Short-term Impacts of Carola Bridge Collapse on Road Traffic

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Short summary

Understanding the short-term impact of unexpected network disruptions is critical for resilient traffic management. This study analyzes traffic flow and pattern changes in Dresden following the Carola Bridge collapse on September 11, 2024, using aggregate traffic data. We employ a paired T-test comparing pre- and post-collapse traffic flows to identify the critical roads with large impacts among the alternative bridges, connectors, and main arteries of the urban network in Dresden. We find that traffic flow changes show clear proximity property, diminishing with increasing distance from the collapsed bridge. Moreover, traffic patterns during workdays on critical roads were analyzed using a rolling index called the Peak Hour Indicator (PHI), which integrates traffic flow and speed to evaluate conditions and detect peak hours. Post-collapse peak hours show an extended period, implying likely changes in departure times. The findings provide insights into the short-term response and resilience of the urban traffic network after disruptions.
Keywords: Bridge collapse, Network disruption, Traffic flow, Traffic pattern

1 Introduction

On September 11, 2024, the Carola Bridge over the Elbe River in Dresden abruptly collapsed at around 2:59 am. Despite no injury, the tragic incident substantially disrupted the urban traffic network, which led to an uncertain traffic condition before the network re-equilibrate itself. A deep understanding of these short-term traffic changes is essential for resilient traffic management in response to future disruption scenarios.

The Carola Bridge collapse happened on one of the most critical arteries of the Dresden traffic network and a few alternatives are available after the collapse. Connecting the old town and new town directly, the bridge served 30000 vehicles on an average day and four tram routes before the collapse. Only two bridge alternatives for motorized traffic, Marien Bridge and Albert Bridge, are available to provide accessibility for intra-city trips crossing the river, while commuters suffered increased travel distance and time. Therefore, not only bridge users but also other travelers were impacted and the traffic dynamics of the entire network changed dramatically.

Unlike planned traffic network disruptions, travelers must respond to the infrastructure and traffic conditions changes with imperfect information after unexpected disruptions, resulting in a dramatic influence on traffic distributions and daily traffic patterns (Danczyk et al., 2017; Donovan & Work, 2017; Gu et al., 2023). Since the critical importance and complicacy of short-term traffic dynamics after unexpected network disruptions, several research has focused on traffic demand and behavior change analysis. Zhu et al. (2010) evaluated the aggregate travel demand evolution and behavioral reactions to the I-35W bridge over the Mississippi River in Minneapolis, US based on multi-source traffic data. Prediction-correction models were also applied to describe the traffic equilibration process, which captured the congestion(He & Liu, 2012). Nevertheless, the limited available data hindered comprehensive analysis of traffic changes after unexpected network disruptions. Moreover, few studies focused on artery collapse in city centers with multimodal traffic.

Considering the unique features of the Carola Bridge collapse, this study analyzes the short-term traffic flow and pattern changes in Dresden after the network disruption based on recorded traffic data in the VAMOS system. The traffic flows before and after the collapse were compared using paired T-test to explore the traffic distribution changes and identify significantly impacted roads. The detection of bottlenecks after the network disruption facilitates efficient traffic management to

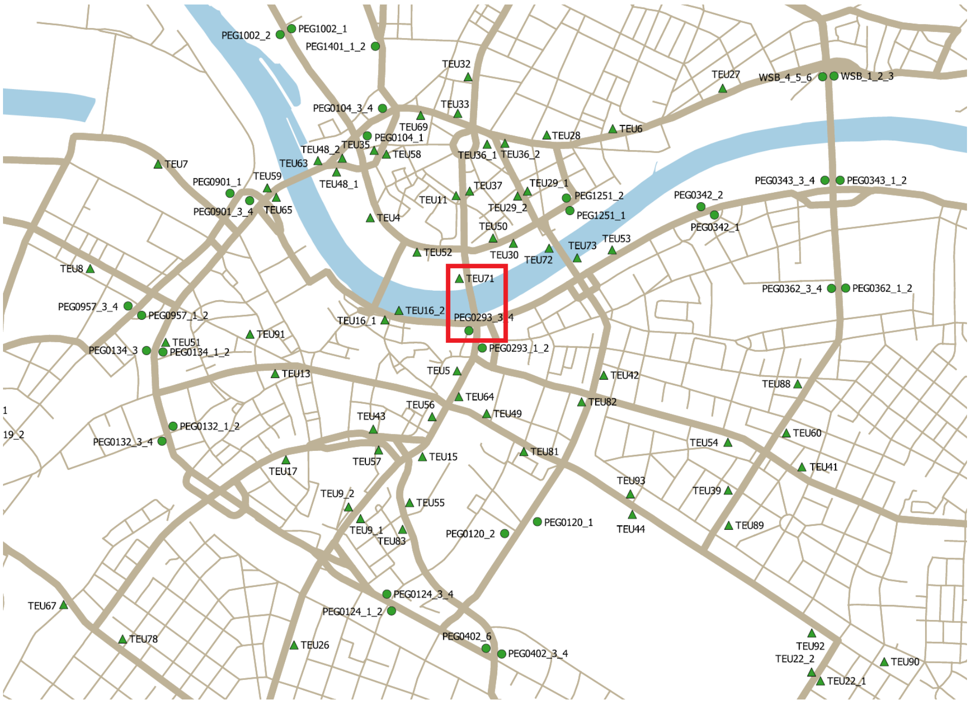


Figure 1: Locations of detectors in VAMOS system, where triangle shapes are traffic eye cameras and circular symbols represent double induction loop detectors and the Carola Bridge section highlighted with a red rectangle.

mitigate the advert influence. Daily traffic patterns of these critical roads on workdays are further analyzed based on a rolling index termed Peak Hour Indicator. This has remarkable implications for finding behavioral effects of travelers and modeling the complicated traffic demands.

2 Data source and analysis methods

Traffic flow and pattern changes are analyzed to explore the short-term impacts of the Carola Bridge collapse. In this section, we first introduced the traffic data in this study, followed by the analysis methods of traffic flow and daily patterns.

Data source

This study was based on the traffic flow and speed data recorded from *VAMOS (Verkehrsanalyse, Management und Optimierungssystem, i.e. Traffic analysis, management and optimization system in English)* in Dresden Yan et al. (2024). It has been built as the traffic management system for the state capital Dresden since 2003. The core of this system is the traffic data center, with approximately 1800 different types of detectors monitoring and recording Dresden and surrounding traffic conditions. Among these, 186 are double induction loops, and 160 are traffic eye cameras. The detectors capture traffic flow, speed, and vehicle classes, illustrated in figure 1. To compare traffic changes before and after the network disruption, we analyzed data from two weeks prior to the event and two weeks following it. The missing data was completed using an in-house imputation method. In some exceptional cases, we selected alternative dates; for example, for the detector "1429_1430," data from August 28 was used as a substitute for September 4 in certain analyses.

Paired T-test analysis

After the network disruption, numerous travelers are forced to change routes because of infrastructure closure or abnormal congestion, leading to traffic reallocation across the network. To identify the significant flow changes in the network, the paired T-test is applied to compare the traffic flow before and after the disruption.
The traffic flows collected from all detectors are respectively compared by the paired T-test, which evaluates whether the mean difference between two paired groups is significantly different from

zero. The pre- and post-collapse test sets were created using two consecutive same weekdays (e.g., 28th August and 4th September for the pre-collapse period, and 18th and 25th September for the post-collapse period). The data was discretized into 15-minute intervals throughout the day and matched to the corresponding time periods for comparison. The sample size of 192 satisfies the T-test condition. Assuming the mean difference between the traffic flow of these two days is zero, the t-statistic is calculated to determine the p-value. The significantly impacted roads whose p-values are smaller than the significance level of 0.05 are identified as critical bottlenecks and analyzed.

Peak hour identification

To fully understand the traffic dynamics after the network disruption, daily traffic changes on critical roads are explored by comparing peak hour changes.
A rolling index called *Peak Hour Indicator (PHI)* is introduced to represent the time-varying traffic conditions for peak hour identification. Compared to traditional criteria, it combines normalized traffic flow and speed over a rolling window, as shown in Equation 1:

$$P_t = \frac{1}{w} \sum_{i=0}^{w-1} \frac{\alpha_1 \cdot \frac{q_{t-i} - q_{min,t}}{q_{max,t} - q_{min,t}} + \alpha_2 \cdot (1 - \frac{v_{t-i} - v_{min,t}}{v_{max} - v_{min,t}})}{\alpha_1 + \alpha_2} \tag{1}$$

where P_t is the PHI at time t, w is the rolling window size, q_{t-i} is the traffic flow at time $t-i$, $q_{max,i}$ and $q_{min,i}$ are the maximum and minimum traffic flow during the rolling window at time t, v_{t-i} is the traffic speed at time $t-i$, $v_{max,i}$ and $v_{min,i}$ are the maximum and minimum traffic speed during the rolling window at time t, and α_1 and α_2 are the weight coefficients of traffic flow and speed, respectively.
It is critical to determine the threshold for PHI, based on the mean value, standard variation, and 90^{th} percentile value over the whole day, which is formulated in Equation 2. The period during which the PHI is greater than the threshold is defined as peak hour.

$$\theta = \max(\frac{1}{N} \sum_t P_t + k \cdot \sqrt{\frac{1}{N} \sum_t (P_t - \frac{1}{N} \sum_t P_t)^2}, P_{90}) \tag{2}$$

where θ is the threshold of PHI for peak hour identification, N is the total number of sampling times during the day, P_{90} is the 90^{th} value of PHI, and k is the weight coefficient of standard variation.
In this study, the rolling window size is 2, the weight coefficients α_1, α_2, and k are 3, 2, and 1.2, respectively. The peak hours identified based on PHI of critical roads are compared to analyze the traffic pattern changes.

3 Results and discussion

This section illustrates the analysis results of traffic changes resulted from Carola Bridge collapse along with the discussions about the network disruptions. The traffic flow changes after the Carola Bridge collapse are demonstrated first, followed by the discussion about traffic pattern changes.

Daily traffic flow trends

A significant change over the whole network was noticed after the Calora Bridge collapse, as shown in Figure 2. The significantly affected roads detected by the paired T-test are denoted in the figure, which are found on the alternative bridges, connectors between them, and main arteries in Dresden center area. Table 1 exhibits the average daily traffic flow and changes on these roads, in which the direction from the old town to the new town is denoted as outbound, and another direction is denoted as inbound.
The impacts of the bridge collapse reduced with the distance to the Calora Bridge, leading to remarkable flow changes on Albert Bridge and Marien Bridge, while other bridges far away from the city center were not influenced. The main traffic of the collapsed bridge changed to Albert Bridge, and the traffic flow of Marien Bridge also increased. Before the bridge collapse, Carola Bridge played the most important role in intra-city across-river traffic, with about 30000 veh/day in work days. A significant increase in traffic flow was found in Albert Bridge. It replaced the role of Carola Bridge with an increase of around 7000 veh/day in each direction, while the traffic of

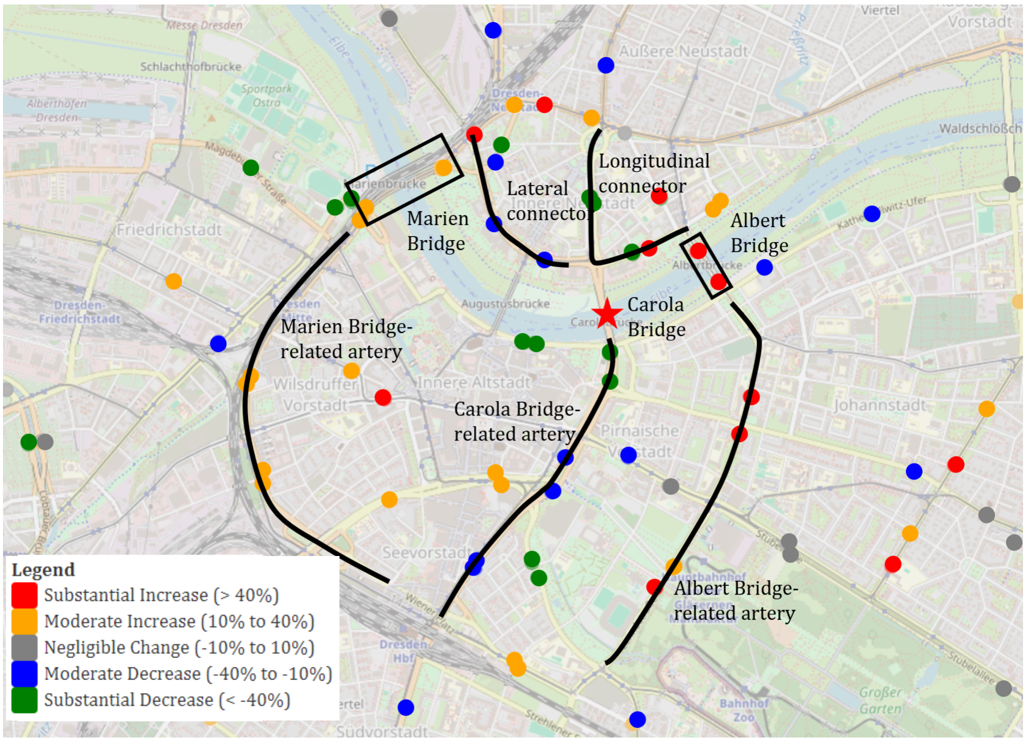
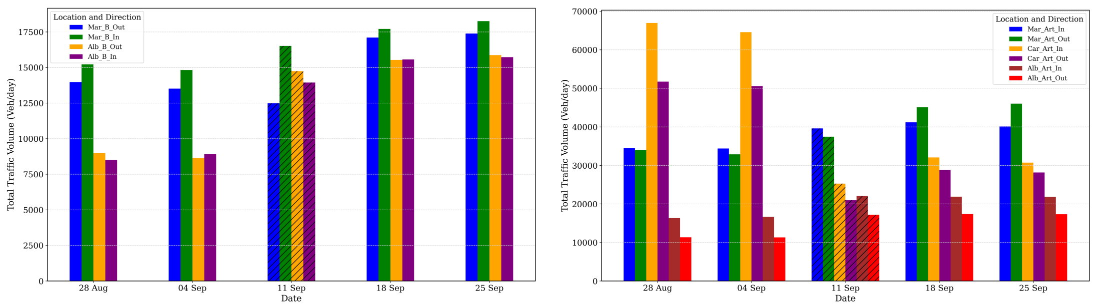


Figure 2: Daily traffic flow changes in Dresden after the Carola Bridge collapse. The alternative bridges are marked with rectangles, while the arteries and connectors are indicated with thick lines.

Marien Bridge increased by 26.54% and 19.43% in outbound and inbound. Additionally, an overall comparison of the traffic flow situation across multiple days for these two bridges is presented in Figure 3(a).

The flow changes of connectors revealed the new traffic distribution in the new town caused by the different options to cross the Elbe River. The two connectors to the Carola Bridge from the center of the new town and outer space of the center were influenced by the reduced traffic flow. Specifically, traffic flow of longitudinal connector, from the center new town, was reduced by more than 34% after the collapse. And that of the lateral connector reduced by 40% to 70%. Obviously, the unavailability of the Carola Bridge forced travelers crossing the river to choose other routes.



(a) Alternative bridges

(b) Related arteries

Figure 3: Comparison of overall daily traffic flow on critical roads.

A directional impact of the Carola Bridge collapse was noticed on the main arteries. Three main arteries were detected severely influenced by the network disruption, which related to the collapsed bridge and the two alternative bridges as shown in Figure 2. They are referred to as Carola Bridge-related artery, Marien Bridge-related artery, and Albert Bridge-related artery. The inbound traffic on the Carola Bridge-related artery dropped significantly from about 5500 to 2200 vehicles per day, representing a 40% decrease. In contrast, the inbound traffic on the Albert Bridge-related artery increased by more than 40%, while the increase percentage of Marien Bridge-related artery was about 20%. This suggests that more drivers diverted to Albert Bridge as an alternative,

Table 1: Daily traffic flow changes on critical roads.

Critical roads	Direction	Detector ID	Traffic flow before collapse (Veh/day)	Traffic flow after collapse (Veh/day)	Change percentage
Marien Bridge	outbound	1388_1389	13512	17099	+26.54%
	inbound	1408_1407	14829	17710	+19.43%
Albert Bridge	outbound	1431_1432	8656	15532	+79.44%
	inbound	1429_1430	8518	15563	+82.70%
Lateral connector	outbound	1392_1393	4980	2814	-43.49%
		1371	7657	2094	-72.65%
		1364	7500	9095	+21.27%
	inbound	1322_1323	7359	2509	-65.91%
		1360_1361	5178	8536	+64.85%
Longitudinal connector	inbound	1308_1309	11941	7770	-34.93%
		1396_1397	11969	7820	-34.66%
Marien Bridge-relatedartery	inbound	1129_1130	11771	13921	+18.27%
		1287	9724	11502	+18.28%
		911_912	12869	15747	+22.36%
	outbound	909_910	8631	11656	+35.05%
		1394_1395	8575	11167	+30.23%
		1416	13107	17684	+34.92%
		1128	2558	4577	+78.93%
Carola Bridge-relatedartery	inbound	1322_1323	7359	2509	-65.91%
		1427_1428	14375	-	-
		291_292	14214	-	-
		1401_1402	17559	13350	-23.97%
	outbound	1319_1320	11070	9220	-16.71%
		1317_1318	9797	7326	-25.22%
		1329_1330	16932	11542	-31.83%
		289_290	16187	-	-
		1371	7657	2094	-72.65%
Albert Bridge-relatedartery	inbound	1359	3059	5155	+68.52%
		1447_1448	6624	10181	+53.70%
		1257	5697	8016	+40.71%
	outbound	1274	5418	6953	+28.33%
		1379	5901	10412	+76.44%

consistent with the conclusion from alternative Bridge analysis. A different influence was found on outbound traffic, with similar changes on traffic flow of both Albert Bridge and Marien Bridge-related arteries. Moreover, the phenomenon that the impact reduced with the distance was also indicated in these arteries. An overall comparison of the traffic flow situation across multiple days for these three arteries is presented in Figure 3(b).

The roads identified as significantly affected by the paired T-test may become the critical bottlenecks of the traffic network after the bridge collapse. To mitigate the effects of the bridge collapse, traffic management and control strategies at these locations should be optimized.

Hourly traffic variations and peak trends

Traffic patterns were also influenced by the Calora Bridge collapse, revealing the detailed impact of the network disruption. This section demonstrates daily traffic pattern changes on critical roads by peak hour analysis based on PHI. The heatmaps of PHI values shown in Figure 5(a) and 5(b) displays a tremendous change in traffic dynamics within workdays. We compared the threshold using the proposed threshold calculation method (2), and Figure 6(a) illustrates the PHI values before and after applying the threshold. Based on the calculated threshold (0.73 in this case), the differences in peak hours on critical roads were determined and visualized in Figure 6(b).

At most locations, both morning and afternoon peak hours extended. This might result from the travel behavior changes. People tended to depart earlier than usual to avoid the congestion after the bridge collapse. The values of PHI reveal a more detailed implication of the network disruption impact on travel behaviors. Although the change value in PHI in peak hours and off-peak hours were similar, greater percentages were detected during off-peak hours. This verifies that travelers tended to avoid congestion by flexible departure time.

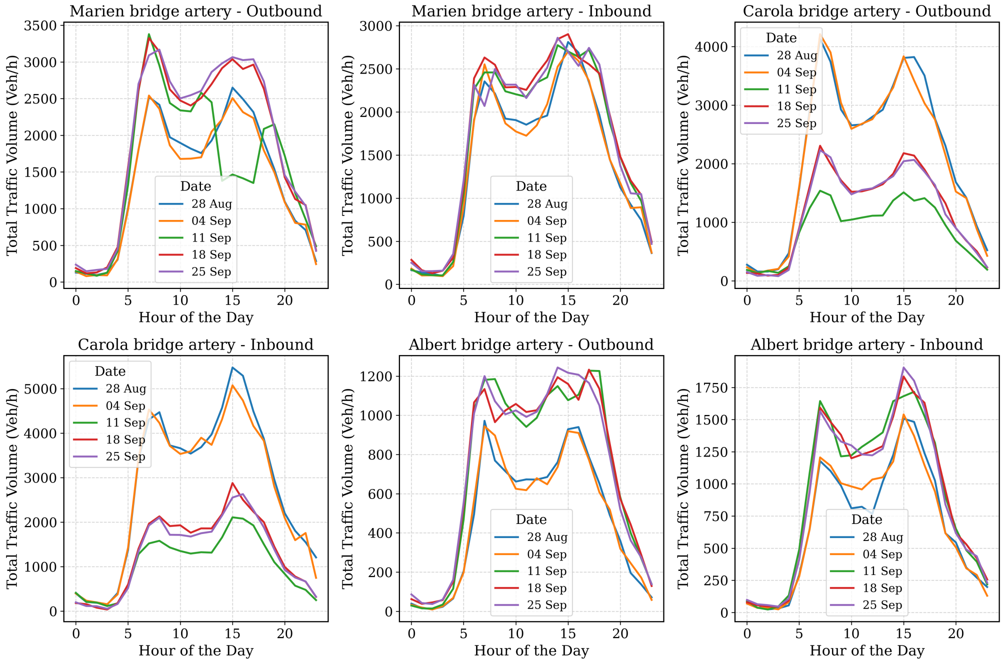
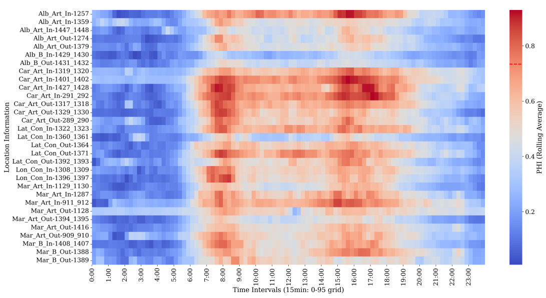
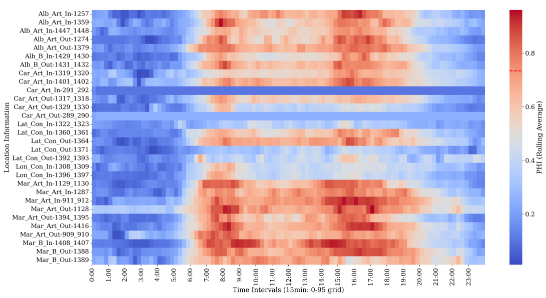


Figure 4: Hourly traffic flow over a 24-hour period for the three related arteries.

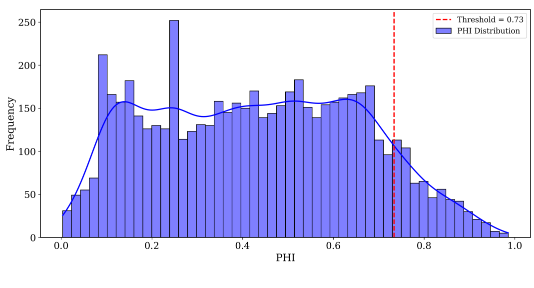


(a) before the collapse

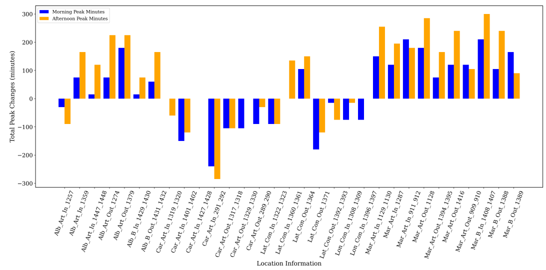


(b) after the collapse

Figure 5: Comparison of PHI heatmap for critical roads.



(a) Distribution of PHI values



(b) Peak hour changes in minutes

Figure 6: Analysis of daily peak hour changes after the corola bridge collapse.

4 Conclusions

This study analyzed short-term effect of the Carola Bridge collapse on Dresden road traffic, including the traffic flow evolution and daily traffic pattern changes, based on historical and real-time data from VAMOS system. Roads with significant daily traffic changes after the collapse were detected as critical bottlenecks by the paired T-test. Results indicated that bridges next to the Carola Bridge, the connectors between bridges, and main arteries in the city center were influenced by the accident, and the impacts were directional and reduced with distance. Within-day traffic patterns on the critical bottlenecks were further explored by a rolling indicator *Peak Hour Indicator (PHI)*, combining the traffic flow and speed data. The peak hours were identified to infer the travel behavior changes after the bridge collapse. The extension of peak hours and greater changes in PHI during off-peak hours suggest that people prefer flexible departure times after the network disruption. This study has a remarkable significance for deeply understanding the traffic dynamics after unexpected traffic network disruptions, and provides a foundation to optimize management and control strategies. Further studies will be conducted to analyze the impact on different vehicle types, compare the short-term and long-term effects of the collapse, and examine changes in travel mode choices, such as switching to public transport.

Acknowledgements

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