# TRB Annual Meeting

## Unveil Short-Term Traffic Change in Baltimore After Francis Scott Key Bridge Collapse

--Manuscript Draft--

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| **Full Title:** | Unveil Short-Term Traffic Change in Baltimore After Francis Scott Key Bridge Collapse |
| **Abstract:** | The catastrophic collapse of the Francis Scott Key Bridge in Baltimore, Maryland, on March 26, 2024, triggered by a collision with the MV Dali container ship, has led to severe mobility disruptions. Commuters are experiencing significant delays, increased traffic density raises the risk of crashes, and emergency response times are likely extended, further jeopardizing public health and safety. This crisis has also exacerbated the socio-economic difficulties faced by nearby low-income and underserved communities. To address these disruptions and restore mobility in the region, a comprehensive understanding of the short-term impact is essential. Therefore, this study employs traditional aggregated speed data and a unique large-scale trajectory data set, which has not been used in previous studies on similar topics, to investigate the impact on regional traffic patterns, bottlenecks, and disadvantaged communities. The analysis reveals severe congestion on the primary detour routes during peak periods. For bottlenecks approximately eight miles in length, travel times increased to two and a half to three times their value before the bridge collapse, or three to four times the free-flow travel time. The increased travel times were substantial enough to cause a notable increase in the duration of entire trips for both commuters and long-distance travelers. A significant portion of the trips traveling along the bottlenecks either originated from or were destined for disadvantaged communities. This percentage is substantially higher than the percentage of the population living in disadvantaged communities in this area, highlighting the disproportionate impact of the bridge collapse on these populations. |
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# Unveil Short-Term Traffic Change in Baltimore After Francis Scott Key Bridge Collapse

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**ABSTRACT**
The catastrophic collapse of the Francis Scott Key Bridge in Baltimore, Maryland, on March 26, 2024, triggered by a collision with the MV Dali container ship, has led to severe mobility disruptions. Commuters are experiencing significant delays, increased traffic density raises the risk of crashes, and emergency response times are likely extended, further jeopardizing public health and safety. This crisis has also exacerbated the socio-economic difficulties faced by nearby low-income and underserved communities. To address these disruptions and restore mobility in the region, a comprehensive understanding of the short-term impact is essential. Therefore, this study employs traditional aggregated speed data and a unique large-scale trajectory data set, which has not been used in previous studies on similar topics, to investigate the impact on regional traffic patterns, bottlenecks, and disadvantaged communities. The analysis reveals severe congestion on the primary detour routes during peak periods. For bottlenecks approximately eight miles in length, travel times increased to two and a half to three times their value before the bridge collapse, or three to four times the free-flow travel time. The increased travel times were substantial enough to cause a notable increase in the duration of entire trips for both commuters and long-distance travelers. A significant portion of the trips traveling along the bottlenecks either originated from or were destined for disadvantaged communities. This percentage is substantially higher than the percentage of the population living in disadvantaged communities in this area, highlighting the disproportionate impact of the bridge collapse on these populations.
**Keywords:** Francis Scott Key Bridge Collapse**,** Traffic Impact, Travel behavior, Transportation Equity

## INTRODUCTION

The catastrophic collapse of the Francis Scott Key Bridge in Baltimore, Maryland, on March 26, 2024, triggered by a collision with the MV Dali container ship, has led to severe mobility disruptions. With no convenient alternate routes available, the incident has drastically affected around 34,000 daily commuters, and even more long-distance travelers. The closure of the outer loop of I-695 up to Quarantine Road and the inner loop at MD 157 (Peninsula Expressway) has forced travelers to take lengthy detours via I-95 (Fort McHenry Tunnel) or I-895 (Baltimore Harbor Tunnel), as depicted in Figure 1.

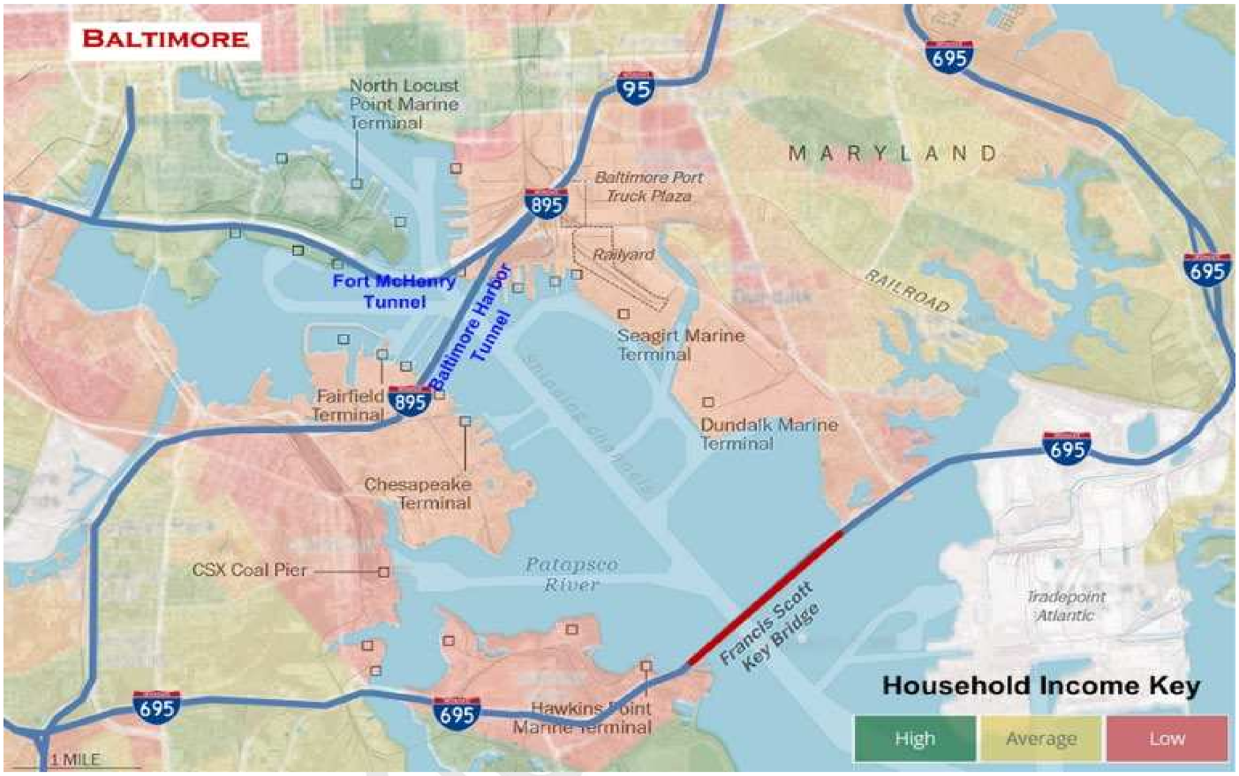


**Figure 1 The impact area and household income index in Baltimore City**

The short-term impacts of this disaster are immediate and widespread. Commuters are experiencing significant delays due to the detours, leading to increased travel times and higher transportation costs. The increased traffic density on these detour routes raises the risk of crashes, and emergency response times are likely extended, further jeopardizing public health and safety. Even worse, the sudden surge in traffic volume on detour routes can lead to a significant drop in roadway capacity, exacerbating congestion. Historical precedents, such as the I-35W Mississippi River bridge collapse in Minneapolis, demonstrated the severe congestion and extensive traffic management interventions required to mitigate disruptions following such an incident (*1*, *2*). This crisis has also exacerbated the difficulties faced by nearby low-income and underserved communities, where over a quarter of residents live in poverty and the rate of respiratory diseases is 35% higher than the national average, compounding existing socio-economic challenges. Therefore, a comprehensive understanding of the short-term impact is essential to develop immediate and effective traffic management strategies to address these disruptions and restore mobility in the region.

The objective of this study is to investigate the short-term traffic changes in Baltimore following the collapse of the Francis Scott Key Bridge. In addition to traditional aggregated speed/travel time data, this study utilizes a unique large-scale trajectory data set that has not been used in previous studies on similar topics. This data set covers the entire Baltimore area and generates more than 3,300 data points per hour during peak periods, allowing for a detailed analysis of traffic patterns, bottlenecks, and the impact on disadvantaged communities. By analyzing these patterns, the study aims to identify critical congestion points, assess the bottlenecks along detour routes, and investigate the broader implications for travelers, particularly those living in underserved communities.

## METHOD AND DATA

To understand the impacts of the bridge collapse on shorter-term traffic patterns, a multi-step analysis (as shown in Figure 2) was conducted. First, the regional traffic pattern changes were examined to identify the broader effects of the collapse. Based on this regional analysis, specific bottlenecks that either worsened or improved were identified, and a detailed statistical analysis of trip durations along these bottlenecks was performed. Lastly, an exploratory study on the origins and destinations of the most affected travelers was conducted to provide valuable insights for planners and policymakers.

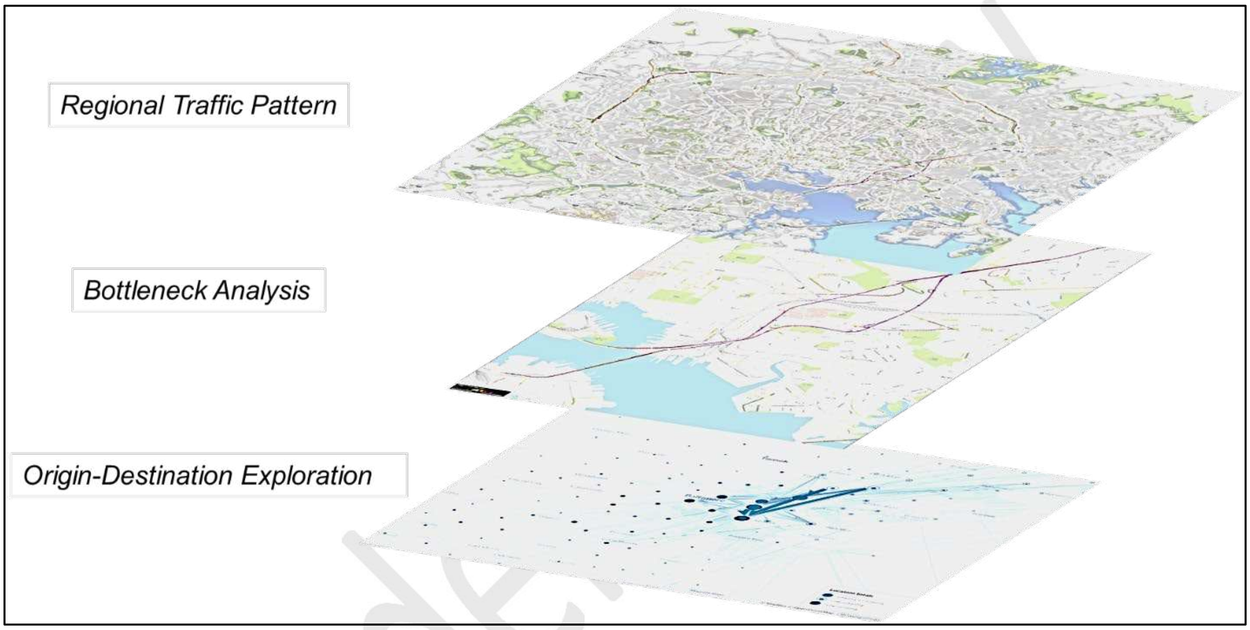


**Figure 2 Study Outline**

### Regional Traffic Pattern

The Probe Data Analytics Suite from Regional Integrated Transportation Information System (RITIS) (*3*) was utilized to analyze traffic pattern changes in the Baltimore area. This tool generates and visualizes performance measures using speed data from probe vehicles. In this study, segment-level travel time index (TTI) was used to measure congestion:

$$TTI = \frac{Travel\ Time}{Free\ Flow\ Travel\ Time} \tag{1}$$

the "free flow" travel time is derived from the 66th-percentile observed speeds for each segment across all time periods, serving as a reliable proxy for free-flow speeds. The change in TTI before and after the collapse was measured to assess its impact on traffic conditions. Additionally, speed was used as the reference for absolute travel time. Both TTI changes and speed were visualized geographically for the AM (6:00-10:00 AM) and PM (4:00-8:00 PM) peak periods. Data was collected from three Wednesdays without severe incidents before (02/28/2024, 03/06/2024, 03/13/2024) and after (04/03/2024, 04/10/2024, 04/17/2024) the collapse.

**Bottleneck Analysis**

The analysis began by identifying bottlenecks that either worsened or improved after the bridge collapse, based on regional traffic patterns. Since traffic patterns can vary between AM and PM peak periods, different bottlenecks were identified for each period. Changes in average speed and Travel Time Index (TTI) for these bottlenecks were then calculated to quantify the impact.

While shifts in travel time (index) along the bottlenecks provide valuable local information, some travelers may be more concerned with the overall impact on their entire trips rather than individual segments. Additionally, bottleneck effects often spill over to upstream and downstream areas. For instance, a queue formed due to a bottleneck can extend further upstream, and a temporarily eased downstream bottleneck may result from a severe upstream bottleneck preventing vehicles from moving downstream.

Therefore, to understand the broader impacts of these bottlenecks, trip durations along them were analyzed using anonymous real-world trip trajectories from RITIS, collected from in-vehicle GPS receivers or cell-phone applications, totaling approximately 160,000 sampled trajectories. Trips were categorized into "shorter" (commuting) and "longer" (other purposes) trips. Considering the characteristics of the study area, the threshold was set at 15 miles, consistent with one of the authors' earlier studies. Paired t-tests were employed to compare mean trip durations before and after the collapse, considering trips from the same origin and destination Traffic Analysis Zones (TAZs) as paired observations. The t-tests were formulated as follows:

$$d_i = TD_{ib} - TD_{ia} \tag{2}$$

$$t = \frac{\bar{d}}{s_d/\sqrt{n}} \tag{3}$$

where $TD_{ib}$ and $TD_{ia}$ are the mean trip durations before and after the collapse; $d_i$ is the difference in trip duration for pair $i$; $\bar{d}$, and $s_d$ are the mean and standard deviation of differences across all pairs; $n$ is the number of O-D pairs; and $t$ is the t-statistic used to find the p-value. If the p-value is below the significance level, the null hypothesis of no difference is rejected, indicating significant changes in trip durations. Three sets of paired t-tests were conducted for all trips, shorter trips, and longer trips.

**Origin-Destination Exploration**

To further understand the impacts of the worsened bottlenecks on travelers following the bridge collapse, an exploratory analysis was conducted to gain insights into the origins and destinations of the trips traveling along these bottlenecks. The impact on underserved populations was inferred by identifying whether these trips originated from or were destined for underserved communities, as defined by the Climate and Economic Justice Screening Tool (CEJST) (*4*).

The CEJST, developed by the U.S. federal government, identifies communities most affected by climate change and economic injustice, using data indicators across eight categories: climate change, energy, health, housing, legacy pollution, transportation, water and wastewater, and workforce development. The CEJST shows disadvantaged communities in census tracts. These tracts were then matched with the origins and destinations of the trip trajectories to identify trips that either originated from or were destined for these disadvantaged areas.

The percentage of trips associated with disadvantaged communities was calculated and compared with the percentage of population living in disadvantaged communities in the study area, as derived from the CEJST. This comparison helped to quantify the impact of the worsened bottlenecks caused by the bridge collapse on disadvantaged populations.

For this exploratory analysis, only trajectories collected from cell-phone applications were used, specifically excluding those from freight trucks to ensure the focus remained on passenger travel patterns.

**RESULTS**

**Regional Traffic Pattern**

Figure 3 illustrates the changes in the TTI across various segments in the Baltimore area during the AM peak. The color coding indicates the degree of change in TTI following the bridge collapse: dark blue, dark green, and light green represent improvements in traffic conditions, with TTI decreasing by more than 100%, between 50% and 100%, and between 20% and 50%, respectively. Conversely, magenta, red, and orange indicate worsening traffic conditions, with TTI increasing by more than 100%, between 50% and 100%, and between 20% and 50%.

In general, the most significant changes occurred along the freeways. The most severe bottlenecks were observed on I-95 and I-895, the major north-south freeway corridors of the East Coast of the U.S. Specifically, the southbound sections before the Fort McHenry Tunnel (I-95) and the Baltimore Harbor Tunnel (I-895) in the southeastern part of Baltimore experienced substantial congestion. These bottlenecks extended approximately 8 miles upstream to the interchange of I-695, indicating a severe spillover effect. As I-95 and I-895 are the primary detour routes for trips originally routed over the Francis Scott Key Bridge, the worsening of these bottlenecks was expected as traffic is now rerouted through these tunnels. A more detailed analysis of these bottlenecks will be presented in the bottleneck analysis section.

For I-695, the ring road of Baltimore City, increased congestion is observed in segments north of the interchange with I-70 (a major east-west interstate with its eastern terminus just outside Baltimore City) and the northeast interchange with US Route 1 (a major north-south US Highway serving the East Coast). Specifically, the outer loop is more congested east of the interchange with I-87 (an interstate running north-south within Baltimore City), while the inner loop is more congested in western segments. The increased travel time may also be due to detoured traffic from the bridge. The increased travel time may also be due to detoured traffic from the bridge, such as vehicles transporting hazardous materials that are prohibited from entering the tunnels, those avoiding tolls, and some avoiding the severely congested. Conversely, travel conditions significantly improved for southern segments of the interchange with I-70 and the collapsed bridge, as traffic originally using the bridge was rerouted.

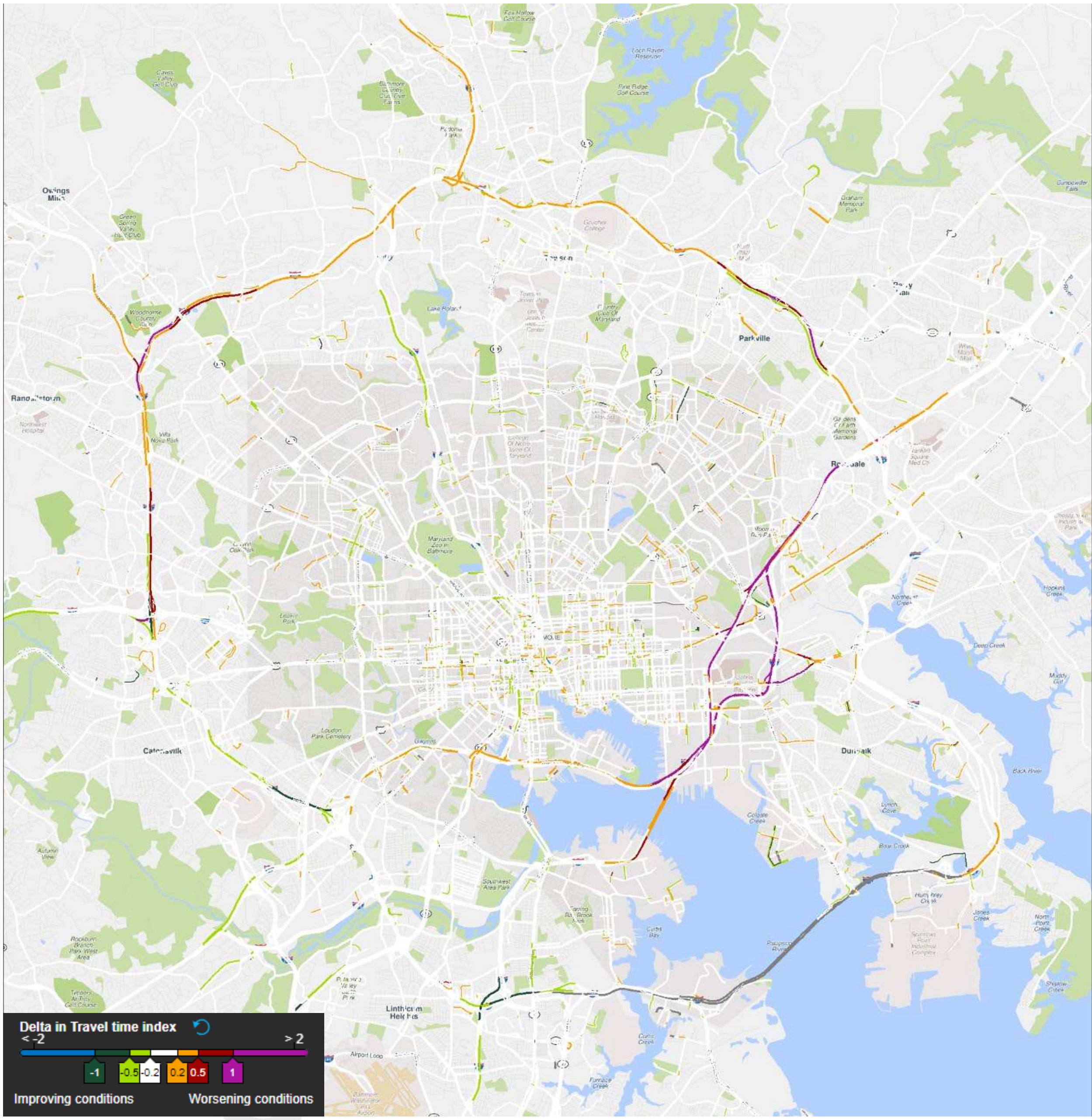


**Figure 3 Change of TTI in Baltimore Area During AM Peak**

In the downtown area, as shown in Figure 4, traffic conditions on certain arterial segments either improved or worsened. For example, travel times increased slightly along eastbound E Eager St and westbound US 40 around I-87, while travel times decreased slightly along eastbound E Lexington St and S Calvert St around the Inner Harbor. However, the magnitude of these changes is not comparable to the freeway bottlenecks mentioned earlier. One possible reason for the lower impacts in the downtown area is that these roadways were already highly congested during peak periods before the bridge collapse. As suggested by Figure 5, the average segmental speeds on almost all arterials and local roads in the downtown area are below 20 mph, with some even less than 10 mph. In other words, the speed along these local roads is even lower than that on the congested freeways, making them less attractive as detours. Therefore, there may be less traffic rerouting to the downtown area.

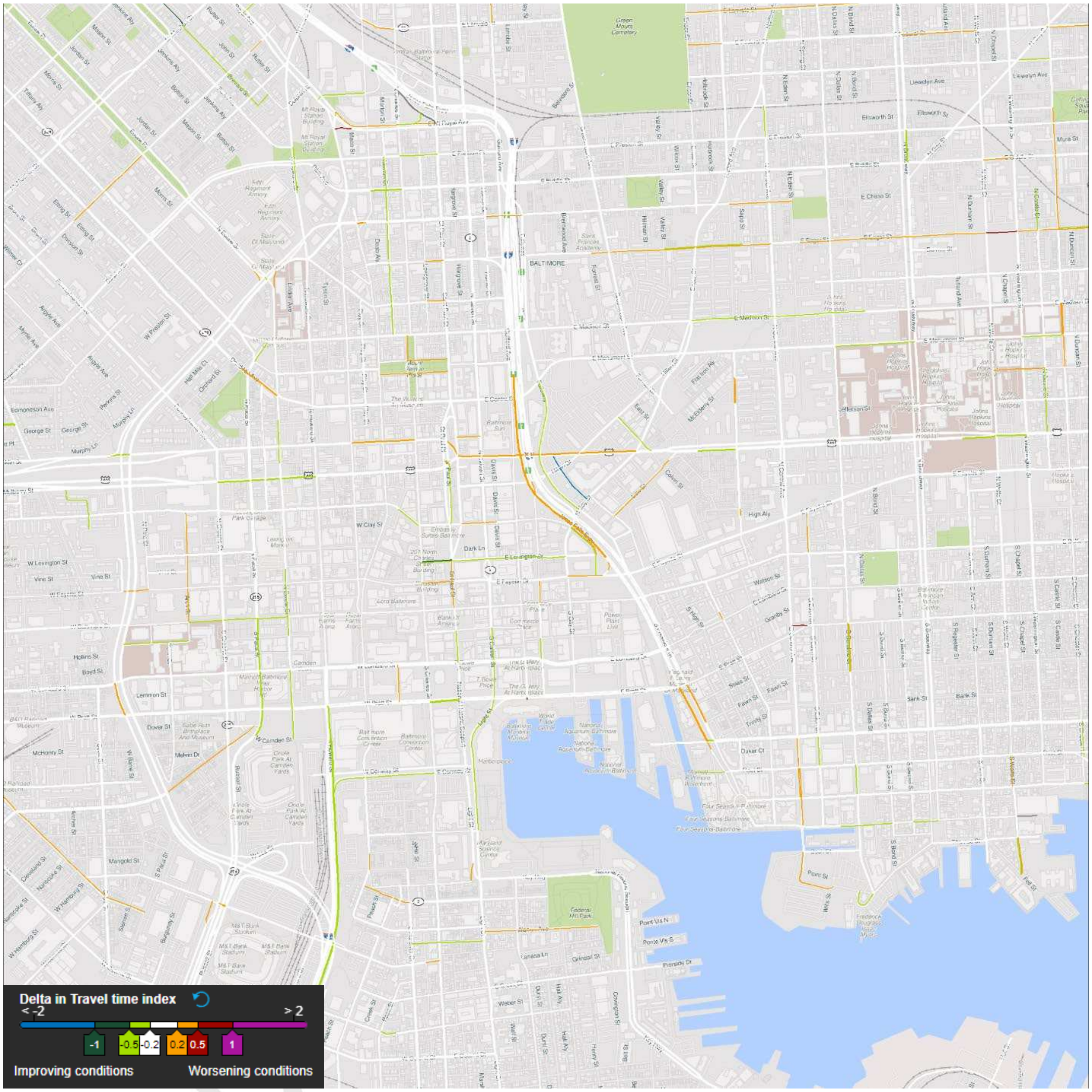


**Figure 4 Change of TTI in Downtown Baltimore During AM Peak**

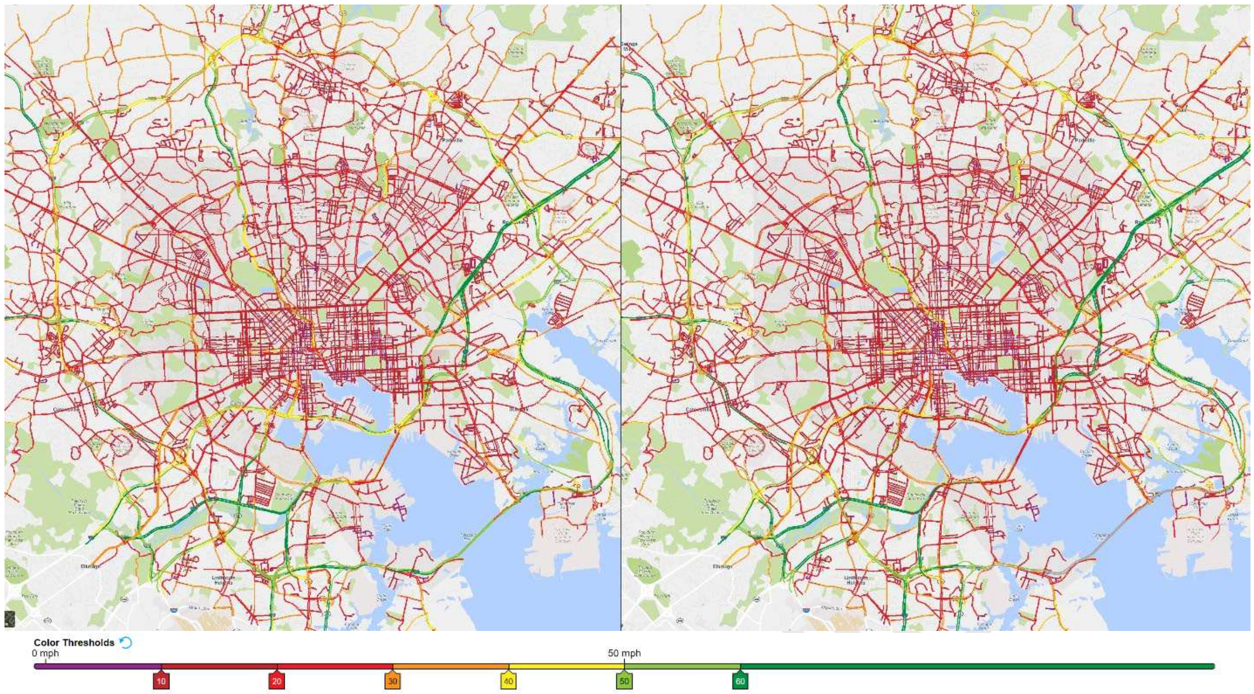


**Figure 5 Speed in Baltimore Area During AM Peak**

During the PM peak, as illustrated in Figure 6, the most significant changes still occurred along the freeways. The top worsening bottlenecks remain I-95 and I-895 before the tunnels due to similar detoured traffic, but the directions have changed from southbound to northbound. The spillover effects are severe. For I-95, the bottleneck extended approximately 9 miles upstream to the interchange of I-195, while the I-895 bottleneck extended approximately 3.5 miles upstream to the interchange of I-895B. A more detailed analysis of these bottlenecks will be presented later. Additionally, along I-895 southbound, a new bottleneck is forming before the tunnel, although it is not severe (the average speed is around 30 mph).

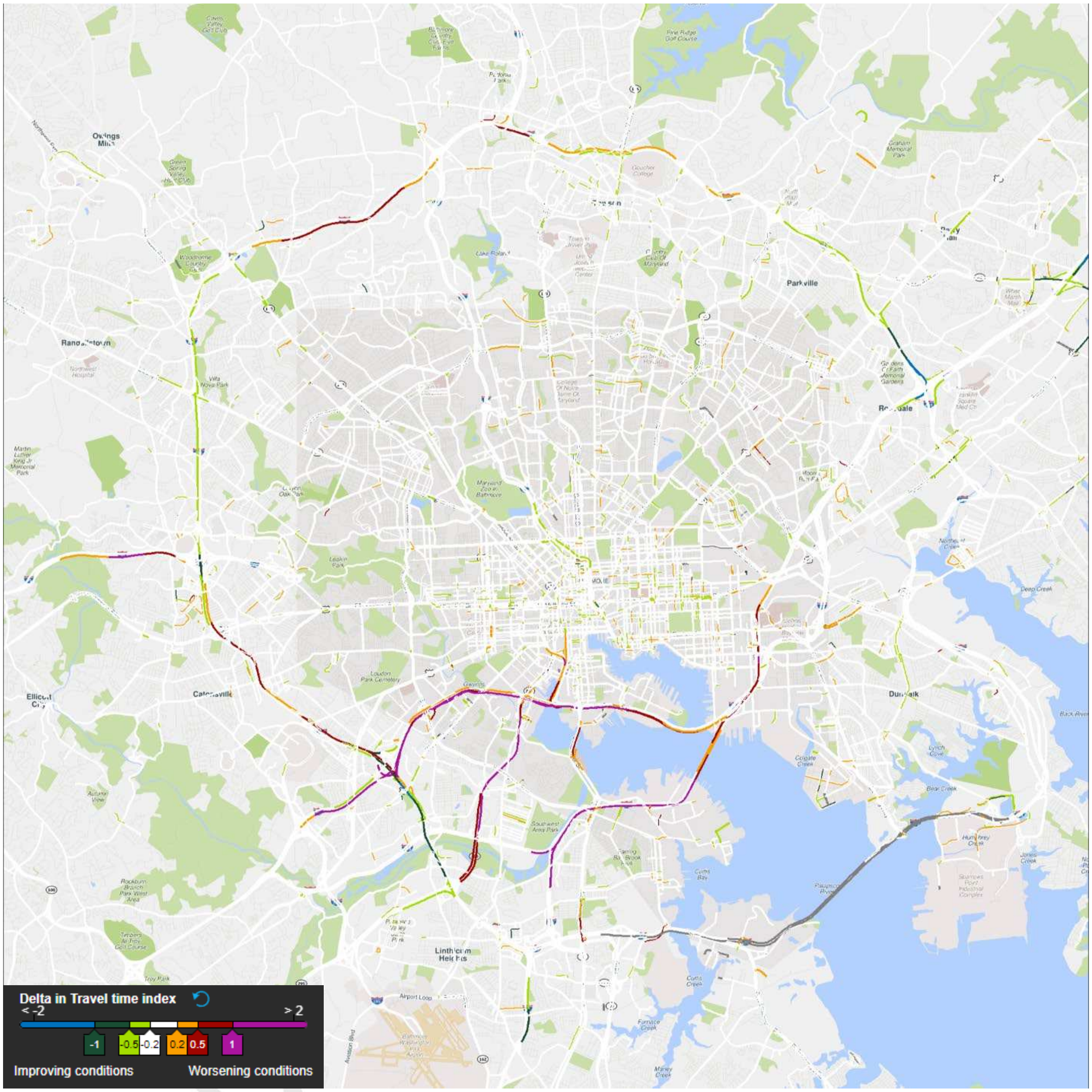


**Figure 6 Change of TTI in Baltimore Area During PM Peak**

The situation on I-695 differs slightly from the AM peak. While exaggerated congestion is still observed in the northern segments between I-795 and the northeast interchange with US Route 1, the travel time on segments along the outer loop (going south) between the interchange of I-70 and I-795 has slightly reduced. One possible reason is that some rerouted bridge traffic during the PM peak originates further north of I-70. In the southern segments, increased congestion was observed along the inner loop (going north) from the southwest interchanges of I-95 to I-70, possibly due to increased congestion from the city through I-95 as no bottlenecks were observed upstream. Additionally, the bottlenecks around the northeast interchange of I-95 and US Route 40 have reduced, possibly due to decreased traffic from the Baltimore Harbor following its closure.

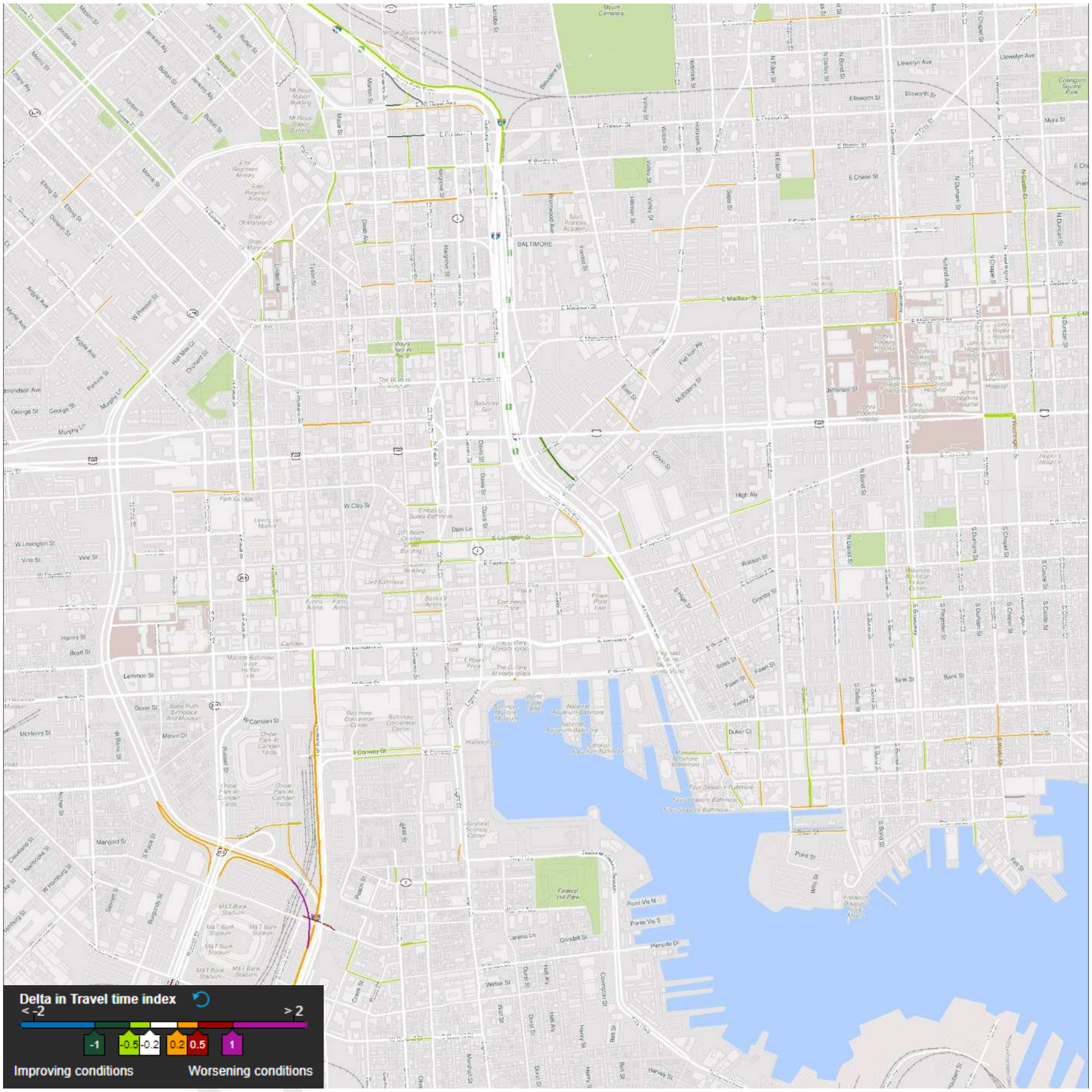


**Figure 7 Change of TTI in Downtown Baltimore During PM Peak**

Similar to the AM peak, there were no predominant changes along arterials and local roads, as shown in Figure 7. However, increased congestion was observed around the interchanges to I-95 outgoing from downtown. It is possible that increased traffic may be detoured traffic from the bridge, but more evidence, such as travel surveys, is needed to confirm this hypothesis.

To summarize, significant changes in short-term traffic patterns have been observed in the Baltimore area following the collapse of the Francis Scott Key Bridge. During peak periods, severe congestion occurred on I-95 and I-895 before the tunnels, which are the primary alternative route detour recommended by the MDTA, due to detoured traffic from the bridge. Increased congestion was also noted on several segments of I-695, such as north of the I-70 interchange and the northeast interchange with US Route 1 during the AM peak. Conversely, other segments of I-695 saw improved traffic conditions due to reduced traffic to or from the vicinity of the bridge and the harbor. Arterials and local roads in downtown experienced slight changes in travel times, with the magnitude of these changes being less significant compared to freeways due to already high congestion levels.

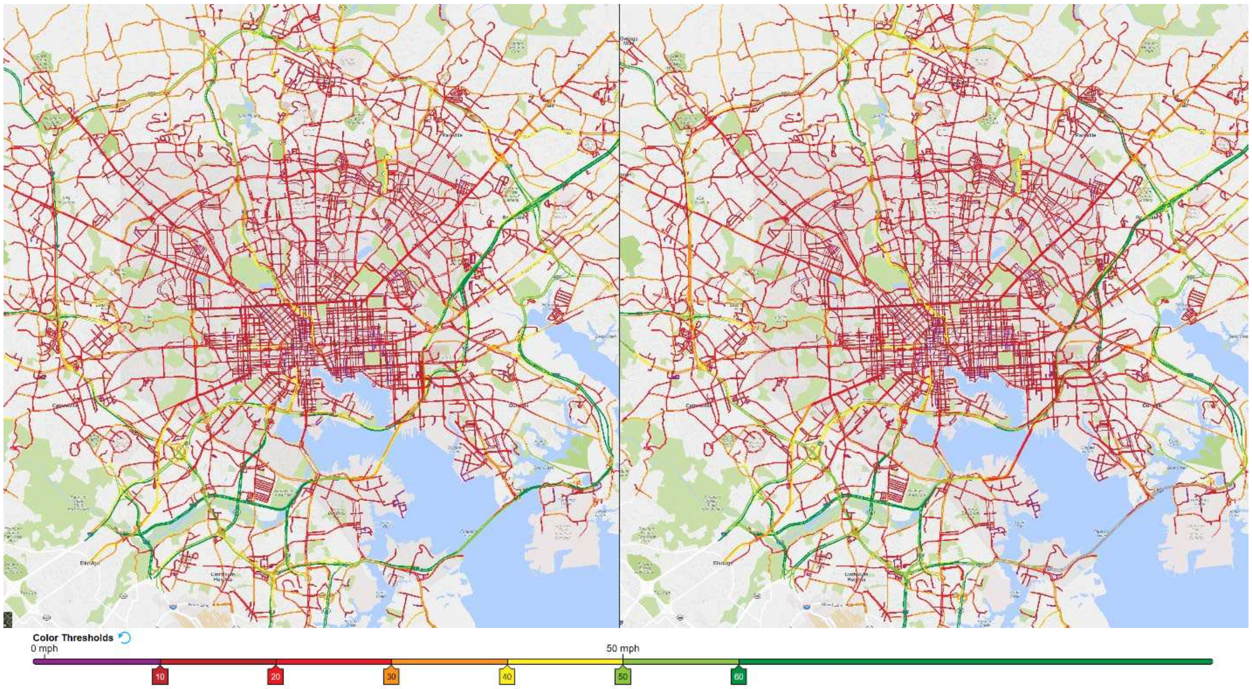


**Figure 8 Speed in Baltimore Area During PM Peak**

**Bottleneck Analysis**

The regional analysis identified the top bottlenecks during the AM and PM peak periods. During the AM peak, the I-95 and I-895 southbound segments before the tunnels (referred to as the 'I-95/I-895 S Tunnel,' approximately 8 miles long, as shown in Figure 9) experienced the worst performance downgrade following the bridge collapse. In contrast, the bottleneck on the I-695 Inner Loop around the I-97 Interchange ('I-695 IL & I-97,' approximately 1.5 miles long, as shown in Figure 10) saw the most significant improvement. During the PM peak, the I-95 northbound segment before the tunnel ('I-95 N Tunnel,' approximately 9 miles long, as shown in Figure 10) and the I-895 northbound segment before the tunnel ('I-895 N Tunnel,' approximately 3.5 miles long, as shown in Figure 11) experienced the most severe performance downgrades. Conversely, the I-695 Outer Loop around the northeast I-95 Interchange ('I-695 OL & I-95,' approximately 1.5 miles long, as shown in Figure 12) exhibited the most notable improvement.

**TABLE 1 Change of Speed and TTI on Top Bottlenecks**

| Bottleneck | Peak | Impact | Mean Speed (mph) | | | Travel Time Index | | |
|---|---|---|---|---|---|---|---|---|
| | | | Before | After | Change | Before | After | Change |
| I-95/I-895 S Tunnel | AM | Worse | 43.6 | 15.8 | -63.76% | 1.40 | 3.87 | 176.43% |
| I-695 IL & I-97 | AM | Better | 33.9 | 55.1 | 62.54% | 1.73 | 1.06 | -38.73% |
| I-95 N Tunnel | PM | Worse | 49.5 | 18.7 | -62.22% | 1.23 | 3.18 | 158.54% |
| I-895 N Tunnel | PM | Worse | 33.4 | 11 | -67.07% | 1.54 | 4.60 | 198.70% |
| I-695 OL & I-95 | PM | Better | 26.8 | 49.9 | 86.19% | 2.22 | 1.19 | -46.40% |

Table 1 provides detailed insights into the changes in mean speed and TTI for these bottlenecks. During the AM peak, for the I-95/I-895 S Tunnel, mean speed dramatically decreased from 43.6 mph to 15.8 mph, a decline of 63.76%. The TTI for this segment surged from 1.40 to 3.87, an increase to nearly three times its original value or almost fourfold compared to free-flow conditions. During the PM peak, the I-95 N Tunnel saw its mean speed decrease from 49.5 mph to 18.7 mph, a 62.22% reduction, with TTI increasing from 1.23 to 3.18, a rise to more than two and a half times its original value. The I-895 N Tunnel experienced an even greater deterioration, with mean speed dropping from 33.4 mph to 11 mph, a 67.07% decline, and TTI escalating from 1.54 to 4.60, an increase to around three times its original value or more than fourfold compared to free-flow conditions. The drastic increase in travel times along these bottlenecks is not surprising. Before the bridge collapse, the speeds at these bottlenecks were already below the free-flow speed during peak periods, particularly for the I-895 N Tunnel, indicating that the demand was already exceeding capacity. According to the congested part of the triangular fundamental diagram (*5*), even a small increase in demand due to detoured traffic can lead to a significant reduction in speed. This, in turn, results in a substantial increase in travel times.

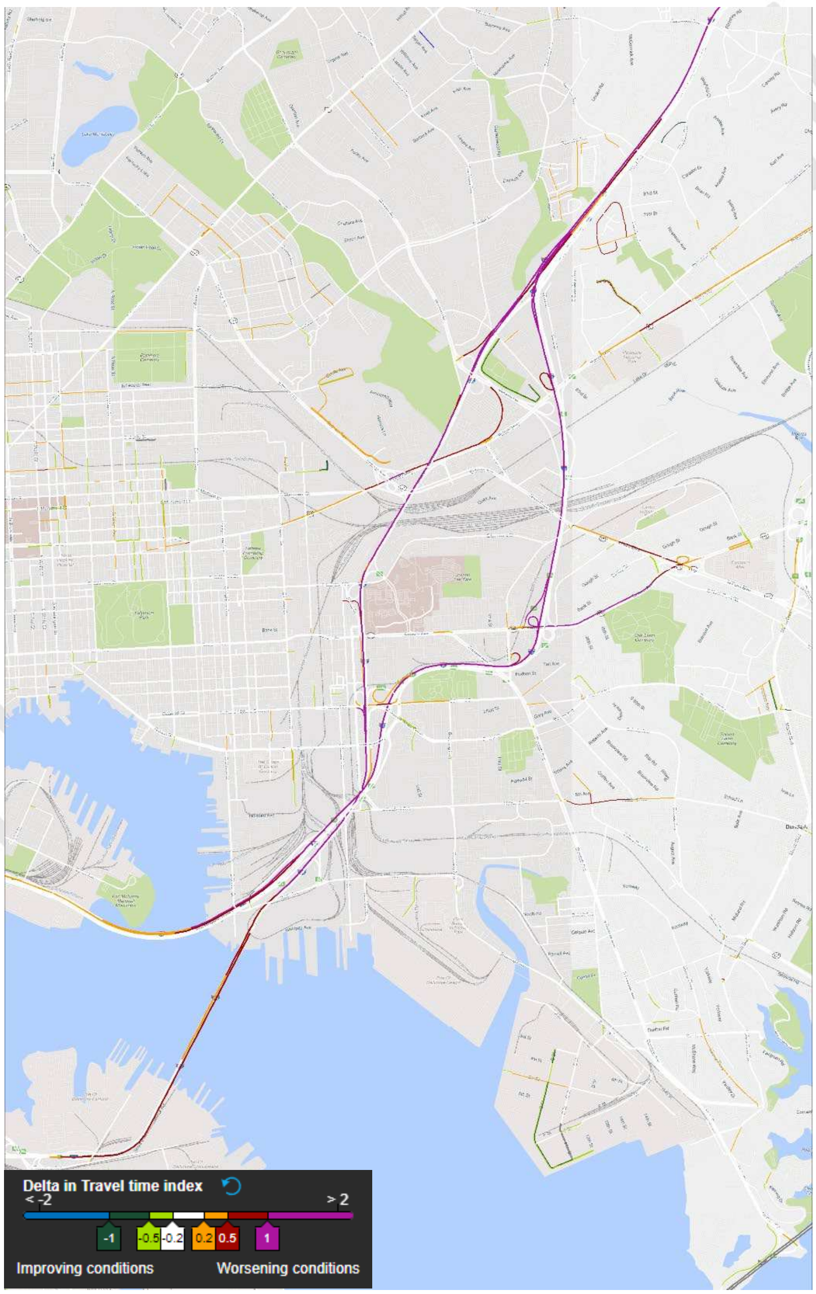


**Figure 9 Worsened AM Bottleneck: I-95 and I-895 Southbound Around the Tunnels**

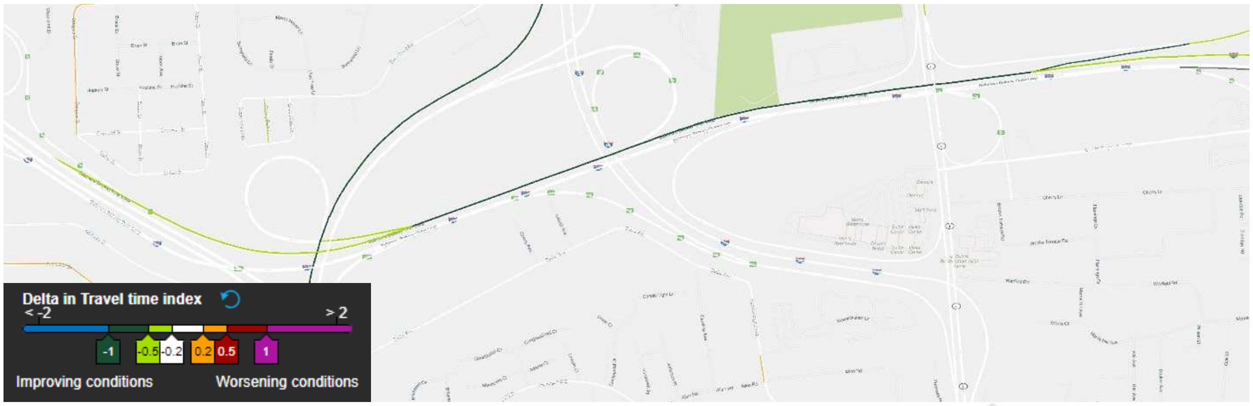


**Figure 10 Improved AM Bottleneck: I-695 Inner Loop Around the Interchange of I-97**

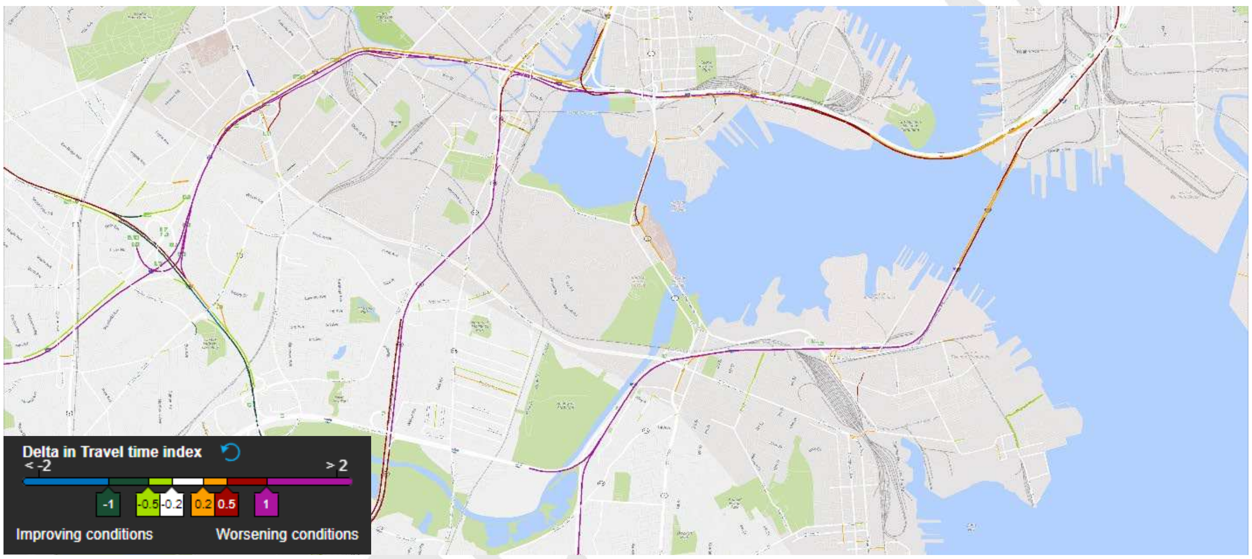


**Figure 11 Worsened PM Bottleneck: I-95 and I-895 Northbound Around the Tunnels**

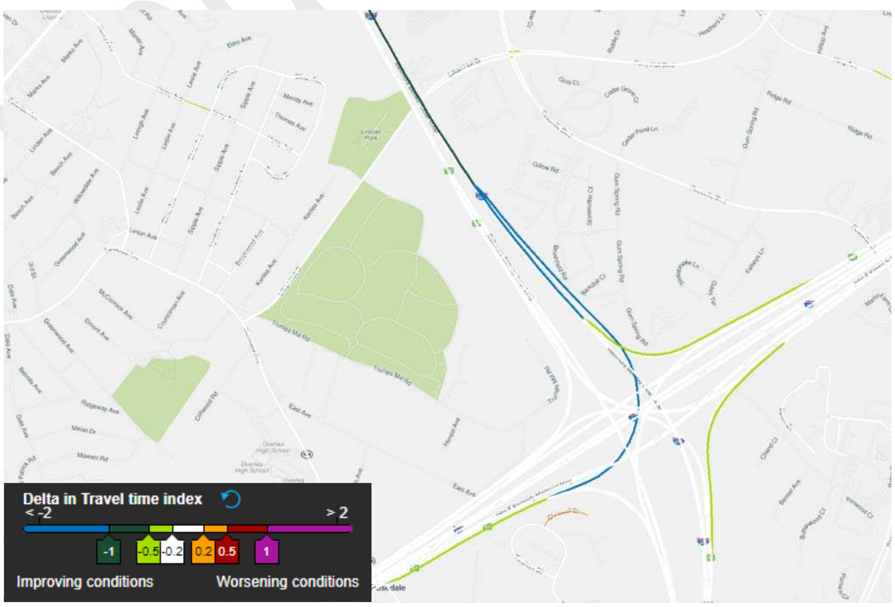


**Figure 12 Improved PM Bottleneck: I-695 Outer Loop Around the Interchange of I-95**

Conversely, the I-695 IL & I-97 bottleneck showed considerable improvement during the AM peak, with mean speed increasing by 62.54% to reach free-flow levels, and TTI decreasing by 38.73%. The I-695 OL & I-95 bottleneck during the PM peak showed substantial improvement, with mean speed rising by 86.19%, and TTI decreasing by 46.40%.

According to Table 2, the impacts on travel durations along the worsened bottlenecks are notable. For the I-95/I-895 S Tunnel during the AM peak, the total duration for all types of trips increased by 10.04%, with shorter trips experiencing a 42.07% increase and longer trips a 12.47% increase. During the PM peak, the I-95 N Tunnel saw the total duration for all trips increase by 8.60%, with shorter trips increasing by 24.00% and longer trips by 7.57%. The I-895 N Tunnel experienced a 20.65% increase in trip durations, with shorter trips increasing by 53.40% and longer trips by 4.59%. These changes were all highly statistically significant. Overall, the bottlenecks that were worsened due to the bridge collapse increased trip durations for both commuters and long-distance travelers. While these impacts are significant, they are not as substantial as the increases in bottleneck TTIs. This is because TTI measures travel times specific to bottleneck segments and is highly sensitive to changes in congestion over short distances. In contrast, trip durations reflect the cumulative effect of travel time over an entire trip, encompassing varying traffic conditions along different segments.

In contrast, the I-695 IL & I-97 bottleneck during the AM peak showed a statistically significant reduction in durations for all trips and longer trips by 8.06% and 1.34%, respectively. The change in durations for shorter trips was statistically insignificant. Similarly, the trip durations along the I-695 OL & I-95 bottleneck during the PM peak were not statistically significant. The possible reason for these statistically insignificant changes is that the improved bottlenecks are not spatially long enough, and the improvements are not substantial enough in magnitude to have a significant impact on entire trips. The savings in travel times along these improved bottlenecks were possibly offset by increased travel times along other segments of the trips.

**TABLE 2 Impacts on Durations of Trips Traveling Along the Top Bottlenecks**

| Bottleneck | Peak | Impact | Trip | Mean Trip Duration (Minutes) | | | Statistics | |
|---|---|---|---|---|---|---|---|---|
| | | | | Before | After | Change | t | p |
| I-95/I-895 S Tunnel | AM | Worse | All | 36.57 | 40.24 | 10.04% | -9.9730 | <0.0001 |
| | | | Short | 13.12 | 18.64 | 42.07% | -5.9865 | <0.0001 |
| | | | Long | 60.11 | 67.61 | 12.47% | -7.9937 | <0.0001 |
| I-695 IL & I-97 | AM | Better | All | 37.39 | 34.37 | -8.06% | -3.4475 | 0.0006 |
| | | | *Short* | *14.71* | *14.91* | *1.34%* | *-0.6376* | *0.5250* |
| | | | Long | 50.62 | 49.94 | -1.34% | -3.4500 | 0.0007 |
| I-95 N Tunnel | PM | Worse | All | 36.36 | 39.49 | 8.60% | -8.1582 | <0.0001 |
| | | | Short | 14.12 | 17.51 | 24.00% | -8.8203 | <0.0001 |
| | | | Long | 62.94 | 67.71 | 7.57% | -4.5282 | <0.0001 |
| I-895 N Tunnel | PM | Worse | All | 33.87 | 40.86 | 20.65% | -6.8495 | <0.0001 |
| | | | Short | 13.62 | 20.90 | 53.40% | -6.1134 | <0.0001 |
| | | | Long | 66.03 | 69.06 | 4.59% | -4.1638 | <0.0001 |
| *I-695 OL & I-95* | *PM* | *Better* | *Total* | *45.66* | *42.71* | *-6.47%* | *-0.0350* | *0.9721* |
| | | | *Short* | *11.28* | *9.94* | *-11.94%* | *2.3958* | *0.0173* |
| | | | *Long* | *76.48* | *75.77* | *-0.93%* | *-0.4861* | *0.6271* |

* *Italicized values indicate measures that are not statistically significant at the 0.01 level.*

In summary, significant performance downgrades for the bottlenecks before the I-95 and I-895 tunnels during both AM and PM peaks were observed. Travel times increased to two and a half to three times their value before the bridge collapse, or three to four times the free-flow travel time. The increased travel times were profound enough to cause a notable increase in the duration of entire trips for both commuters and long-distance travelers. Conversely, improvements in the bottlenecks along I-695 were not significant enough to impact overall trip durations.

**Origin-Destination Exploration**

As the bottleneck analysis indicates, travelers whose routes include the I-95/I-895 bottleneck experienced increased trip durations. Figures 13 and 14 illustrate the origins and destinations of these trips during the AM and PM peaks, respectively.

During the AM peak, a significant number of trips originated from a census tract in southeastern Baltimore City, near Bayview. According to the CEJST, this census tract faces several disadvantages, including a high proportion of low-income households, low education levels, linguistic isolation, and legacy pollution. Another top origin for trips is also a disadvantaged census tract near Bayview, which experiences issues such as low income, high housing rates, low education levels, linguistic isolation, high respiratory diseases rates, and legacy pollution. The top destinations include areas in southeastern Baltimore City, close to Dundalk. Many of the census tracts in this region are also disadvantaged, facing similar socio-economic challenges.

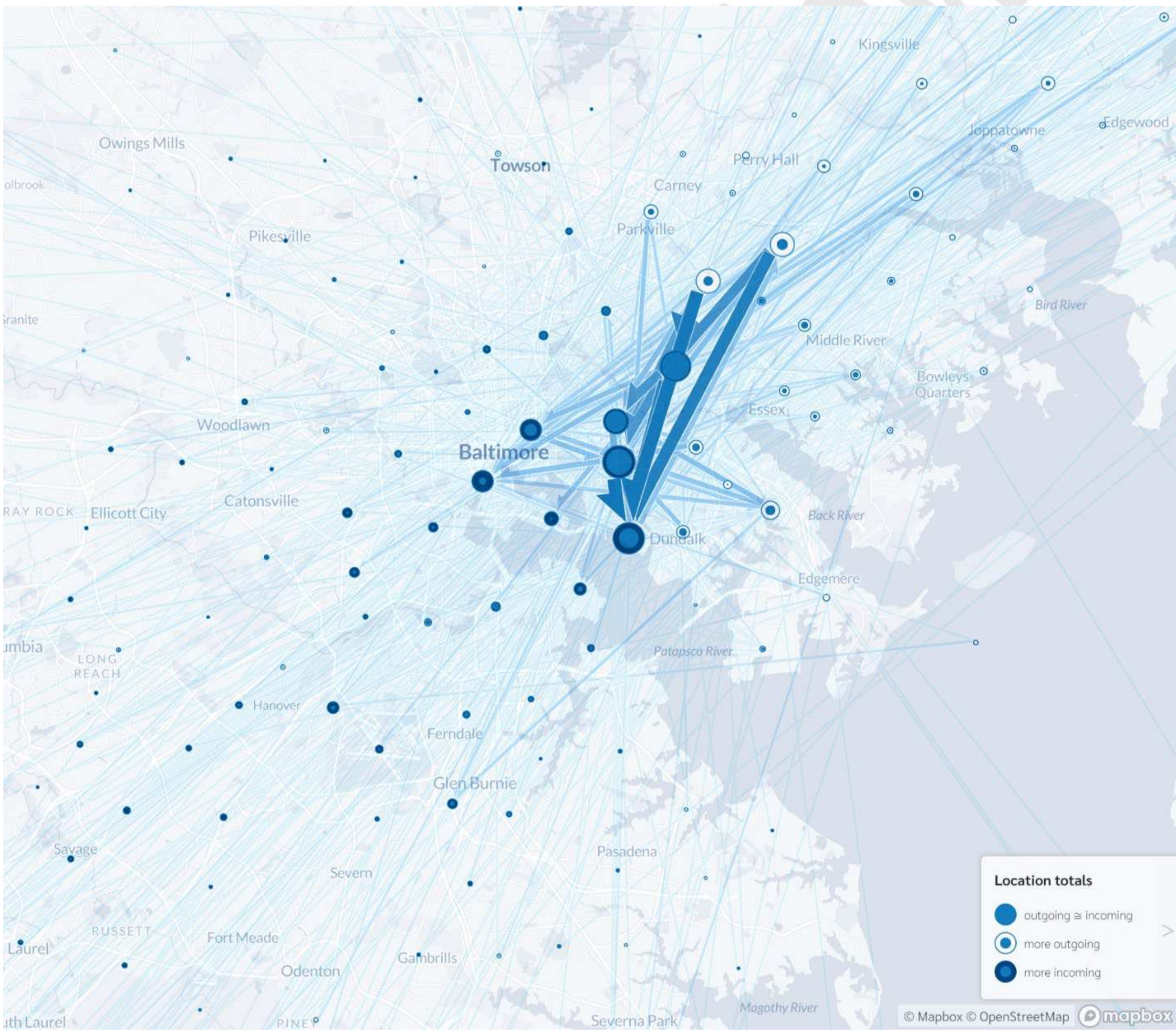


**Figure 13 Origins-Destinations of Trips Traveling Along the I-95/I-895 Bottleneck During AM Peak**

During the PM peak, a significant number of trips are destined for several census tracts in southwestern Baltimore City, north of Arbutus. These census tracts face several disadvantages, including low income, low education levels, and legacy pollution. Another top destination for trips is census tracts in southeastern Baltimore City. These census tracts face disadvantages such as low income, high respiratory diseases rates, and legacy pollution. Many trips originate from downtown Baltimore, indicating the pattern of employees leaving their workplaces in these areas.

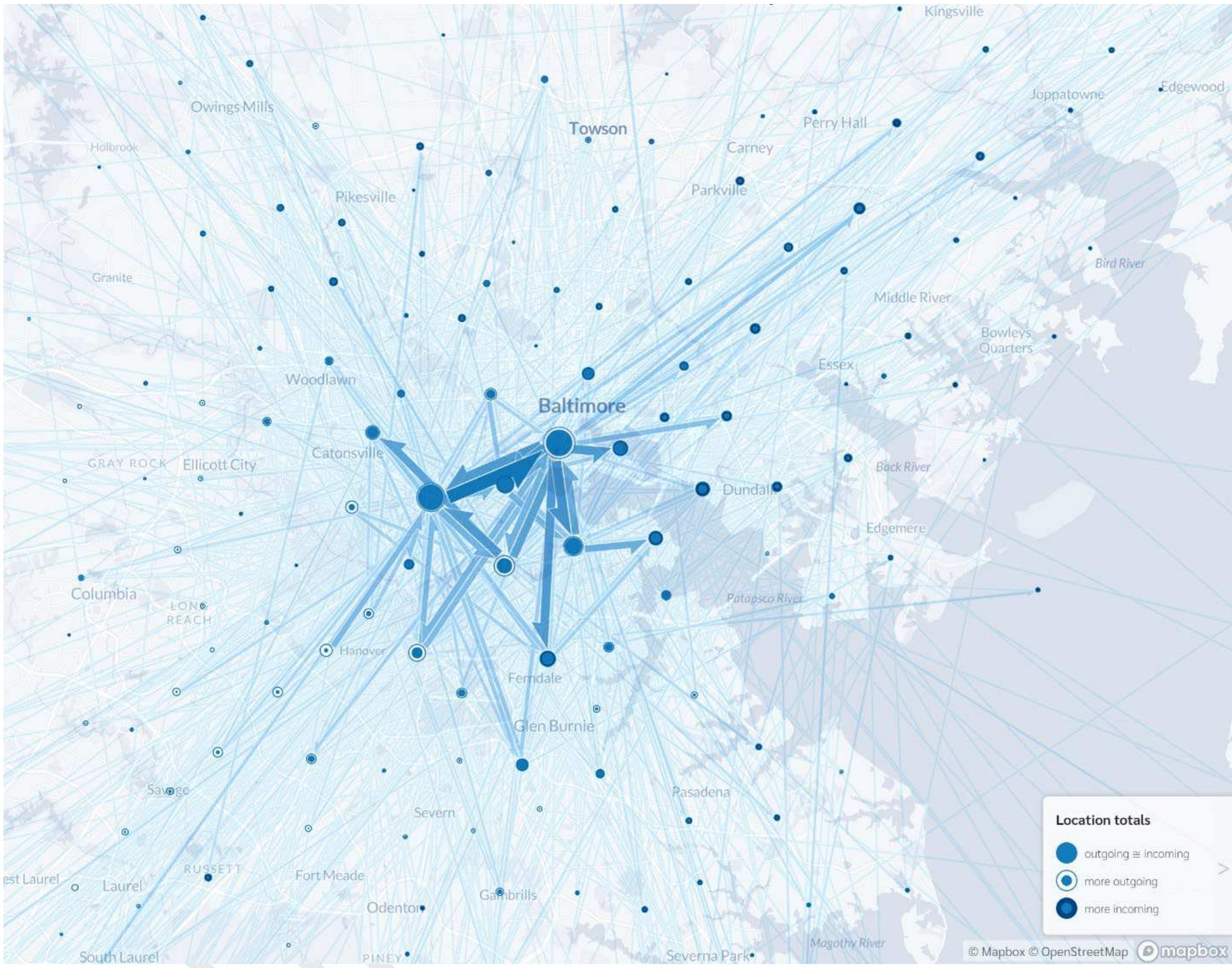


**Figure 14 Origins-Destinations of Trips Traveling Along the I-95/I-895 Bottleneck During PM Peak**

Table 3 shows the percentage of trips related to disadvantaged communities among all trips traveling through the bottlenecks. During the AM peak, a significant portion of trips (62.73%) either originate from or are destined for disadvantaged communities. Specifically, 30.32% of trips originate from these communities. In the PM peak, although the percentage is lower compared to the AM peak, 41.46% of trips are related to disadvantaged communities, with 24.63% destined for these areas. These percentages are substantially higher than the overall percentage of the population living in disadvantaged communities, highlighting the disproportionate impact of the bridge collapse on these populations.

**TABLE 3 Percentage of Trips Related to Disadvantaged Communities**

| Peak | Percentage of Trips Related to Disadvantaged Communities | | | Percentage of Population Living in Disadvantaged Communities |
|---|---|---|---|---|
| | Either from or to | From | To | |
| AM | 62.73% | 30.32% | 46.84% | 5.37% |
| PM | 41.46% | 23.62% | 24.63% | |

**Discussion**

During peak periods, severe congestion occurred on the primary detour routes for bridge traffic recommended by transportation agencies following the collapse of the Francis Scott Key Bridge. Similar short-term increases in congestion on recommended detours were observed after the collapse of the I-35W Mississippi River bridge in Minneapolis, Minnesota, in 2007 (*1*, *2*). In Minneapolis, to add capacity and reduce bottlenecks along the detours, transportation agencies implemented a series of projects, including adding an additional lane, reducing or eliminating shoulders, restriping roads to provide narrower lanes, and converting a highway with two traffic signals into a freeway by closing several access points and reconstructing interchanges and on- and off-ramps. While similar projects could be implemented on the upstream freeways of the tunnels in Baltimore to increase capacity, they are not applicable for underwater tunnels. Thus, the capacity constraint of tunnels may still exist after such projects. Rigorous studies need to be conducted to evaluate the costs and benefits of these projects if they are to be implemented.

Encouraging rerouting to signalized arterials rather than limited-access, already severely congested freeways may be another solution to reduce the demand on detouring freeways, as observed during a main road tunnel closure in Oslo, Norway (*6*). In the Baltimore area, although limited, the collected trajectory data showed that some traffic was detoured to arterials such as US Route 1 and US Route 40, passing through the downtown area. However, these arterials were already congested before the bridge collapse, as the regional analysis showed. Therefore, appropriate traffic management strategies, such as smart adaptive traffic signal systems, should be implemented to better utilize the capacity of the arterials.

Demand management can be another feasible solution if increasing capacity is challenging. Surveys on earlier disruptions (*6*, *7*) of major road corridors have shown that commuters may change their starting times of commuting trips or work from home to avoid delays during peak periods. Additionally, some commuters may switch to public transportation. Further studies on travel behavior are needed to assess the feasibility of these strategies.

It should be noted that this study presents only short-term changes in traffic patterns. In the long term, more aspects require careful consideration. For instance, when the data used in this study were collected, the Port of Baltimore had not yet reopened. With the port fully reopened in June this year (*8*), additional traffic to the port may further deteriorate the condition of the tunnel bottlenecks. Moreover, earlier studies (*6*) have pointed out that in the long run, travelers may passively adapt to the new traffic pattern, resulting in reduced traffic along the bottlenecks. Continuous monitoring is essential to understand the long-term traffic impact.

**CONCLUSIONS**

The collapse of the Francis Scott Key Bridge has had profound short-term impacts on traffic patterns in the Baltimore area. This study has provided a comprehensive analysis of these impacts, utilizing both traditional aggregated speed data and a unique large-scale trajectory data set that offers detailed insights into traffic patterns, bottlenecks, and the effects on disadvantaged communities.

Significant changes were found in regional traffic patterns. During peak periods, severe congestion occurred on the primary detour routes, I-95 and I-895, before the tunnels due to detoured traffic from the bridge. Increased congestion was also noted on several segments of I-695, such as north of the I-70 interchange and the northeast interchange with US Route 1 during the AM peak. Conversely, other segments of I-695 saw improved traffic conditions due to reduced traffic to or from the vicinity of the bridge and the harbor. Arterials and local roads in downtown experienced slight changes in travel times, with these changes being less significant compared to freeways due to already high congestion levels.

The analysis of identified top bottlenecks reveals significant performance downgrades for the bottlenecks before the I-95 and I-895 tunnels during both AM and PM peaks. For bottlenecks approximately 8 miles in length, travel times increased to two and a half to three times their value before the bridge collapse, or three to four times the free-flow travel time. The increased travel times were substantial enough to cause a notable increase in the duration of entire trips for both commuters and long-distance travelers. Conversely, improvements in the bottlenecks along I-695 were not significant enough to impact overall trip durations.

The exploratory study on origins and destinations of trips traveling through the I-95/I-895 bottlenecks shows that a significant portion of the trips either originated from or were destined for disadvantaged communities. This percentage is substantially higher than the percentage of the population living in disadvantaged communities in this area, highlighting the disproportionate impact of the bridge collapse on these communities.

To mitigate the impacts such mobility disruptions, historical precedents have proposed or implemented interventions such as increasing bottleneck capacities by adding lanes and converting signalized arterials to freeways, as well as managing travel demand by promoting public transportation. Special attention should also be paid to disadvantaged populations. However, additional studies and continuous monitoring of traffic patterns and travel demand are needed before implementing such measures.

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**AUTHOR CONTRIBUTIONS**

The authors confirm contribution to the paper as follows: study conception and design: Y. Gong, X. Yang; data collection: S. Tarafdar, Y. Gong; analysis and interpretation of results: Y. Gong, Y. Zhang, K. Yang, X. Yang; draft manuscript preparation: Y. Gong, X. Yang, D. Yang. All authors reviewed the results and approved the final version of the manuscript.

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