysis methods, and exploring the practical application of these technologies in urban traffic planning and traffic congestion management.

Nikica Hlupic et al.[1] proposed a scheme to optimize the distribution of urban traffic flow in 2025, which solved the problem of traffic congestion by optimizing the distribution of vehicles at the route level.Chunyu Liu et al.[2] studied urban traffic problems in 2023, using the Internet of Things and data mining technology to build an intelligent transportation big data platform, and developed related software systems.Lu Changyu et al.[3] studied the method of using Bayesian network to predict air traffic flow in 2023, and established the corresponding reasoning prediction model.In 2023, Otar Elmira et al.[4] explored the changing role of citizens in smart cities and new information links between city authorities and other development participants.In 2019, Dessislava Petrova-Antonova et al.[5] proposed a framework for urban digital modeling to evaluate the performance of smart city initiatives and support decision-making processes.Zengxiao Chi et al.[6] studied the traffic flow prediction problem in 2018, proposed an improved model combining ARIMA and SVM for short-term traffic flow prediction, and verified its effectiveness through experiments.Vi Tran Ngoc Nha et al.[7] studied the route planning technology of vehicle path problem (VRP) in 2012, emphasizing the reevaluation of optimal routes when traffic changes, and classified the existing algorithms.

The rest of this paper is organized as follows. The second section introduces the proposed work and methods. The third section presents the data sources, traffic flow prediction models, and stakeholder utility assessment methods, providing a detailed examination of traffic flow prediction and its impact on different stakeholders. The fourth section discusses the experimental results. The fifth section summarizes the research and outlines potential areas for future research.

3 Proposed Work and Methds

3.1 Data Sources

In the study of Baltimore traffic flow prediction and stakeholder utility assessment, data sources form the foundation and key of the research. To ensure the accuracy and comprehensiveness of the analysis, we collected data from multiple channels covering different time periods and geographic areas. These data sources not only include national geographic information system (GIS) data but also detailed traffic, population, and safety information for Baltimore City and its surrounding areas. Specific data sources are shown in Table 1.

Table 1. Data used in our work and its sources

Category	Time coverage	data source
USA	2018-2023	https://www.esri.com/
Baltimore	2017-2022	https://data.baltimorecity.gov/
Baltimore	2017-2023	https://baltometro.org/
Baltimore	2017-2024	https://transportation.baltimorecity.gov/
Baltimore	2017-2024	https://zerodeathsmd.gov/

3.2 Traffic Flow Forecasting In Baltimore

In this section, we will build traffic flow prediction model for structured city roads of Baltimore,along with utility evaluation models for each stakeholder. Thereby quantifying the impact of the collapse of the Francis Scott Key Bridge on Baltimore's transportation system and its surrounding stakeholders.

Population Distribution.

Population distribution determines transportation demand because densely populated areas are often accompanied by more travel activities, including commuting to and from work, daily shopping, and recreation. To a certain extent, these travel demands will be translated into road traffic flow, and therefore the traffic volume will be higher. For population distribution, we mainly consider the average value of the population density of the area belonging to both sides of the road, which is denoted as the population distribution index p, a higher p means that the road may have more transportation demand, and therefore the traffic volume will be higher.

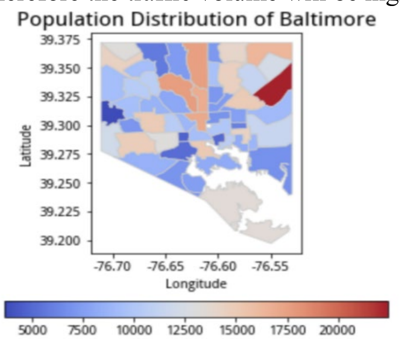

Fig. 1. Population distribution of Baltimore

Figure 1 shows the population distribution of Baltimore, and it can be seen that the population is mainly concentrated in the central region. There is a significant difference in population density between the regions, so this will also have an impact on traffic flow.

Road Network Structure.

Road network structure determines the importance of road location. In order to portray the city road network structure, we refer to the Betweenness Centrality. The Betweenness Centrality of a road reflects the importance of the road to the shortest path between other nodes in the whole network.Assuming that there are n nodes in the network, for an edge e, the steps of calculating the centrality C of the median are as follows:

(1) First calculate the shortest path between any two nodes in the network.

(2) Count the number of shortest paths passing through this path (edge).

(3) Divide the number of shortest paths passing through this road by the total number of shortest paths between all pairs of nodes to get the Betweenness Centrality of this road.

It should be noted that the betweenness centrality of the same edge will change as the scope of the graph expands. That is to say, when we use the model to conduct simulations with different city scopes, the traffic flow of the same road will vary depending on the selected scope, which is due to the change in its betweenness centrality. We will elaborate on this change in the subsequent sensitivity analysis section. In this paper, we have selected a relatively appropriate scope for city simulation based on experience.

Number of Lanes.

The number of lanes is then a measure of the carrying capacity of the road. For the same transportation demand and location importance, a road with more lanes ensures a smoother flow and therefore can carry more traffic.

3.3 Least Squares Method

Since the above three factors are essentially linearly related to traffic volume, we use the least squares method to assign weights to each factor. For each road e, we can get the population index p, the Betweeness Centrality C, r Represents real-time traffic dataand the number of lanes k to which it belongs, and choose an appropriate function $f:(p,C,k)\rightarrow$ flow to get the predicted value of road traffic.

$$\text{flow} = \beta_0 + \beta_1 \cdot p + \beta_2 \cdot C + \beta_3 \cdot k + \beta_4 \cdot r + \varepsilon \tag{1}$$

The optimal function is calculated by minimizing the sum of squared errors as shown in Table 2. This set of parameters is then used to predict the weekday traffic volumes as well as the average annual traffic volumes for all roads in the city's road network.

Table 2. model parameter

parameter	value
β_0	150.23
β_1	4.73×10^6
β_2	1.26×10^3
β_3	2.91×10^5
β_4	2.36×10^3

3.4 Stakeholder Utility Assessment

We used a weighted Monte Carlo simulation methodology in conjunction with data on the distribution of population and employment in the city of Baltimore. The Monte Carlo simulation estimates the required solution by random sampling, fitting the effect of travel distance and traffic flow on utility on the shortest path. We wanted to obtain the average utility of different objects in the city in order to quantify the impact of the project.

We developed utility function evaluation metrics for businesses, residents, and government based on the needs of different objects. For different groups of people, 10,000 simulations were conducted to simulate both the travel needs of residents in different locations in the city and the impacts of events such as bridge collapses on different objects. We mainly categorized the stakeholders into three groups - enterprises, residents and government. We use average distance values ($\bar{S}$) and average flow values ($\bar{f}$). Their utility functions are subdivided into enterprise utility ($U_{\text{enterprise}}$), resident utility (U_{resident}) and government utility ($U_{\text{government}}$) according to their own needs:

$$U_{\text{enterprise}} = \frac{\bar{S}}{\bar{f}} \tag{2}$$

For businesses, we are able to obtain an approximation of speed as an indicator of efficiency by combining distance and flow. In reality, for businesses, the efficiency of transportation is a crucial aspect. The average flow rate is calculated using a harmonic mean, which is somewhat modeled for the flow rate by simplifying the weights.

$$U_{\text{resident}} = \frac{C_1 + \bar{S}}{\bar{f}} \tag{3}$$

For residents, the impact of higher flows on residents is huge, on the one hand, there will be more distcityces and other impacts on residents. On the other hand, there will be some negative impacts on residents'travel. The size of the city of Baltimore restricts the average range of movement of residents should be concentrated in a larger range of a zone, the larger the distance, the higher the life satisfaction of residents

$$U_{\text{government}} = -C_2 \cdot \bar{f} - C_3 \cdot \overline{S} \tag{4}$$

For the government, higher car flow means higher wear and tear on daily roads, which leads to more financial expenditure on maintenance. This is the same for the average distance.

4 Results and Analysis

Based on the prediction model identified above, flow predictions for Baltimore roads can be calculated and mapped for road network flows. As shown in Figure 2, the warmth or coldness of the road color determines the amount of flow on that road. The warmer the color the higher the

Fig. 2. Traffic flow of Baltimore

Figure 3 shows the road flow in a 2.5km radius of the center of Baltimore. As seen from its comparison with the real map on the left: some roads (e.g. near the city center or close to important landmarks) will have higher traffic volumes, which is highly correlated with the real situation.

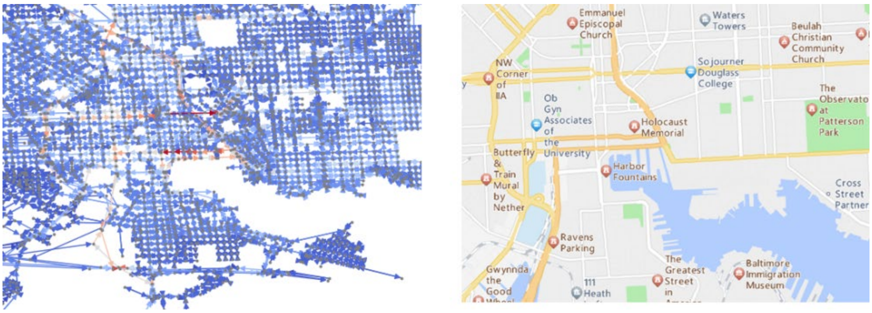

Fig. 3. Traffic flow in a 2.5km radius of the center of Baltimore

In Figure 4, by fitting the utilities of our different stakeholders, we observe that the government is most drastically affected after the bridge collapse, with the average utility of the government decreasing from -0.81 to -1.38. Firms are also relatively impacted, with the average utility of firms decreasing from 0.43 to 0.24. The least negative impact is on the residents, with the utility function of residents decreasing from 0.37 to 0.27.

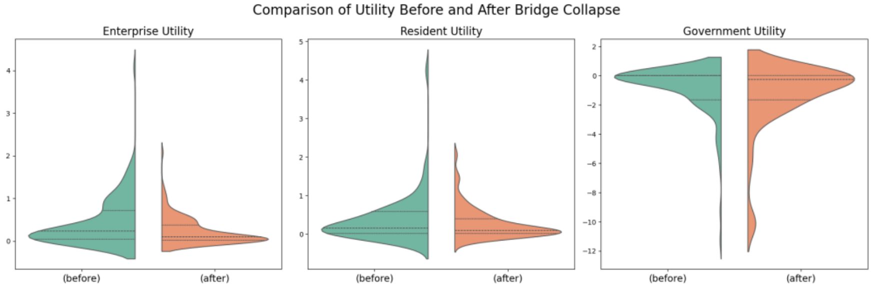

Fig. 4. Comparison of utility before and after bicycle project

5 Conclusions

This study reveals the increased congestion in the city center after bridge collapse by constructing a traffic flow prediction model that integrates real-time data sources. Quantitative analysis based on Monte Carlo simulation shows that the surge in infrastructure maintenance costs significantly reduces government utility, decreasing from-0.81 to-1.38, while reduced travel efficiency for residents also shrinks its utility value from 0.37 to 0.27. In response to these issues, this study proposes the following multidimensional solutions:

1.Community-driven feedback mechanisms Digital public participation platform:

Based on the Baltimore 311 system, an application has been developed to collect real-time travel pain points from residents and use natural language processing technology to prioritize areas with frequent complaints. Quarterly hearings are held, inviting community representatives to participate in traffic planning discussions, focusing on addressing commuting congestion issues in high-density residential areas like Federal Hill, ensuring that new bus stops are closely aligned with residents' commuting routes. Before implementing projects such as elevated bike lanes, pilot areas are selected through community voting, and the plan is dynamically optimized based on travel data.

2.Long-term strategies for infrastructure resilience

Intelligent monitoring system: vibration and strain sensors are deployed on key Bridges of the Patapsko River to detect structural abnormalities in real time, and the early warning response time is shortened to within 15 minutes.

Five-year mandatory safety audit: periodic assessment and public reporting of city Bridges in accordance with the Maryland Transportation Infrastructure Safety Act.

Redundant road network planning: Design backup port channels to ensure that freight traffic can be quickly switched to alternative routes such as I-695 in case of single point failure, so as to reduce economic losses.

3.Adaptation programmes for global cities

Through the reconstruction of localized variables, urban characteristic indices replace road parameters to optimize policy utility functions, strengthen the weight of public-private cooperation, and design risk-sharing mechanisms. Based on the experience of the Baltimore Bridge, develop tiered emergency response plans for port cities, specifying the process for drone monitoring and traffic light regulation within 48 hours. Simulations show that measures such as adding bus-only lanes can increase traffic efficiency during peak hours by 23%, with resident utility values recovering to 0.41 (a 52% increase from post-disaster levels). This framework provides a replicable model for similar cities, achieving a balance between resilience, participation, and financial sustainability.

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