HOW MUCH WILL THE DETOUR COST? IMPACTS ON ROAD FREIGHT TRANSPORTATION BY THE FRANCIS SCOTT KEY BRIDGE COLLAPSE

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ABSTRACT

On March 26, 2024, the Francis Scott Key Bridge in Baltimore suffered a catastrophic collapse when the container ship MV Dali collided with a support pillar. This collapse has had profound impacts on the road freight transportation industry in the region. Utilizing over two million truck trajectories, this study aimed to quantify these impacts by analyzing changes in travel times, detour patterns, and the incurred operational costs associated with the bridge collapse. The investigation reveals that, depending on the type of truck and the alternative routes used, average travel times increased by up to 58% for trucks traveling through Baltimore. Heavy-duty trucks experienced more significant travel time increases due to restrictions in the Baltimore Harbor Tunnel and forced detours to the longer I-695 Western Sections because of prohibitions on transporting hazardous materials through the tunnels. The impact of rerouting extends beyond the detour routes to connecting arterials, alternative arterials when the freeways are congested, and further upstream and downstream freeway sections. An economic analysis demonstrated a substantial increase in operational costs for the road freight transportation sector in the Baltimore area following the collapse. Assuming current conditions remain unchanged, the region-wide annual increase of around 1.1 million hours in travel time translates to an additional $93 million in operational costs annually. This underscores the significant broader economic implications of the Key Bridge collapse.

Keywords: Francis Scott Key Bridge Collapse, Road Freight Transportation, Travel behavior, Economic Analysis

INTRODUCTION

The Francis Scott Key Bridge ("the Key Bridge"), located in Baltimore, Maryland, was a critical link in the I-695. On March 26, 2024, the bridge suffered a catastrophic collapse when the container ship MV Dali collided with a support pillar. The incident resulted in the closure of the outer loop of I-695 to Quarantine Road and the inner loop at MD 157, forcing traffic to divert to already-congested routes via I-95 (Fort McHenry Tunnel, cyan route in Figure 1) or I-895 (Baltimore Harbor Tunnel, magenta route in Figure 1), as recommended by the Maryland Transportation Authority (MDTA) that maintains the collapsed bridge. Vehicles transporting hazardous materials, prohibited in tunnels, were even detoured to the lengthy western section of I-695 around tunnels (red route in Figure 1).

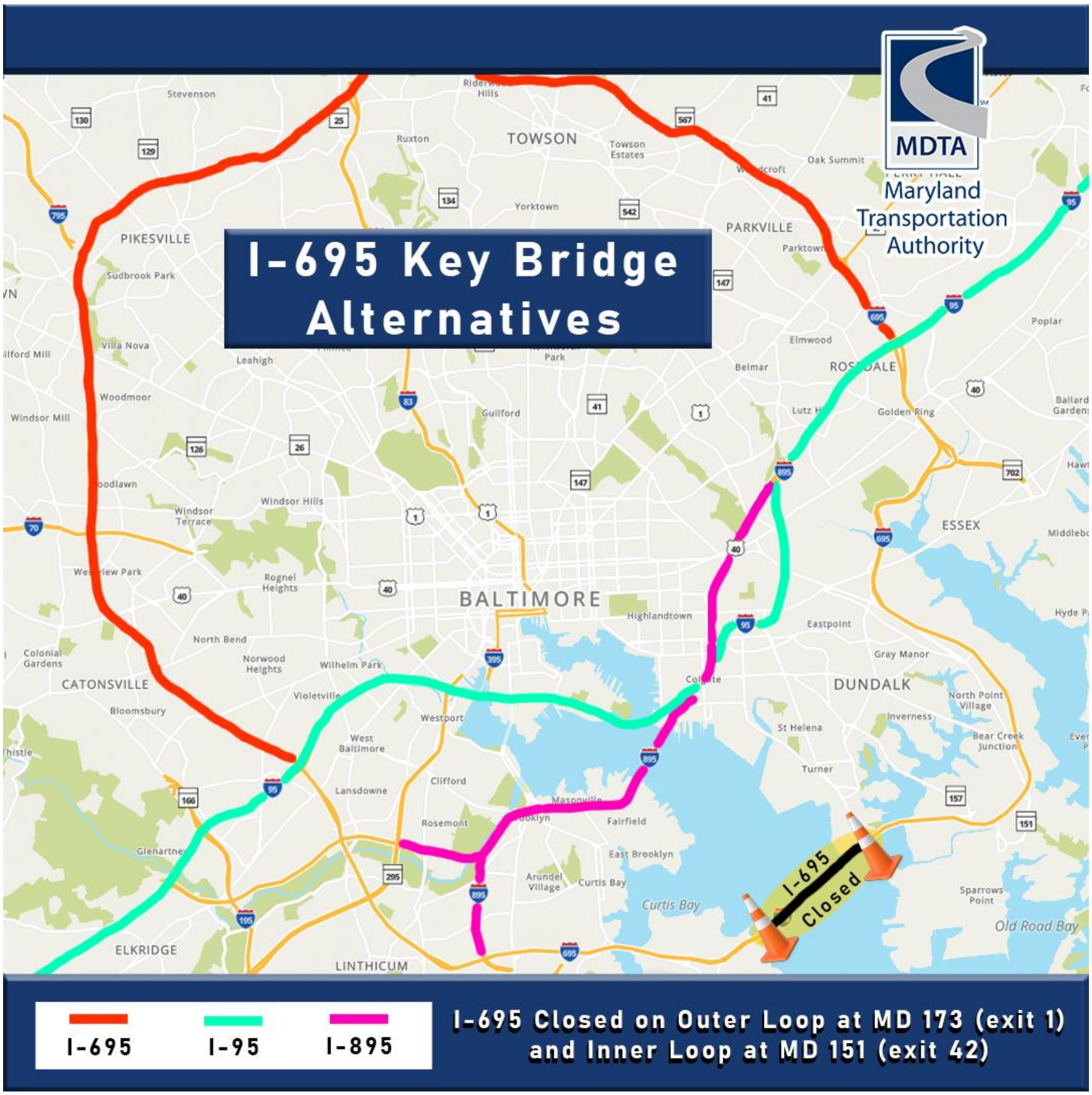

Figure 1 Recommended Alternative Routes by MDTA (Adopted from (*1*)**)**

The collapse of the Key Bridge severely disrupted not only local commuting traffic but also regional and national road freight operations. Road freight transportation faced significant delays and rerouting challenges, which affected supply chains and delivery schedules. The rerouting of freight traffic has resulted in increased operational costs, including longer travel times and higher fuel consumption, directly impacting the logistics industry. Additionally, the detour routes have introduced substantial delays in the delivery of goods, leading to stock shortages, production halts, and increased inventory costs, thereby affecting the broader economy. Understanding the impact of such disruptions is essential for developing effective responses and allocating resources efficiently.

Therefore, this study aims to quantify the impact of the Key Bridge collapse on freight operations and explore the cascading effects on the supply chain. Utilizing over two million real-world trajectories collected from trucks traveling through the Baltimore Area during March and April 2024, the study assesses how freight routes have changed and the resultant increase in travel times. The rerouting behavior of representative origin-destination (OD) pairs will also be discussed to provide insights into the service disruptions. Moreover, the operational costs the operational costs incurred by the road freight transportation industry operating in Baltimore Area following the Key Bridge collapse will be estimated.

DETOUR ANALYSIS

Data

To understand the rerouting behavior of trucks, over two million anonymous real-world trajectories of trucks passing through the Baltimore Area were obtained from the Regional Integrated Transportation Information System (RITIS) (2). These trajectories were collected from in-vehicle GPS receivers. The data spans two periods: before the collapse of the Key Bridge (03/01/2024-03/25/2024) and after the collapse (03/27/2024-04/30/2024). The study focuses on two different vehicle types: medium-duty trucks and vans weighing between 14,001 and 26,000 pounds, and heavy-duty trucks weighing over 26,000 pounds. The trajectory data underwent preliminary filtering to exclude outliers, such as extremely short trips with disproportionately long travel times.

Method

The detour analysis consists of two steps: macroscopic analysis and microscopic analysis. The objective of the macroscopic analysis is to investigate, for all truck trips using the Key Bridge before its collapse, how many of them detoured to the three recommended alternative routes and the resultant increase in travel time. The microscopic analysis, on the other hand, delves into a detailed examination of the detour behavior of several representative origin-destination pairs, including but not limited to the aforementioned recommended alternative routes.

As shown in Figure 2, the macroscopic analysis begins by grouping the origins and destinations of the truck trajectories into traffic analysis zones (TAZs). By aggregating origins and destinations into TAZs, the complexity of analyzing individual trip data is significantly reduced. This simplification facilitates more manageable and interpretable analysis and helps in identifying broader patterns and trends in truck movements that might be obscured in a more granular, trip-by-trip analysis. Moreover, TAZs are commonly used in

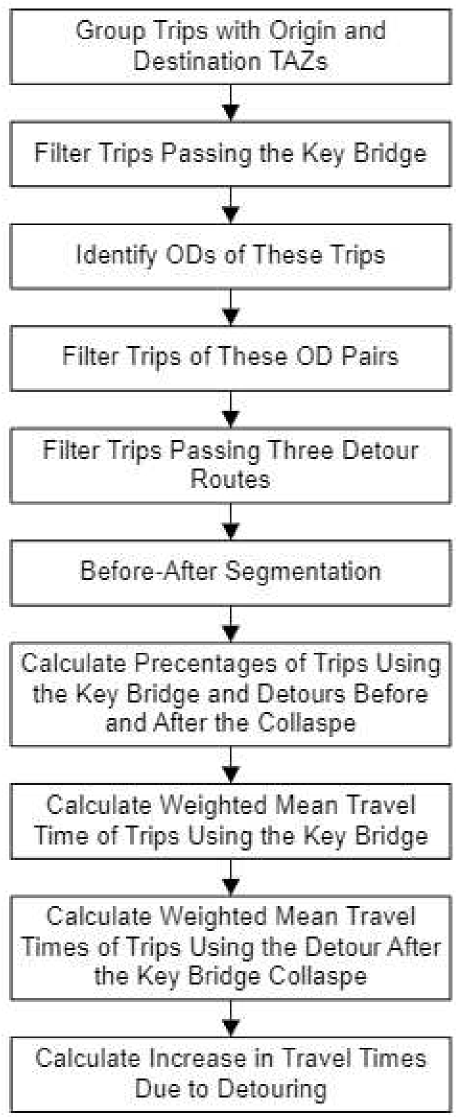

Figure 2 Process of Macroscopic Detour Analysis

transportation planning. Grouping data in this manner aligns the analysis with planning practices, making the results more relevant and actionable for policymakers.

Then, the trajectories passing the Key Bridge before its collapse and their associated OD pairs are geographically filtered out. This step identifies trips directly affected by the bridge collapse and their corresponding ODs. It should be noted that even before the collapse, trips between these OD pairs could use other routes, including the recommended alternative routes. Therefore, all trips between these OD pairs are identified, and those passing the three alternative routes are specifically noted.

The trajectory data is then segmented into before and after periods. Next, the proportion of truck trips that used the Key Bridge and the alternative detour routes before and after the collapse is determined. The weighted average travel times of trips using the Key Bridge before the collapse and trips using the detours after the collapse are calculated to determine the increase in travel times due to the detouring. The weights used in this calculation are the number of sampled trips. Although these weights do not represent the actual number of trips, as the trajectory data is collected from a sample of all truck trips, the weighted averages provide a more accurate representation of the actual conditions than the simple averages, which may be biased toward OD pairs with very few sampling trips and typically longer travel times.

It is important to note that the analysis was conducted separately for heavy-duty and medium-duty vehicles, as their travel behaviors differ significantly. For instance, heavy-duty vehicles typically travel at slower speeds than medium-duty vehicles and are generally used for longer-distance transportation. To provide a general overview, only the overall average change in travel time across all OD pairs by week is presented.

For the microscopic analysis, several representative origin-destination (OD) pairs were selected based on factors such as the number of trips, locations of the ODs, types of vehicles, and other relevant criteria. Illustrations of the representative routes before and after the Key Bridge collapse are presented. The rerouting behavior and potential resultant disruptions to logistics are thoroughly discussed.

Results

Figure 3 illustrates the change in average travel times for all OD pairs with trips passing the Key Bridge before its collapse. A significant increase in average travel times was observed immediately following the bridge collapse. The travel times remained higher than the pre-collapse period even five weeks after, indicating a possible persistent impact.

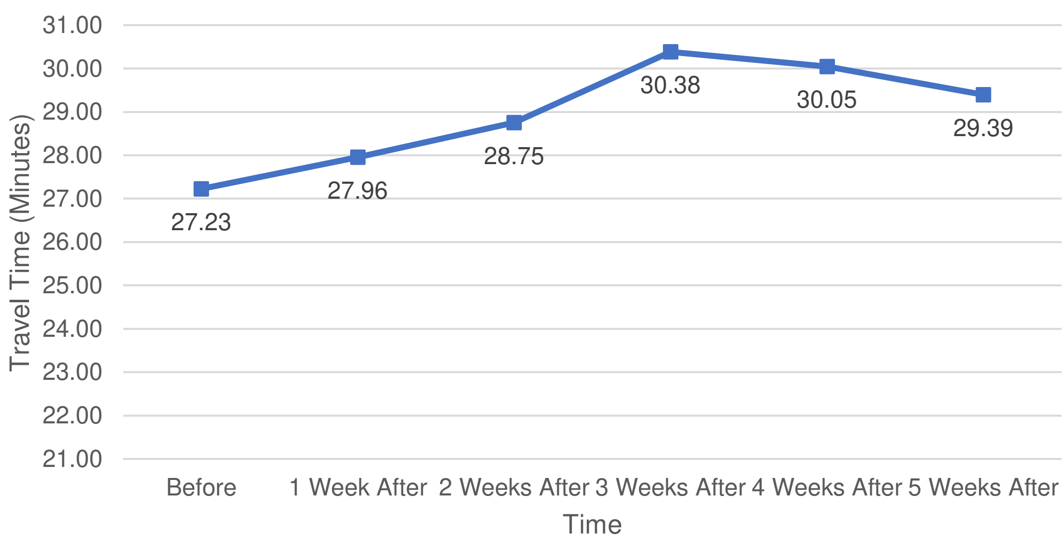

Figure 3 Change in Average Travel Times for All OD Pairs with Trips Passing the Key Bridge Before Its Collapse

TABLE 1 Travel Time of Detouring Routes and Percentages of Trips Using Detours

Route	Type	Mean Travel Time (Minutes)		Trip Percentage	
		Value	Increase	Before	After
The Key Bridge	Heavy	112.42	N/A	41.05%	N/A
	Medium	44.53		31.93%	
Fort McHenry Tunnel (I-95)	Heavy	133.99	19.18%	22.99%	54.28%
	Medium	50.84	14.18%	6.46%	24.73%
Baltimore Harbor Tunnel (I-895)	Heavy	119.49	6.28%	1.32%	3.53%
	Medium	46.08	3.49%	4.84%	17.05%
I-695 Western Sections	Heavy	153.41	36.46%	8.63%	16.46%
	Medium	70.35	58.00%	4.07%	5.90%

Table 1 clearly demonstrates the significant increase in travel time and the rise in trips using the recommended alternative routes following the collapse of the Key Bridge.

For instance, heavy-duty vehicles using the Fort McHenry Tunnel (I-95) experienced a 19.18% increase in travel time, while medium-duty vehicles faced a 14.18% increase. The proportion of trips using this route increased dramatically, from 22.99% to 54.28% for heavy-duty vehicles and from 6.46% to 24.73% for medium-duty vehicles after the collapse. This shift highlights the increased reliance on I-95 as a primary detour route following the bridge collapse.

Heavy-duty vehicles passing through the Baltimore Harbor Tunnel (I-895) experienced a 6.28% increase in travel time, while medium-duty vehicles faced a 3.49% increase. The proportion of trips using this route also rose, from 1.32% to 3.53% for heavy-duty vehicles and from 4.84% to 17.05% for medium-duty vehicles. These increases are smaller compared to the Fort McHenry Tunnel, partly due to the restrictions on heavy-duty vehicles exceeding 13 feet, 6 inches in height, or 96 inches (8 feet) in width, and all double trailers, which are prohibited from using the Baltimore Harbor Tunnel. Consequently, I-895 could not serve as a detour route for the majority of heavy-duty vehicles, thereby increasing the traffic burden on the nearby Fort McHenry Tunnel.

Vehicles detouring via the I-695 Western Sections experienced the most significant increase in travel time due to the considerably longer detour distances. Heavy-duty vehicles experienced a 36.46% increase in travel time, while medium-duty vehicles faced a 58.00% increase. The proportion of trips using this route increased from 8.63% to 16.46% for heavy-duty vehicles and from 4.07% to 5.90% for medium-duty vehicles. The higher increase in trips for heavy-duty vehicles can be attributed to the fact that a substantial portion of these vehicles carry hazardous materials, such as bottled propane gas in excess of 10 pounds per container (maximum of 10 containers), bulk gasoline, explosives, and significant amounts of radioactive materials, which are prohibited from using both tunnels.

Seven distinct origin-destination (OD) pairs were selected for further microscopic analysis. The rerouting behavior of heavy-duty vehicles was analyzed in detail for four of these pairs, while the rerouting behavior of medium-duty vehicles was examined for the remaining three pairs. Figures 4 to 10 illustrate the routes, where the thickness of the lanes indicates the volume of trips using each route.

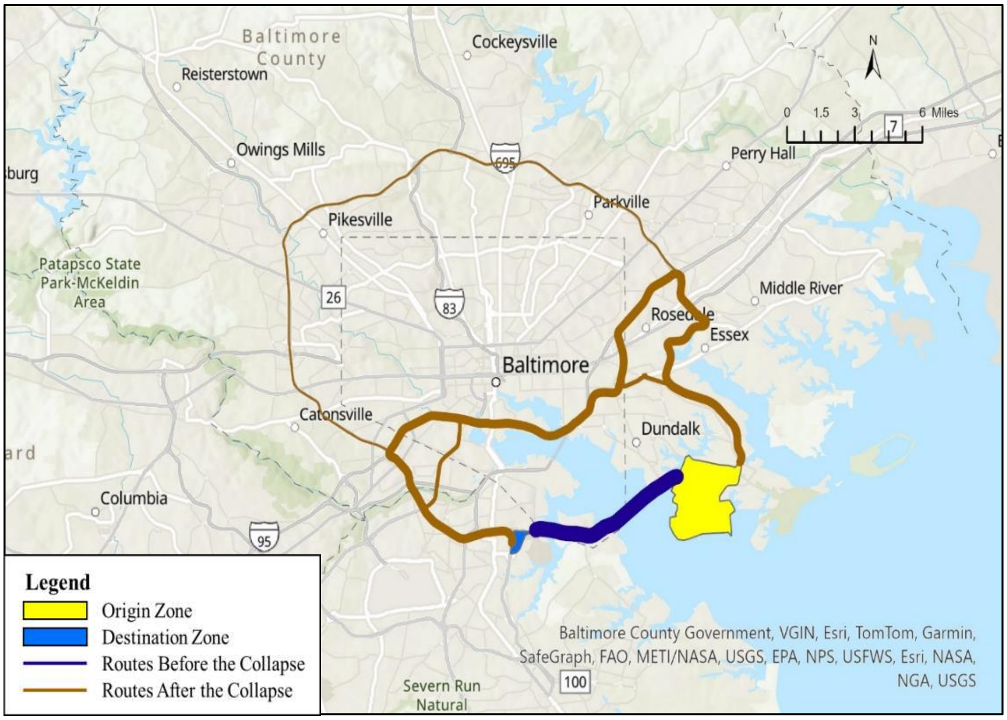

Figure 4 Routes of the OD Pair One Before and After the Collapse of the Key Bridge

For the first OD pair, illustrated in Figure 3, heavy-duty trucks traveling from the Baltimore Port to freight distribution centers near Brooklyn Park primarily utilized the Key Bridge before its collapse. After the collapse, the majority of these trucks now detour via I-95, with some using the I-695 Western Sections. Notably, no heavy vehicles detour on I-895 due to restrictions on larger trucks, as mentioned earlier. For trips connecting two nearby distribution centers, these detours are disproportionately longer than the original routes, potentially leading to significant losses for the distribution operators.

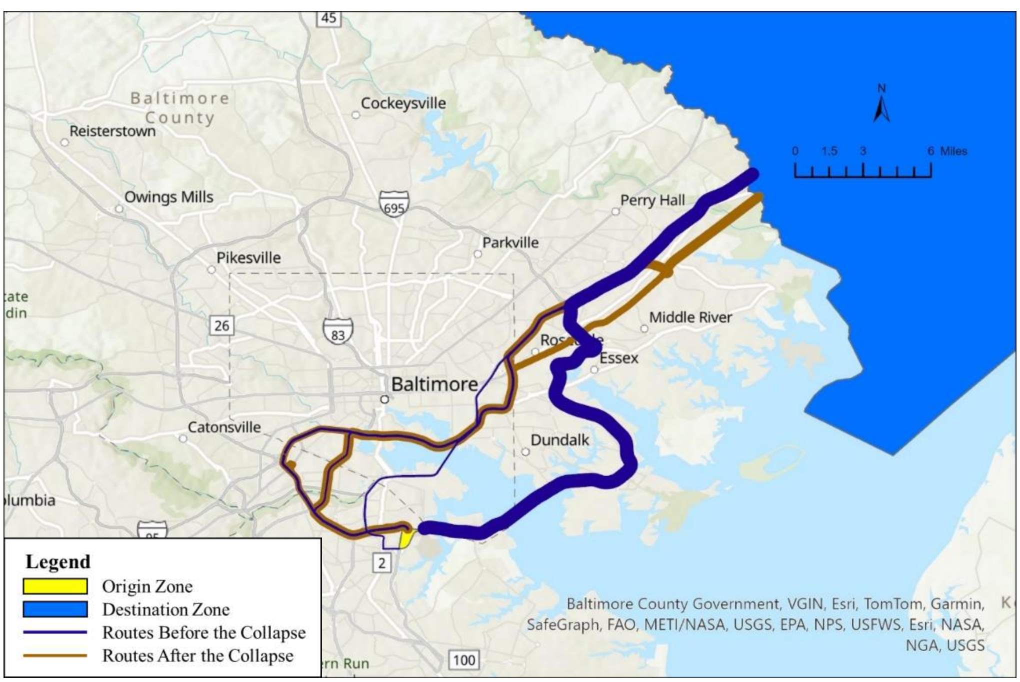

Figure 5 Routes of the OD Pair Two Before and After the Collapse of the Key Bridge

The second OD pair has its destination as the origin of the first OD pair, which are freight distribution centers in the Baltimore area, with origins in freight distribution centers northeast of Baltimore outside the study area, close to Aberdeen. Prior to the collapse, heavy-duty trucks primarily relied on the Key Bridge, with very few using I-95 or I-895. Notably, when vehicles exited I-695, effectively leaving the Baltimore area, they chose to use I-95. Post-collapse, trucks were primarily rerouted to I-95; however, some exited I-95 to US-40 after passing the Fort McHenry Tunnel. A possible reason for this shift is the increased congestion on I-95 due to detour traffic, not only from trucks but also other vehicles. Furthermore, the increased volume on US-40, a major signalized arterial, from I-95 may introduce further congestion. Continuous monitoring of the traffic conditions along US 40 is necessary to determine if additional traffic management measures are required.

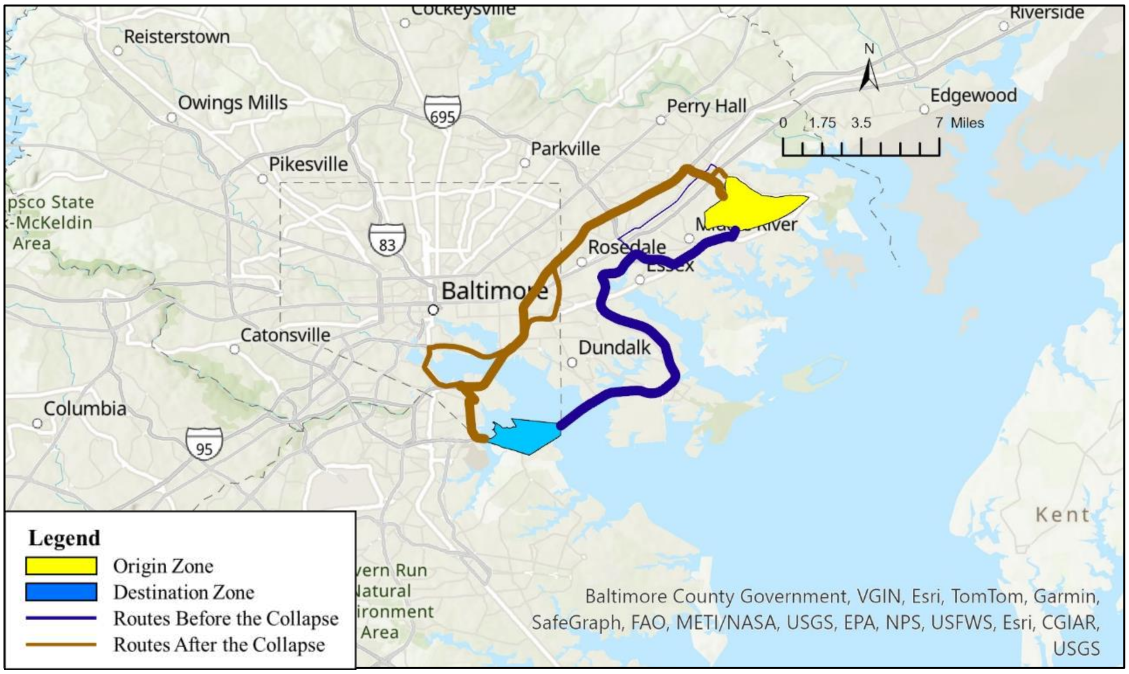

Figure 6 Routes of the OD Pair Three Before and After the Collapse of the Key Bridge

For the third OD pair, medium-duty trucks traveled to freight distribution centers in the Baltimore area near Hawkins Point from distribution centers northeast of Baltimore, close to Middle River. Before the collapse, these trucks primarily relied on the Key Bridge. However, after the collapse, approximately two-thirds of them rerouted to I-895, with the remaining third using I-95. As indicated in Table 1, the traffic conditions on I-895 are better than those on I-95. Since medium-duty vehicles are not restricted by the Baltimore Harbor Tunnel, it is not surprising that the majority chose I-895. Another interesting finding is that, since they use different freeways before and after the collapse, different arterials connecting the origins to the freeway interchanges had to be used. This may also lead to shifts in traffic conditions along these arterials, similar to the case of the second OD pair.

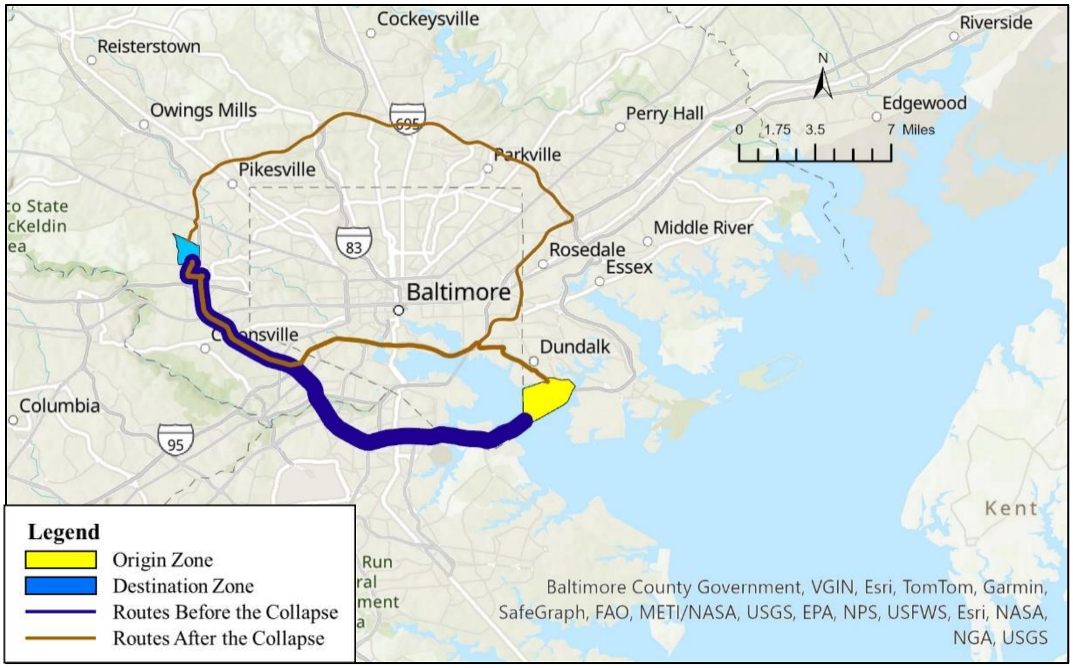

Figure 7 Routes of the OD Pair Four Before and After the Collapse of the Key Bridge

Medium-duty trucks traveling along the fourth OD pair were from the Baltimore Port to a local distribution center in Windsor Mill in the western Baltimore area. Before the collapse, while a few of these trucks used I-95, the vast majority relied on the Key Bridge. After the collapse, around 60% of the trucks rerouted to I-95, while a substantial portion of the remaining trips used the I-695 Western Sections. A possible reason for rerouting to the lengthy I-695 Western Sections is that these trucks may be transporting hazardous materials, which are prohibited from using tunnels.

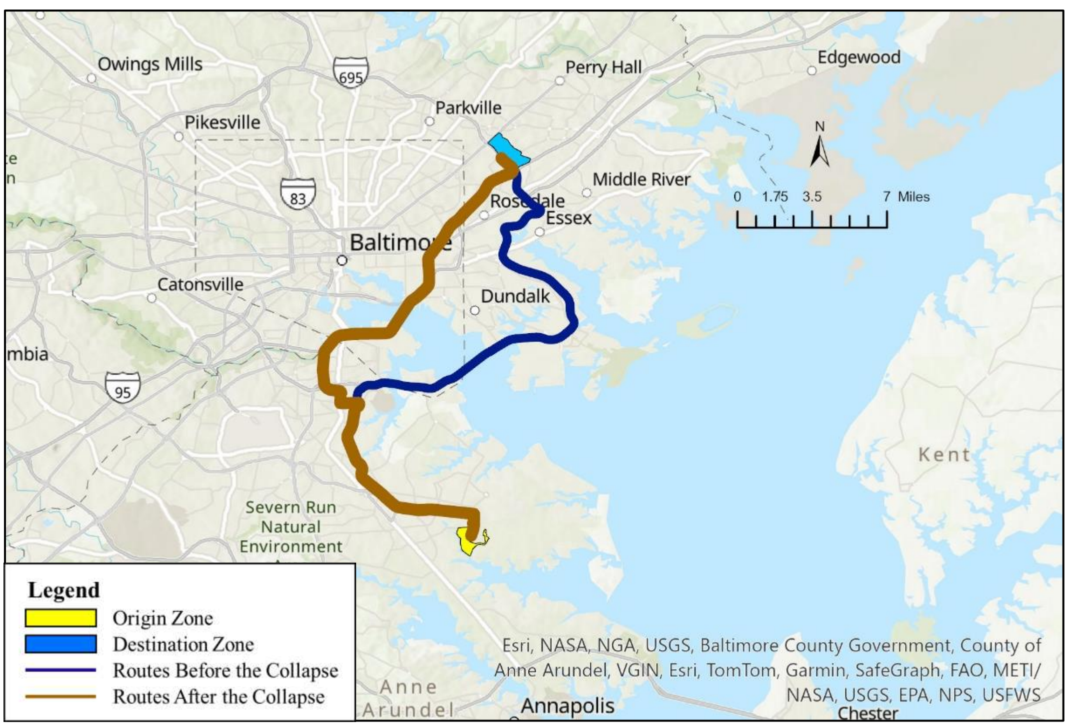

Figure 8 Routes of the OD Pair Five Before and After the Collapse of the Key Bridge

For the fifth OD pair, medium-duty trucks traveled from residential areas in Lake Shore to freight distribution centers in the northeastern Baltimore area near Overlea. Before the collapse, these trucks primarily relied on the Key Bridge. After the collapse, they were rerouted to I-895. Notably, despite the complete change of routes, the number of trips remained similar. This indicates a less elastic logistic demand, which is expected to introduce long-term pressures on detour routes, particularly on tunnels.

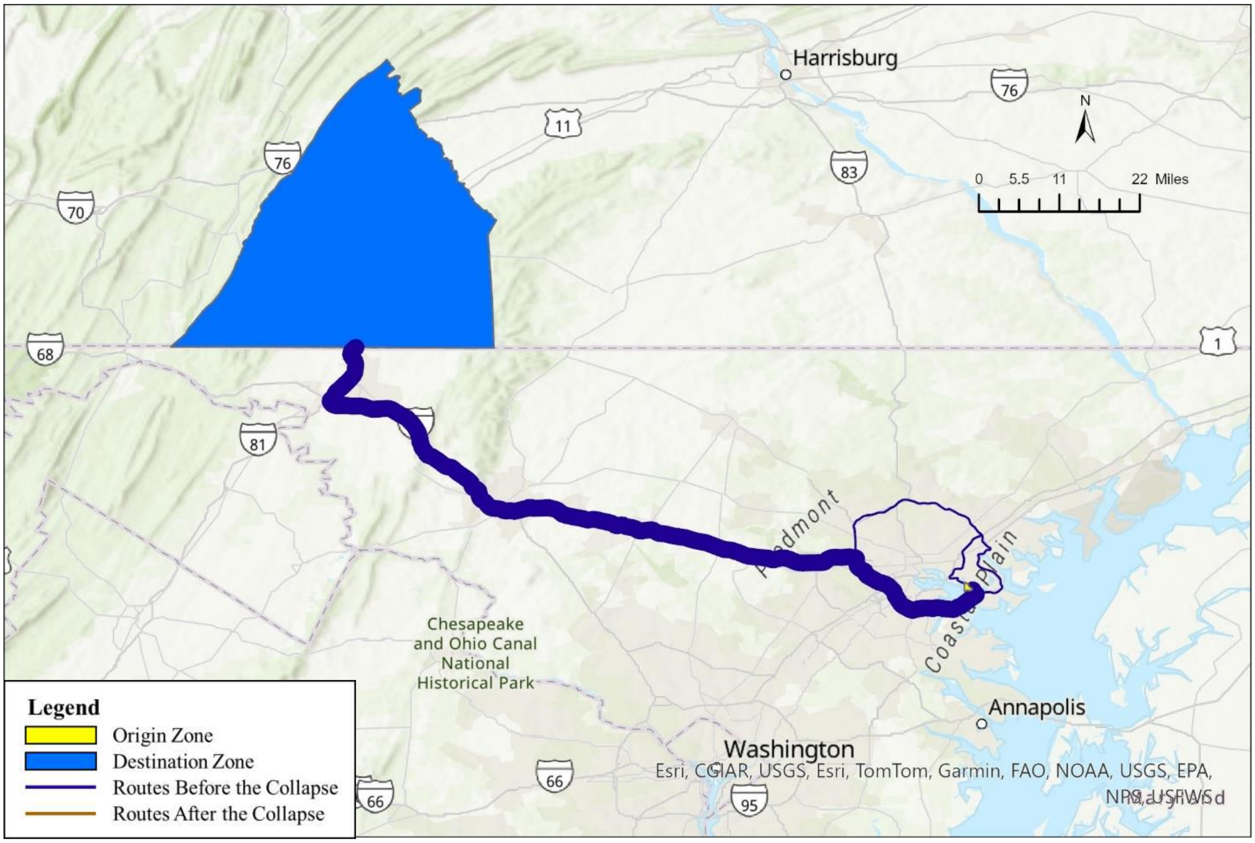

Figure 9 Routes of the OD Pair Six Before (and after) the Collapse of the Key Bridge

Heavy-duty vehicles traveling along the sixth OD pair were from the Baltimore Port to several manufacturers on the border of Pennsylvania, northwest of Baltimore. Interestingly, after the collapse, no trips were observed for this OD pair, illustrating the severe disruptions in logistic operations. A likely reason is that the collapse of the Key Bridge led to a complete closure of the Baltimore Port, preventing the delivery of shipments. This disruption in the supply chain halted the transportation of goods from the Port to the manufacturers, likely causing production delays and operational disruptions. The collapse underscores the far-reaching short-term impact of infrastructure failures on the logistics industry and regional commerce. However, in the long term, such disruptions are expected to be relieved following the complete reopening of the Baltimore Port in June 2024(3).

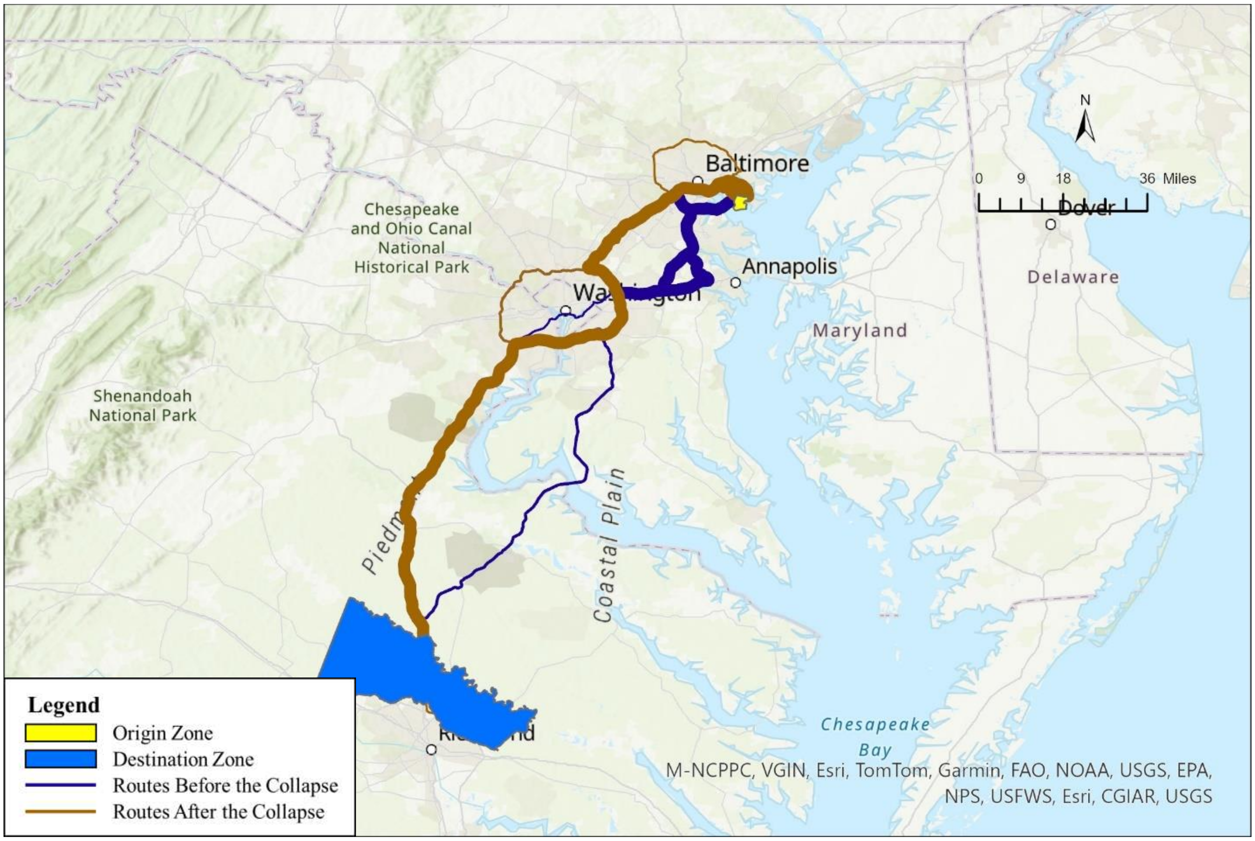

Figure 10 Routes of the OD Pair Seventh Before and After the Collapse of the Key Bridge

The last OD pair represents long-distance travel to the south, with the origin at the Baltimore Port and destinations located in the Richmond area, Virginia. Before the collapse, after passing the Key Bridge, heavy-duty trucks could take either I-95 or I-97/US-301 to Washington, DC, and then continue south via I-95 or use other local arterials to Richmond. These alternatives provided flexibility, allowing truck drivers to choose between routes depending on real-time traffic conditions, helping to avoid congestion. However, after the collapse, trucks have to rely on the Fort McHenry Tunnel (I-95) or even the I-695 Western Sections. In this scenario, using I-97/US-301 means additional travel distance. As a result, these routes could no longer serve as convenient alternatives, leading to further congestion along I-95 and longer travel times for the trucks.

In summary, the collapse of the Key Bridge led to increases in average travel times ranging from 3.48% to 58% for trucks traveling through the Baltimore area, depending on the type of truck and the alternative routes used. Heavy-duty trucks experienced more substantial travel time increases due to restrictions on larger trucks in the Baltimore Harbor Tunnel, which has significantly better traffic conditions than other routes. Additionally, more heavy-truck trips were rerouted to the longer I-695 Western Sections because of prohibitions on transporting hazardous materials through the tunnels. The microscopic analysis of rerouting behavior indicates that the impact of rerouting extends beyond the detour routes. It affects arterials connecting the origins and destinations to the detour freeways, alternate arterials that could serve as detour routes when the recommended freeways are congested, and further upstream and downstream freeways for long-distance transportation. Moreover, in the short term, the collapse of the Key Bridge caused far-reaching disruptions in logistics operations. In the long term, the less elastic logistic demand is expected to continue to put pressure on the traffic conditions of the detour routes.

OPERATIONAL COST ESTIMATION

Data

In addition to the trajectory data used in the detour analysis, the estimation of the operational costs incurred by the road freight industry in Baltimore Area after the Key Bridge Collapse involved the latest 2022 Annual Truck Origin–Destination (OD) Data from the Next Generation National Household Travel Survey (NHTS) (4). Since the trajectory data represents only a fraction of truck volumes rather than the total number of truck trips, it is essential to scale up these sampled truck volumes to accurately estimate the costs incurred by the freight industry due to the detours. The NHTS Truck OD Data includes travel between 583 zones, encompassing metropolitan statistical areas (MSAs) and non-MSA areas within each state and the District of Columbia. The data provides estimated annual trip counts for eight different trip distances, ranging from 0 to 10 miles to distances greater than 300 miles, between each OD MSAs.

It is important to note that the rerouting of trucks may impact traffic conditions beyond the detour routes. Therefore, trajectories of all trucks either originating from or destined for the Baltimore MSA were used, rather than only those using the Key Bridge or alternative routes, which differs slightly from the earlier detour analysis. In other words, trajectories with both origins and destinations outside the area were excluded due to their limited sample size.

Method

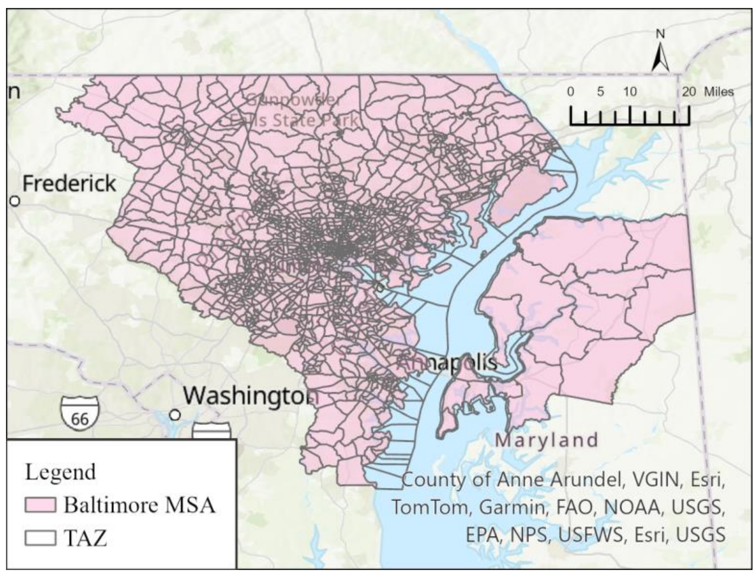

Figure 11 TAZs in Baltimore MSA

Two key aspects were considered in the cost estimation. First, the detouring increases the travel time for trucks, which ultimately raises operational costs. These costs include vehicle-based expenses such as fuel and truck/trailer lease or purchase payments, as well as truck drivers' salaries and benefits. Second, since the Key Bridge has tolls (5), rerouting can result in savings on toll fees, particularly for routes that do not involve tolled tunnels. Therefore, toll costs were analyzed separately.

Since the travel times and truck volumes came from different data sources, the first step was to match them. This task is particularly challenging because the datasets use different identification methods. The NHTS Truck OD Data provides truck counts for specific NHTS zones, which can be metropolitan statistical areas (MSAs), across various trip distance ranges, referred to as "NHTS-Zone+Distance-Category" (NZDC). For example, all trips with distances ranging from 0 to 10 miles within NHTS Zone "12580_MD" are classified into the same NZDC. NHTS zones are very large and can encompass many traffic analysis zones (TAZs), as shown in Figure 11. Meanwhile, the trajectory data are not tied to a specific zonal system. Simply grouping trajectory data into NHTS zones would be nearly equivalent to averaging all trajectories, which could result in a significant loss of information. For example, the characteristics of travel time increases for long-distance trips (greater than 100 miles, such as the seventh OD pair) are completely different from those of shorter distances (such as the first OD pair). Therefore, to provide a more accurate estimation that better utilizes the truck counts by distance provided by the NHTS Truck OD Data, trips were grouped not only by their geographical origin and destination NHTS zones but also by their distance.

However, using the actual trip distances could lead to serious errors in the estimations of increased travel time. The NHTS Truck OD Data was generated based on trip distances from 2022, before the Key Bridge collapsed. As discussed earlier, trip distances could significantly increase after rerouting to alternative routes. If the actual trip distances were used, some trips might be misclassified into longer distance categories, leading to erroneous estimations of total increased travel time. For example, the typical trip distance between distribution centers A and B might be 8 miles before the collapse ("the before trip") and 12 miles after the collapse ("the after trip"). If actual trip distances were used, the before trip would be classified into the "0 to 10 miles" category, while the after trip would fall into the "10 to 25 miles" category. This misclassification could result in inaccurate calculations of average travel times. The after trip would not be considered in the "0 to 10 miles" category, leading to a misleading conclusion that rerouting reduces travel times for trips in that distance range. Additionally, since the after trip is only 12 miles, it is significantly shorter than the average trip distance in the "10 to 25 miles" category, potentially resulting in shorter calculated average travel times for that category. This could erroneously suggest that rerouting leads to significant travel time savings.

To address this issue, all trips between specific TAZ pairs were labeled with a mean trip distance calculated using the actual trip distances before the Key Bridge collapse. The classification of trips was then based on this mean trip distance rather than their actual trip distances. To calculate the mean trip distance, trips were grouped by their geographical origin and destination TAZs. A "TAZ-NZDC" lookup table was generated based on the geographical relationship between TAZs and NHTS zones, as well as the mean trip distances between TAZ pairs. Meanwhile, the number of sampled trips and the average travel time between specific TAZ pairs were also calculated. These values were then used to derive the average travel times for NZDCs.

The total change of the travel time (T_{change}) in hours is calculated using:

$$T_{change} = \sum_{i=1}^{N} [q_i \left(\frac{\sum_{j=1}^{n_i} q_{ja} t_{ja}}{\sum_{j=1}^{n_i} q_{ja}} - \frac{\sum_{j=1}^{n_i} q_{jb} t_{jb}}{\sum_{j=1}^{n_i} q_{jb}} \right)] \tag{1}$$

where N is the total number of NZDC; q_i is the truck count in 2022 for NZDC i; n_i is the total number of TAZ pairs in NZDC i; q_j and t_j are the number of sampled trips and the average travel time for TAZ pair j; a and b indicate the after and before the collapse of the Key Bridge. In Equation (1), $\frac{\sum_{j=1}^{n_i} q_{ja/b} t_{ja/b}}{\sum_{j=1}^{n_i} q_{ja/b}}$ represents the weighted average travel time for NZDC i after or before the collapse. Note that NZDCs with fewer than 1,000 sampled trips during the study period were excluded to minimize the impact of outliers.

The total annual cost of the change of travel time ($C_{traveltime}$) is then calculated as follows:

$$C_{traveltime} = T_{Change} c_{marginal} \tag{2}$$

where $c_{marginal}$ is the adjusted marginal operational cost of trucking per hour. The value is derived from the 2024 update of "An Analysis of the Operational Costs of Trucking" by American Transportation Research Institute (6). The average marginal cost per hour in 2023 was \$91.27. Since toll costs are analyzed separately in this study, the marginal cost is adjusted by subtracting the average marginal toll per hour, which is \$1.35. Therefore $c_{marginal}$ used in this study is \$89.92.

Regarding the change in toll costs, the sampled trips using specific toll facilities—including the Key Bridge, Fort McHenry Tunnel, and Baltimore Harbor Tunnel—were first filtered out. These trips were then grouped by their geographical origin and destination TAZs, and the number of sampled trips using each specific facility between the TAZ pairs was calculated. These values were matched with the total number of sampled trips between the specific TAZ pairs. This information was then used to calculate the percentage of trips using each facility before and after the collapse of the Key Bridge.

The total annual change of the toll revenue of a specific toll facility ($C_{faclity}$) calculated as:

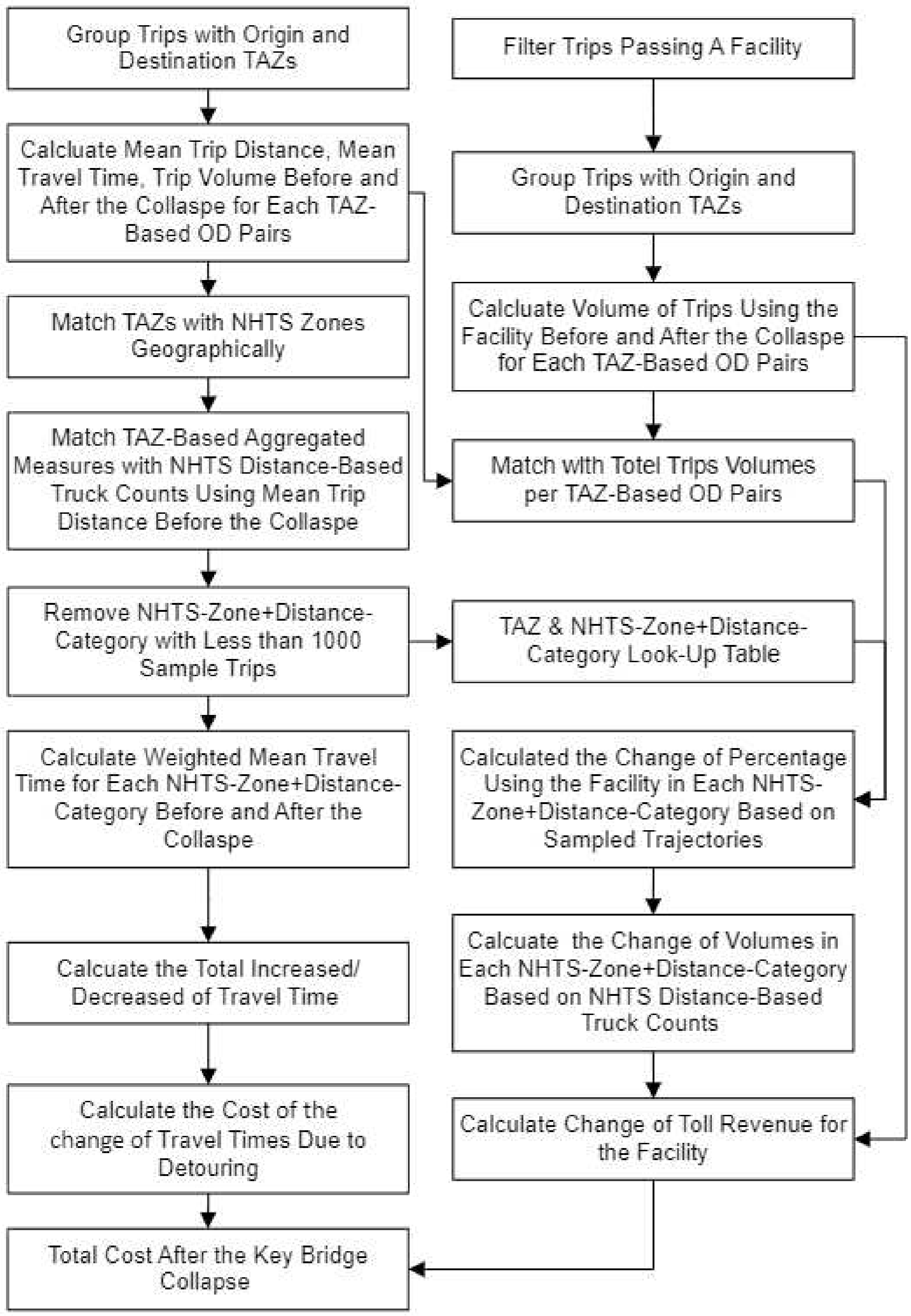

Figure 12 Process of Cost Estimation

$$C_{faclity} = \sum_{i=1}^{N}[q_i\left(toll_{avga}\frac{\sum_{j=1}^{n_i} q_{jfa}}{\sum_{j=1}^{n_i} q_{ja}} - toll_{avgb}\frac{\sum_{j=1}^{n_i} q_{jfb}}{\sum_{j=1}^{n_i} q_{jb}}\right)] \tag{3}$$

$$toll_{avgb} = p_{hb}toll_h + p_{mb}toll_m \tag{4}$$

$$toll_{avga} = p_{hb}\frac{q_{hb}}{q_{ha}}toll_h + p_m\frac{q_{mb}}{q_{ma}}toll_m$$

where $q_{jfb/a}$ is the number of sampled trips using the specific toll facilities before (b) or after (a) the collapse of the Key Bridge; $\frac{\sum_{j=1}^{n_i} q_{jfb/a}}{\sum_{j=1}^{n_i} q_{jb/a}}$ represents the proportion of trips that used the facility for NZDC i. For the Key Bridge, the value is zero for the after period. $toll_{avgb/avga}$ is the average toll before and after the Key Bridge collapse, calculated using the toll rates for heavy-duty ($toll_h$) and medium-duty ($toll_m$) trucks and their percentages $p_{b/a,h/m}$. The average toll for the heavy-duty trucks is assumed to be $12 (4-axle) and for medium-duty trucks is assumed to be $4 (80% of 2-axle and 20% of 3-axle) (5). $q_{hb/a}$ and $q_{mb/a}$ represent the numbers of sampled heavy-duty and medium-duty trucks using the facility from the trajectory data before and after the collapse, respectively.

The NHTS Truck OD Data do not provide truck counts by vehicle type. Therefore, the proportion of heavy-duty trucks before the collapse was estimated using 2022 truck volumes collected from the nearest count station by the Maryland Department of Transportation State Highway Administration(7)For the post-collapse period, the percentages were adjusted using sample trip volumes $q_{b/a,h/m}$ to account for changes in truck composition due to the detours.

Finally total annual operational cost by the road freight industry (C_{total}) is given by:

$$C_{total} = C_{traveltime} + \sum C_{faclity} \quad (5)$$

Results

Table 2 presents the estimated annual operational costs incurred by the road freight transportation industry in the Baltimore area. The results show that the collapse of the Key Bridge has had a significant financial impact on the freight industry in this region. The additional truck travel time due to altered traffic conditions has resulted in substantial operational costs. Specifically, the annual increase of 1,096,399 hours in travel time translates to an additional $98,588,198 in operational costs, excluding tolls.

Furthermore, the complete cessation of trips across the Key Bridge resulted in a toll cost decrease of over $12 million. Meanwhile, increased usage of the Fort McHenry Tunnel and Baltimore Harbor Tunnel led to toll cost increases. Despite these increases, there was an overall net toll cost decrease of approximately $5.8 million.

In total, if current conditions remain unchanged, the collapse of the Key Bridge could lead to an annual increase in operational costs for the road freight transportation sector in the Baltimore area amounting to $92,824,917. This underscores the significant broader economic implications of the Key Bridge collapse.

TABLE 2 Annual Operational Cost Estimation Results

Cost in Travel time					
Item	Hourly Marginal Cost		Change in Hours		Cost in Travel time
Subtotal	$89.92		1,096,399		$98,588,198
Cost in Toll					
Toll Facility	Before		After		Cost Change
	Toll	Volume	Toll	Volume	
The Key Bridge	$7.94	1,520,831	$0.00	0	($12,075,398)
Fort McHenry Tunnel	$8.42	4,060,292	$8.25	4,833,593	$5,689,484
Baltimore Harbor Tunnel	$5.06	1,524,743	$5.06	1,647,793	$622,633
Subtotal					($5,763,282)
Total Cost					$92,824,917

Discussion

If the rebuild of the Key Bridge is completed on schedule in Fall 2028 (8) and assuming a 3% inflation rate, the total operational cost increase could amount to approximately $446 million, assuming current conditions remain unchanged. However, the data used in this study only represents the short-term change in travel behavior. In the long term, more aspects require careful consideration. For instance, at the time of data collection for this study, the Port of Baltimore had not yet reopened. Since its full reopening in June this year (3), additional traffic heading to the port may further exacerbate tunnel bottlenecks. Additionally, earlier studies (9) suggest that, in the long run, road users may gradually adapt to new traffic patterns, potentially leading to a more balanced traffic network and reduced travel times. Continuous monitoring is essential to understand the long-term traffic impacts.

Moreover, the data used to estimate travel times and the usage of toll facilities in this study represent only a portion of the truck trips, introducing intrinsic sampling errors despite measures taken to exclude data records with small sample sizes. For example, the sample rate of trucks using the Baltimore Harbor Tunnel is comparatively lower than for other facilities. Although the impact of toll costs for the Baltimore Harbor Tunnel is minor, accounting for no more than 1% of the total cost, this discrepancy remains noteworthy. Furthermore, due to data availability, truck counts from earlier years were used, which may not accurately reflect current conditions. Similarly, the selection of toll rates was not based on real-world data due to the same data availability issue.

CONCLUSIONS

The collapse of the Key Bridge in Baltimore has had profound and far-reaching impacts on the road freight transportation industry in the region. This study aimed to quantify these impacts by analyzing changes in travel times, detour patterns, and the operational costs associated with the bridge collapse.

Significant changes in travel patterns for trucks previously using the Key Bridge were observed. Depending on the type of truck and the alternative routes used, average travel times increased between 3.48% and 58% for trucks traveling through the Baltimore area. Heavy-duty trucks experienced more pronounced travel time increases due to restrictions on larger trucks in the Baltimore Harbor Tunnel, which is less congested than other routes. Additionally, more heavy trucks had to use the longer I-695 Western Sections because of prohibitions on transporting hazardous materials through the tunnels. The impact of rerouting extends beyond the detour routes. It affects arterials connecting the origins and destinations to the detour freeways, alternate arterials that could serve as detour routes when the recommended freeways are congested, and further upstream and downstream freeways for long-distance transportation. In the short term, the collapse of the Key Bridge caused significant disruptions in logistics operations. In the long term, certain logistics services with inelastic demands are expected to continue to pressure the traffic conditions of the detour routes.

The economic analysis demonstrated a substantial increase in operational costs for the road freight transportation sector in the Baltimore area post the collapse of the Key Bridge. Assuming current conditions remain unchanged, the region-wide annual increase of 1,096,399 hours in travel time translates to an additional $98,588,198 in operational costs for the sector. However, an annual net toll cost decrease of $5,763,282 reduces the total increase in operational cost to $92,824,917. This underscores the significant broader economic implications of the Key Bridge collapse.

While the data used in this study provides valuable insights, it represents only the short-term changes in travel behavior. Continuous monitoring is essential to understand these long-term impacts. Moreover, the study faced intrinsic sampling errors and data limitations. More comprehensive data collection and analysis are needed in future studies.

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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: Y. Gong; analysis and interpretation of results: Y. Gong, K. Yang, Y. Zhang; draft manuscript preparation: Y. Gong, Y. Zhang, K. Yang, X. Yang, D. Yang. All authors reviewed the results and approved the final version of the manuscript.

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