Comparing travel time performance-based measures to assess the effect of a freeway road construction project on freeway and connecting arterial street links

Venu Madhav Kukkapalli a and Srinivas S. Pulugurtha a,b

a Infrastructure and Environmental Systems Ph.D. Program, The University of North Carolina at Charlotte, Charlotte, NC, USA; b Civil & Environmental Engineering Department, Infrastructure, Design, Environment, and Sustainability (IDEAS) Center, The University of North Carolina at Charlotte, Charlotte, NC, USA

ABSTRACT
A road construction project has a significant effect on traffic congestion and operational performance of the project corridor and connecting street links. However, not many researchers focused on travel time performance-based measures to assess the effect of a road construction project on the project corridor and connecting street links. Therefore, travel time data for a freeway road resurfacing project on 100 links within its vicinity were gathered and processed to assess the effect on freeway and connecting arterial street links. A paired t-test was used to examine the differences in means between the before and during road resurfacing project period travel time performance-based measures. There is a significant difference in travel time performance-based measures before and during the road resurfacing project period on freeway links and connecting arterial links. Their significance varied by the time-of-the-day and day-of-the-week on the freeway and connecting arterial links. The average travel time, planning time, and travel time index can consistently explain the effect of a road resurfacing (construction) project on transportation system performance when compared to buffer time and buffer time index. The findings can be used to enhance temporary traffic control practices in the vicinity of road construction projects.

Introduction
Travel demand has been progressively increasing with the advancement of modern civilization and the need for more travel on the roads. The subsequent effect of this increase in travel demand is recurring congestion on the limited road network, growing air quality problem, and lack of safe and reliable transportation. Fastest-path was considered, for years, as motorists’ preference to travel from their origin to destination. The motorists usually plan for some expected delay due to recurring congestion, which is common today in many cities. However, motorists’ approach towards trip planning seems to be changing due to fluctuations and uncertainty in the traffic condition.

CONTACT Srinivas S. Pulugurtha sspulugurtha@uncc.edu Civil & Environmental Engineering Department, Infrastructure, Design, Environment, and Sustainability (IDEAS) Center, The University of North Carolina at Charlotte, 9201 University City Boulevard, Charlotte, NC 28223-0001, USA

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Further, the unexpected or non-recurring congestion on a day-to-day basis troubles motorists the most. Therefore, the reliability of a route plays a prominent role in motorists’ departure and route choice, among various other travel time performance measures.

Construction projects and related activity on roads influence capacity, flow rate, queue lengths, and travel time, and hence reliability. The number of work zones in the United States has increased in recent years, to upgrade and expand the life span of highways and roads (Abdelmohsen & El-Rayes, 2016). These work zones, including the related traffic management measures, influence traffic capacities of the infrastructure and the travel times for motorists. The activities at work zones influence operational performance, such as reduced freeway capacity, increased delay, increased travel time, increased crash rate, and increased fuel consumption. In short, road construction projects create physical changes on roads that result in capacity reduction and travel time increase during the construction project period.

The traffic flow decreases, and delay increases due to rehabilitation works on freeways. Kim et al. (2001) developed multiple regression models and observed that contributing factors such as the number of closed lanes, the proportion of heavy vehicles, grade, and intensity of work activity were found to have a significant effect on capacity reduction. Jiang (2002) predicted the traffic flow rate and congestion at work zones by using a Kalman predictor model. Zheng et al. (2011) found that the neuro-fuzzy model is more accurate than other linear and multi-linear freeway work zone capacity prediction models. Ramezani and Benekohal (2011) investigated the mechanism of queue propagation and dissipation at two potential bottlenecks at freeway work zones. They found that, when the volume exceeds capacity in the transition area and the work zone, both locations will be the active bottlenecks.

One of the major concerns in the work zones is the traffic delay. Martinelli and Xu (1996) developed a mathematical model to determine the optimal length of the work zone so that delays can be lowered. Chien et al. (2002) utilized a simulation-based technique to demonstrate that delays may be underestimated by using deterministic queuing theory. Imran and Pulugurtha (2014) used Vissim traffic simulation software to model and examine the effect of the reduced speed limit along with the length of the work zone, the number of lanes closed, and the traffic volume on delay and queue length. They observed that, both, delay and queue lengths typically increase with the increase in speed limit reduction. Garcia et al. (2006) presented possible options to improve safety due to unexpected events at construction work zones on freeways. In the past, researchers (Jiang, 2002; Martinelli & Xu, 1996) developed models for estimating capacity, queue length, and traffic flow rate at freeway work zones. Likewise, a few researchers focused on reducing the number of crashes and delay at the construction work zones (Chien et al., 2002; Kwon et al., 2011). Overall, majority of the past research efforts related to construction work zones were focused on examining capacity reduction, queue propagation and dissipation, flow rate, and safety. Collecting data to compute these measures is tedious, time consuming, and expensive. They are also not readily available for assessment.

The use of travel time and related measures such as travel time reliability in the field of transportation has increased in recent years. Data for computing, analyzing, and modeling travel time performance-based measures are captured using different types of probe
data collection systems such as test vehicles, Bluetooth detectors, toll tag readers, license plate readers, road-side sensors, cell phone tracking, automatic vehicle location, and global positioning systems (Brennan et al., 2018; Chen et al., 2019; Federal Highway Administration [FHWA], 2017; Lu & Dong, 2018; Martchouk et al., 2011; Singh et al., 2019). The data collected were used for characterizing congestion (Brennan et al., 2018), validating the adaptability of travel time performance-based measures (Chen et al., 2019), estimating travel time (Lu & Dong, 2018), exploring travel time reliability (FHWA (Federal Highway Administration), 2006; Lomax et al., 2004; Lyman & Bertini, 2008; Martchouk et al., 2011; McLeod et al., 2012; Sisiopiku & Islam, 2012; Van Lint & Van Zuylen, 2005), and examining distributions for modeling travel time or related reliability measures (Moylan & Rashidi, 2017; Yang & Wu, 2016; Zheng et al., 2017; Zhong et al., 2020; Zou et al., 2020). Heuristic and statistical methods were also explored to assess travel time reliability for various travel conditions (Abdel-Aty et al., 1995; Chen et al., 2002; Haitham & Emam, 2006; Du & Nicholson, 1997). The relationships between travel time performance-based measures were also researched in the past to recommend the best measure for transportation analysis based on the study purpose (Alemazkoor et al., 2015; Pu, 2011; Pulugurtha et al., 2015, 2016; Pulugurtha & Koilada, 2020; Wakabayashi & Matsumoto, 2012). A few researchers have also focused on travel time performance-based level of service thresholds (Gore et al., 2021; Kodupuganti & Pulugurtha, 2019; Pulugurtha & Imran, 2017).

A few studies on the effect of construction work zones on travel time performance measures are also documented in the literature. Kwon et al. (2011) proposed an empirical, corridor-level method to divide the travel time unreliability or variability over a freeway section into incidents, weather, work zones, special events, and inadequate base capacity or bottlenecks for developing effective strategies to mitigate congestion. Yesantaraao and Pulugurtha (2017) and Kukkapalli and Pulugurtha (2018) examined the travel time and travel time variations before, during, and after the completion of selected road construction projects by computing the ratios of travel time performance-based measures before, during and after the completion of selected road construction projects. The subject link, upstream link and downstream link characteristics were observed to have a significant effect on the link-level average travel times due to a road construction project (Kukkapalli & Pulugurtha, 2021). However, none of the past researchers have compared travel time performance-based measures to assess the effect of a road construction project. Overall, literature documents no research exploring or comparing travel time performance-based measures to assess the effect of a road construction project using link-level data.

Several travel time performance-based measures such as the average travel time (ATT), planning time (PT), buffer time (BT), buffer time index (BTI), and travel time index (TTI) were proposed and used to assess transportation systems in the past (FHWA (Federal Highway Administration), 2006; Lomax et al., 2004; Lyman & Bertini, 2008). As stated previously, these measures could be correlated to each other. Not all of them may be applicable to assess the effect of a road construction project. Additionally, the effect could be different on the project corridor and connecting street links before and during the road construction project period. However, not many researchers explored differences in travel time performance-based measures, before and during the road construction project period, on project corridor links as well as connecting street links within
their vicinity. In summary, there are no studies comparing, documenting, and/or recommending travel time performance-based measures for assessing the effect of a road construction project on the project corridor and connecting street links. This research paper aims to bridge this gap and contribute by focusing on travel time performance-based measures to assess the effect of a freeway road construction project on freeway and connecting arterial street links. It is based on a project conducted with support from federal, state, and local agencies (Kukkapalli & Pulugurtha, 2019). The findings can be used to evaluate the affects, proactively plan, and enhance temporary traffic control practices in the vicinity of road construction projects.

Methodology

The methodology adopted for this research includes: selecting a road construction project, identifying study links, collecting and processing travel time data, computing travel time performance-based measures, and conducting statistical analysis.

The type of road construction project and construction period have different effects on the project corridor and connecting street links. They also have an effect on the downstream and upstream links along the project corridor. Adequate data (number of days) are vital to derive meaningful interpretations for future planning. The data should be available, continuously, before and during the road construction project period along the project corridor (including downstream and upstream links) and connecting street links. The availability of six months of travel time data (at least 120 weekdays and 50 weekend days) for the study links, each, before and during the road construction project period was used as a criterion to select the road construction project. Additionally, it was ensured that no other major road construction projects or developments were happening within the vicinity of the project corridor or connecting street links. The raw travel time data, at link-level, was gathered and processed to compute travel time performance-based measures for the project corridor and connecting street links.

Travel time performance-based measures such as the ATT, PT (95th percentile travel time), BT, BTI, and TTI were considered for comparison and evaluation in this research. The BT is the difference between the PT and the ATT (FHWA, 2006; Lomax et al., 2004), while BTI is the ratio of BT to the ATT (FHWA, 2006; Lomax et al., 2004; Lyman & Bertini, 2008). The TTI is the ratio of the peak hour travel time (say, the ATT) to the free-flow travel time (say, 15th percentile travel time) (Lyman & Bertini, 2008). The travel time performance-based measures considered were expressed per mile for easy comparison and assessment.

As the travel time performance-based measures are time and traffic dependent, they were computed by the time-of-the-day and day-of-the-week. Scatter plots were first developed to compare the computed travel time performance-based measures before and during the construction project periods, by time-of-the-day and day-of-the-week. This was then followed by statistical analysis.

Statistical analysis

To check the statistical significance of the change in travel times and travel time performance measures, one-tail paired t-test was performed at a 95% confidence level.
The null hypothesis is ‘H0: Travel time performance measure remained the same before and during the road construction project period (i.e. the mean difference in the travel time performance measure of before and during the road construction project periods is zero). The alternative hypothesis is ‘H1: Travel time performance measure increased when compared between before and during the construction project period (i.e. the mean difference in the travel time performance measure of before and during the road construction project periods is greater than zero). The t-Stat, t critical, and P-value (at a 95% confidence level) were used for assessment.

**Study area, data, and data processing**

The data relevant to a road construction project constructed and completed in 2015 in and around the Charlotte, North Carolina city limits, on a freeway was obtained from the North Carolina Department of Transportation (NCDOT). The selected construction project was a resurfacing project on I-485. While 39 freeway links were selected on I-485 with the resurfacing construction project, 61 links were selected on the connecting arterials. The 39-freeway links include links three miles upstream and downstream of the construction area. Each link is in a given travel direction (for example, eastbound). The speed limit on the road resurfacing project corridor (I-485) was 65 miles/hour at the time of the road construction project.

The data collected consists of characteristics of the work zone area, the extent of the work zone (8 miles), start and end dates of the project, the number of lanes available and closed during the construction project period, and the location of the construction. For the selected resurfacing project on I-485, the number of lanes closed during the construction is one-lane in both the directions, while two lanes were open for traffic in both the directions. The construction project was started in June 2015 and completed in six months. It was observed that traffic volumes on the freeways from before to during the construction project period was reduced. However, an increase in traffic volumes was observed on the connecting arterial links during the construction project period.

The raw unprocessed travel time data collected by a private data source was gathered as a datafile with support from state/local agencies. The raw travel time datafile consists of link id, date, time, average speed, reference speed, and travel time at one-minute intervals. The raw travel time data was gathered for, both, the freeway construction zone links and connecting arterial links within the vicinity of the road resurfacing project. Similarly, it was gathered three miles upstream and downstream beyond the actual construction activity zone, to capture the travel times while entering and leaving the construction zone. These links were selected as the travel time could reduce while moving away from the construction zone and could increase while approaching the construction zone. The gathered travel times on upstream and downstream links were also used for conducting the statistical analysis, along with the links on the road resurfacing project study corridor.

The raw travel time data was processed to remove null values and other miscalculated values. It was then processed to extract travel time records for six months before the start of the construction project and six months during the construction of the project. The data for six months was used for during the construction project period as the road resurfacing was completed in six months. To keep it consistent, data for only six months
was used for the before construction period as well. Each period includes at least 120 weekdays and 50 weekend days, and is considered as a reasonable sample size for the analysis. The data processing and mining were performed using Microsoft SQL Server 2012.

As stated previously, ATT, PT, BT, BTI, and TTI were computed per mile by time-of-the-day and day-of-the-week for evaluating and comparing the travel time performance-based measures. Four different study hours on a weekday and a weekend day were considered. They are 7 AM – 9 AM (morning peak), 10 AM – 12 PM (daytime off-peak), 5 PM – 7 PM (evening peak), and 10 PM – 12 AM (nighttime off-peak). The considered travel time performance-based measures were computed for each selected link on the freeway and connecting arterials before and during the road resurfacing project.

**Results**

The results from the plots (for evening peak and nighttime off-peak) and statistical analysis are discussed in this section.

**Average travel time (ATT)**

Figure 1 shows the ATTs on the selected freeway links and connecting arterial links, before and during the road resurfacing project periods, for evening peak and nighttime off-peak hours. The ATTs before and during the road resurfacing project periods are the same on almost all the freeway links, in the case of both the study hours. However, as expected, the ATTs are greater during the road resurfacing project period on the majority

![Figure 1. Average travel time (ATT) before and during the road resurfacing project period.](image-url)
of the connecting arterial links when compared to the before road resurfacing project period, in the case of both the study hours.

The mean differences, t-stat, and t-critical values computed using the average travel times are summarized in Table 1. The means of the average travel time during the road resurfacing project period is lower than the means of the average travel time before the road resurfacing project period on the freeway links. The t-stat and t-critical (one tail) results indicate that there was a significant decrease in the average travel time on the freeway links at a 95% confidence level. However, the mean average travel time on the connecting arterial links increased during the road resurfacing project period when compared with before the road resurfacing project period. The mean difference is comparatively higher on the connecting arterial links during the construction project period, during the evening peak hours (weekday), when compared with the freeway links at a 95% confidence level. This could be possible as the vehicular traffic might have shifted to the connecting arterial links during the road resurfacing project period to avoid major delays on the freeway links.

**Planning time (PT) or 95th percentile travel time**

Figure 2 shows the PTs on the selected freeway links and connecting arterials links, before and during the road resurfacing project periods, for evening peak and nighttime off-peak hours. The PTs are the same on majority of the freeway links. However, the PTs during the road resurfacing project period is generally greater than before the road resurfacing project period, on almost all the connecting arterial links, in the case of both the study hours.

The mean differences, t-stat, and t-critical values computed using the PTs are summarized in Table 2. The mean differences in the PTs during and before the road resurfacing project period followed a similar trend as the ATT. The PTs are significantly higher before the road resurfacing project period when compared with during the road resurfacing project period, at a 95% confidence level, during all the considered study hours. In addition, the mean PTs on connecting arterial links are significantly higher during the road resurfacing project period when compared with mean PTs before the

| Freeway Links | 7 AM – 9 AM | 10 AM – 12 PM | 5 PM – 7 PM | 10 PM – 12 AM |
|---------------|-------------|---------------|-------------|---------------|
| Mean | During | 1.01 | 1.08 | 1.40 | 1.03 |
| | Before | 1.16 | 1.08 | 1.54 | 1.05 |
| Diff. between means | –0.15 | –0.03 | –0.14 | –0.02 |
| t-Stat | –2.91 | –6.50 | –6.46 | –3.90 |
| PT(T ≤ t) one-tail | <0.01 | <0.01 | 0.26 | 0.99 |
| t Critical one-tail | 1.69 | 1.69 | 1.69 | 1.69 |

| Connecting Arterial Links | 7 AM – 9 AM | 10 AM – 12 PM | 5 PM – 7 PM | 10 PM – 12 AM |
|---------------------------|-------------|---------------|-------------|---------------|
| Mean | During | 2.25 | 2.16 | 2.58 | 1.66 |
| | Before | 2.24 | 2.17 | 2.24 | 1.47 |
| Diff. between means | 0.01 | –0.05 | 0.34 | 0.19 |
| t-Stat | 0.07 | –1.91 | 5.75 | 8.99 |
| PT(T ≤ t) one-tail | 0.47 | 0.30 | <0.01 | <0.01 |
| t Critical one-tail | 1.67 | 1.67 | 1.67 | 1.67 |
road resurfacing project period. As stated earlier, vehicular traffic might have shifted from the freeway links to the connecting arterial links during the construction to avoid the non-enduring delays.

**Buffer time (BT)**

Figure 3 shows the BTs on the selected freeway links and connecting arterial links, before and during the road resurfacing project periods, for evening peak and nighttime off-peak hours. The BTs on a few freeway links are greater than before the road resurfacing project period when compared with during the road resurfacing project period. The freeway

**Buffer Time (BT)**

Figure 3 shows the BTs on the selected freeway links and connecting arterial links, before and during the road resurfacing project periods, for evening peak and nighttime off-peak hours. The BTs on a few freeway links are greater than before the road resurfacing project period when compared with during the road resurfacing project period. The freeway

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**Table 2. T-test results: planning time or 95th percentile travel time.**

|                      | 7 AM – 9 AM | 10 AM – 12 PM | 5 PM – 7 PM | 10 PM – 12 AM |
|----------------------|-------------|---------------|-------------|---------------|
| **Freeway Links**    |             |               |             |               |
| Mean                 |             |               |             |               |
| During               | 1.06        | 0.93          | 0.97        | 0.91          |
| Before               | 1.42        | 0.95          | 0.98        | 0.96          |
| Diff. between means | −0.36       | −0.02         | −0.01       | −0.05         |
| t-Stat               | −4.23       | −2.46         | −0.28       | −3.59         |
| P(T ≤ t) one-tail    | <0.01       | <0.01         | <0.01       | <0.01         |
| t Critical one-tail  | 1.69        | 1.69          | 1.69        | 1.69          |
| **Connecting Arterial Links** |       |               |             |               |
| Mean                 |             |               |             |               |
| During               | 3.73        | 2.26          | 2.63        | 2.60          |
| Before               | 3.19        | 1.97          | 2.41        | 2.26          |
| Diff. between means | 0.54        | 0.29          | 0.22        | 0.34          |
| t-Stat               | 5.32        | 5.62          | 4.34        | 4.75          |
| P(T ≤ t) one-tail    | <0.01       | <0.01         | <0.01       | <0.01         |
| t Critical one-tail  | 1.67        | 1.67          | 1.67        | 1.67          |

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**Figure 2. Planning time before and during the road resurfacing project period.**
links on which they were higher varied by the study hours. On the other hand, the BTs during the road resurfacing project period are generally greater than before the road resurfacing project period, on almost all the connecting arterial links, in the case of both the study hours. The trends on connecting arterial links are similar for BT and PT based graphs.

The mean differences, t-stat, and t-critical values computed using the BTs are summarized in Table 3. The mean BTs are higher during the road resurfacing project period, during nighttime off-peak, when compared with before the road resurfacing project period. This could be possible since most of the construction activities occur during the nighttime off-peak, as an interruption to vehicular traffic would be minimum. In

Table 3. T-test results: buffer time (BT).

|                        | Freeway Links | Connecting Arterial Links |
|------------------------|---------------|---------------------------|
|                        | 7 AM – 9 AM   | 10 AM – 12 PM             | 5 PM – 7 PM                 | 10 PM – 12 AM                |
|                        | Weekday       | Weekend                   | Weekday                    | Weekend                     |
| Mean                   |               |                           |                            |                            |
| During                 | 0.39          | 0.27                      | 0.11                       | 0.08                       | 0.90              | 0.09              | 0.26              | 0.21              |
| Before                 | 0.40          | 1.12                      | 0.11                       | 0.10                       | 1.03              | 0.10              | 0.21              | 0.16              |
| Diff. between means    | −0.01         | −0.85                     | 0.00                       | −0.02                      | −0.13             | −0.01             | 0.05              | 0.05              |
| t-Stat                 | −0.17         | −7.71                     | 0.05                       | −1.18                      | −0.82             | −1.47             | 0.68              | 0.75              |
| P(T ≤ t) one-tail      | 0.43          | <0.01                     | 0.48                       | 0.12                       | 0.21              | 0.07              | 0.25              | 0.23              |
| t Critical one-tail    | 1.69          | 1.69                      | 1.69                       | 1.69                       | 1.69              | 1.69              | 1.69              | 1.69              |
|                        |               |                           |                            |                            |
| Mean                   | 1.47          | 0.60                      | 0.81                       | 0.81                       | 2.04              | 0.89              | 0.67              | 0.73              |
| Before                 | 1.18          | 0.42                      | 0.70                       | 0.60                       | 1.60              | 0.65              | 0.37              | 0.36              |
| Diff. between means    | 0.29          | 0.18                      | 0.11                       | 0.21                       | 0.44              | 0.24              | 0.30              | 0.37              |
| t-Stat                 | 4.59          | 4.67                      | 3.21                       | 3.92                       | 4.62              | 4.89              | 5.57              | 5.08              |
| P(T ≤ t) one-tail      | <0.01         | <0.01                     | <0.01                      | <0.01                      | <0.01             | <0.01             | <0.01             | <0.01             |
| t Critical one-tail    | 1.67          | 1.67                      | 1.67                       | 1.67                       | 1.67              | 1.67              | 1.67              | 1.67              |
addition, from the t-stat and t-critical results, there was a decrease in ATTs from before to during the road resurfacing project period. However, it is not significant on the freeway links, excluding the morning time peak (weekend day).

The mean BTs during the road resurfacing project period is significantly higher on the connecting arterial links. The BT on the connecting arterial links increased significantly from before to during the road resurfacing project period, at a 95% confidence level. The mean difference in BTs is high particularly during the evening peak hours (weekday) and nighttime off-peak hours (weekday and weekend day).

**Buffer time index (BTI)**

Figure 4 shows the BTIs on the selected freeway and connecting arterial links, before and during the road resurfacing project periods, for evening peak and nighttime off-peak hours. The trends on the freeway links are consistent during the peak hour. However, the differences between before and during road resurfacing project periods are very high on a few freeway links. Except on a couple of connecting arterial links, the trends in BTIs are consistent before and during the road resurfacing project periods.

The mean differences, t-stat, and t-critical values computed using the BTIs are summarized in Table 4. The results from the t-test analysis showed that the BTIs are nearly equal during and before the road resurfacing project period, on the freeway links, except during the morning peak hours on a weekday and weekend day. Therefore, there is no significant change in BTI before and during the road resurfacing project period on the freeway links.

![Figure 4](image_url)

**Figure 4.** Buffer time index (BTI) before and during the road resurfacing project period.
Table 4. T-test results: buffer time index (BTI).

|                      | 7 AM – 9 AM | 10 AM-12 PM | 5 PM – 7 PM | 10 PM – 12 AM |
|----------------------|-------------|-------------|-------------|--------------|
|                      | Weekday     | Weekend     | Weekday     | Weekend      | Weekday     | Weekend     |
| Freeway Links        |             |             |             |              |             |             |
| Mean                 | During      | 17.30       | 12.57       | 11.07        | 11.94       | 65.19       | 12.51       | 21.89       | 19.40       |
|                      | Before      | 31.51       | 10.79       | 13.04        | 12.38       | 66.23       | 12.38       | 21.59       | 15.54       |
| Diff. between means  | −14.21      | −1.78       | −1.97       | −0.44        | −1.04       | 0.13        | 0.30        | 3.86        |
| t-Stat               | −4.06       | 2.83        | −1.05       | −0.57        | −0.15       | 0.14        | 0.07        | 0.72        |
| P(T ≤ t) one-tail    | <0.01       | <0.01       | 0.15        | 0.29         | 0.44        | 0.44        | 0.47        | 0.24        |
| t Critical one-tail  | 1.69        | 1.69        | 1.69        | 1.69         | 1.69        | 1.69        | 1.69        | 1.69        |
| Connecting Arterial Links |       |             |             |              |             |             |
| Mean                 | During      | 96.16       | 64.24       | 73.56        | 74.32       | 111.70      | 80.80       | 62.23       | 64.11       |
|                      | Before      | 159.78      | 73.89       | 108.19       | 98.72       | 196.39      | 96.56       | 62.14       | 59.90       |
| Diff. between means  | −63.62      | −9.65       | −34.63      | −24.40       | −84.69      | −15.76      | 0.09        | 4.21        |
| t-Stat               | −4.80       | −1.43       | −5.73       | −3.22        | −5.47       | −3.20       | 0.02        | 1.00        |
| P(T ≤ t) one-tail    | <0.01       | 0.08        | <0.01       | <0.01        | <0.01       | <0.01       | 0.49        | 0.16        |
| t Critical one-tail  | 1.67        | 1.67        | 1.67        | 1.67         | 1.67        | 1.67        | 1.67        | 1.67        |

The mean differences in BTIs are significantly higher on the connecting arterial links. The BTI has increased significantly during the road resurfacing project period when compared with before the road resurfacing project period. The mean difference is higher particularly during the morning peak and evening peak hours on a weekday. The travel times increased significantly as the vehicular traffic shifted from the freeway links to the connecting arterial links during the road resurfacing project, and so did BTI. This seems to be during the peak hours. The BTI during the nighttime off-peak on a weekday did not show any increase or decrease when before and during the road resurfacing project period data are compared.

**Travel time index (TTI)**

Figure 5 shows the TTIs on the selected freeway links and connecting arterial links, before and during the road resurfacing project periods, for evening peak and nighttime off-peak hours. The TTIs are close to each other, in the case of both the study hours, except on a few links. However, the TTIs on the majority of connecting arterial links during the road resurfacing project period is greater than before the road resurfacing project period, in the case of both the study hours.

The mean differences, t-stat, and t-critical values computed using the TTIs are summarized in Table 5. Similar trends were observed on the freeway links and the connecting arterial links. The mean TTIs before the road resurfacing project period is higher when compared with during the road resurfacing project period on the freeway links. The TTIs during the morning peak and day-time off-peak hours on a weekday and weekend day decreased significantly from before to during the road resurfacing project period on the freeway links. A statistically significant change was not observed on the freeway links during the evening peak and nighttime off-peak hours.

The mean TTI values are higher during the road resurfacing project period, on connecting arterial link links, when compared with before the road resurfacing project period. A significant increase was observed on the connecting arterial links during all the considered study hours.
Analysis summary

Table 6 summarizes the travel time performance-based measures and significance (positive, negative, or no significance) by the time-of-the-day and day-of-the-week. The ‘P’ indicates an increase in the travel time performance-based measure during the road resurfacing project period when compared with before the road resurfacing project period. On the other hand, ‘N’ indicates a decrease in the travel time performance-based measure during the road resurfacing project period when compared with before the road resurfacing project period. From Table 6, the ATT and PT can consistently explain the effect of the road resurfacing project, on the freeway links, during the
Table 6. Significance of travel time performance-based measures.

|                      | Freeway Links | Connecting Arterial Links |
|----------------------|---------------|----------------------------|
|                      | 7 AM – 9 AM   | 10 AM – 12 PM              | 5 PM – 7 PM | 10 PM – 12 AM |
|                      | Weekday | Weekend | Weekday | Weekend | Weekday | Weekend | Weekday | Weekend |
| ATT                  | N      | N      | N      | N      | N      | N      | N      | N      |
| PT                   | N      | N      | N      | N      | N      | N      | N      | N      |
| BT                   | N      |         |         |         |         |         |         |         |
| BTT                  | N      |         |         |         |         |         |         |         |
| TTI                  | N      | P      | N      | N      | N      | N      | N      | N      |

P = Positive, N = Negative; Blank cell indicates no significant relation.

construction project period when compared with before the construction project period. No significant effect or consistent trend was observed when BT, BTT, and TTI are considered for assessment. Except in the case of BTT, a significant positive effect on the connecting arterial links performance was observed during the road resurfacing project period when compared with before the road resurfacing project. The effect can be consistently observed when PT and TTI are used for assessment.

Conclusions

The travel time performance-based measures during the road resurfacing project period decreased significantly on the freeway links and increased significantly on the connecting arterial links. To avoid unnecessary delays during the construction, vehicular traffic could have altered from the freeway links to the connecting arterial links. The relatively lower speed limit, reduced capacity, and increased traffic volume on the connecting arterial links resulted in significantly higher travel times during the road resurfacing project period when compared to the freeway links.

The performance-based measures and their significance varied by the time-of-the-day and day-of-the-week on the freeway and connecting arterial links. The ATT, PT, and TTT can consistently explain the effect of a road construction project on transportation system performance, when compared to PTI and BTTI. Therefore, the ATT, PT, and TTI are recommended for evaluating and assessing the effect of a road construction project on the project corridor and connecting street links.

Predominantly, the performance on freeway links is expected to be lower during the construction period, since the actual number of lanes, lane widths, shoulder widths, and speed limits are reduced. However, from the paired t-test analysis, it was observed that the average travel time and travel time performance-based measures have improved on the freeway links but have worsened on the connecting arterial links. Practitioners are, therefore, recommended to forecast the effects on freeway links and connecting arterial links due to construction project activities. It will lead to a better understanding of the effect of road construction projects on mobility and congestion to proactively plan improvements and implement temporary traffic control practices within their vicinity.
The focus of this research was on travel time performance-based measures to assess the effect of a road construction project on the project corridor and connecting street links by time-of-the-day and day-of-the-week. The methodology and findings from this research can be transferred to other road construction project sites in the study area or road construction project sites in cities similar in population, land use, and travel characteristics.

Travel time data for several links on a freeway with a road construction project and selected connecting arterial links within its vicinity was used in this research. Considering data for a spatially distributed sample of road construction projects from multiple cities/towns would help extend the scope of this research, identify suitable performance measures for evaluation, and formulate regional-, state-, or national-level recommendations and temporary traffic control policies by the type of road construction project.

Several factors like the type of road construction project, construction times, temporary traffic control practices, number of lanes closed, posted speed limit in the construction zones, traffic volumes, area type, and geometric features influence travel times during the construction project period. Traffic volume data was not available by time-of-the-day and day-of-the-week for the study links. Examining the effects of these factors on travel times of the project corridor and connecting street links considering data for multiple road construction projects merits further research.

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**Disclaimer**

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ORCID

Srinivas S. Pulugurtha http://orcid.org/0000-0001-7392-7227

References

Abdel-Aty, M. A., Kitamura, R., & Jovanis, P. P. (1995). Investigating effect of travel time variability on route choice using repeated-measurement stated preference data. Transportation Research Record: A Journal of the Transportation Research Board, 1493(1), 39–45. http://onlinepubs.trb.org/Onlinepubs/trr/1995/1493/1493-005.pdf

Abdelmohsen, A. Z., & El-Rayes, K. (2016). Optimal trade-offs between construction cost and traffic delay for highway work zones. Journal of Construction Engineering and Management, 142(7), 05016004. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001132

Alemaazkoor, N. M., Burris, W., & Danda, S. R. (2015). Using empirical data to find the best measure of travel time reliability. Transportation Research Record: A Journal of the Transportation Research Board, 2530(1), 93–100. https://doi.org/10.3141/2530-11

Brennan, T. M., Jr., Venigalla, M., Hyde, A., & LaRegina, A. (2018). Performance measures for characterizing regional congestion using aggregated multi-year probe vehicle data. Transportation Research Record: A Journal of the Transportation Research Board, 2672(42), 170–179. https://doi.org/10.1177/036119818797190

Chen, A., Ji, Z., & Recker, W. (2002). Travel Time Reliability with Risk-sensitive Travelers. Transportation Research Record: A Journal of the Transportation Research Board, 1783(1), 27–33. https://doi.org/10.3141/1783-04

Chen, Z., Cathy Liu, X., Farnsworth, G., & Burs, K. (2019). Validating the adaptability of travel time reliability measurements using probe data. Transportation Research Record: A Journal of the Transportation Research Board, 2673(6), 57–67. https://doi.org/10.1177/0361198119843097

Chien, S. I. J., Goulas, D. G., Yahalom, S., & Chowdhury, S. M. (2002). Simulation-based estimates of delays at freeway work zones. Journal of Advanced Transportation, 36(2), 131–156. https://doi.org/10.1020/atr.5670360202

Du, Z.-P., & Nicholson, A. (1997). Degradable transportation systems: sensitivity and reliability analysis. Transportation Research Part B, 31(3), 225–237. https://doi.org/10.1016/S0191-2615(96)00023-9

Federal Highway Administration. (2006). Travel time reliability: making it there on time, all the time. https://ops.fhwa.dot.gov/publications/tt_reliability/TTTR_Report.htm#:~:text=The%20travel%20time%20index%20represents,travel%20time%20that%20is%20necessary .

Federal Highway Administration. (2017). Work zone performance measurement using probe data. https://ops.fhwa.dot.gov/wz/resources/publications/fhwahop13043/ch2.htm#:~:text=Probe%20data%20is%20defined%20as,a%20specific%20place%20and%20time .

Garcia, C., Huebschman, R., Abraham, D. M., & Bullock, D. M. (2006). Using GPS to measure the impact of construction activities on rural interstates. Journal of Construction Engineering and Management, 132(5), 508–515. https://doi.org/10.1061/(ASCE)1090-0266(2006)132:5(508)

Gore, N., Pulugurtha, S. S., Arkatkar, S., & Joshi, G. (2021). Congestion index and reliability-based freeway level of service. Journal of Transportation Engineering, Part A: Systems, 147(6), 04021027. https://doi.org/10.1061/JTEPBS.0000531

Haitham, A. D., & Emam, B. (2006). New methodology for estimating reliability in transportation networks with degraded link capacities. Journal of Intelligent Transportation Systems, 10(3), 117–129. https://doi.org/10.1080/15472450600793586

Imran, M. S., & Pulugurtha, S. S. (2014). Assessment of the effect of freeway posted speed limit reduction on vehicular delay at a work zone. In The 93rd annual meeting of the transportation research board of the national academies.

Jiang, Y. (2002). Dynamic prediction of traffic flow and congestion at freeway construction zones. Journal of Construction Education, 7(1), 45–57. https://doi.org/10.1.1.630.9425&rep=rep1&type=pdf
Kim, T., Lovell, D., & Paracha, J. (2001). A new methodology to estimate capacity for freeway work zones. In The 80th annual meeting of the transportation research board of the national academies.

Kodupuganti, S., & Pulugurtha, S. S. (2019). Link-level travel time measure-based level of service thresholds by the posted speed limit. Transportation Research Interdisciplinary Perspectives, 3 (2019), 100068. https://doi.org/10.1016/j.trip.2019.100068

Kukkapalli, V. M., & Pulugurtha, S. S. (2018). Effect of road construction projects on travel time reliability. In The proceedings of international conference on transportation & development (ICTD).

Kukkapalli, V. M., & Pulugurtha, S. S. (2019). Modeling the effect of a road construction project on transportation system performance. Published by the Mineta Transportation Institute Publications. https://transweb.sjsu.edu/sites/default/files/1702B-Pulugurtha-Effect-Road-Construction-Travel-Time.pdf

Kukkapalli, V. M., & Pulugurtha, S. S. (2021). Modeling the effect of a freeway road construction project on link-level travel times. Journal of Traffic and Transportation Engineering (English Edition), 8(2), 267–281. https://doi.org/10.1016/j.jtte.2019.11.002

Kwon, J., Barkley, T., Hranac, R., Petty, K., & Compin, N. (2011). Decomposition of travel time reliability into various sources: Incidents, weather, work zones, special events, and base capacity. Transportation Research Record: Journal of the Transportation Research Board, 2229(1), 28–33. https://doi.org/10.3141/2229-04

Lomax, T., Turner, T., & Margiotta, R. (2004). Monitoring urban roadways in 2002: Using archived operations data for reliability and mobility measurement. Published by the Texas Transportation Institute, Texas A&M University.

Lu, C., & Dong, J. (2018). Estimating freeway travel time and its reliability using radar sensor data. Transportmetrica B: Transport Dynamics, 6(2), 97–114. https://doi.org/10.1080/21680566.2017.1325785

Lyman, K., & Bertini, R. (2008). Using travel time reliability measures to improve regional transportation planning and operations. Transportation Research Record: Journal of the Transportation Research Board, 2046(1), 1–10. https://doi.org/10.3141/2046-01

Marchouk, M., Mannering, F., & Bullock, D. M. (2011). Analysis of freeway travel time variability using bluetooth detection. Journal of Transportation Engineering, 137(10), 697–704. https://doi.org/10.1061/(ASCE)TE.1943-5436.0000253

Martinelli, D. R., & Xu, D. (1996). Delay estimation and optimal length for four-lane divided freeway work zones. Journal of Transportation Engineering, 122(2), 114–122. https://doi.org/10.1061/(ASCE)0733-947X(1996)122:2(114)

McLeod, D. S., Elefteriadou, L., & Jin, L. (2012). Travel time reliability as a performance measure: Applying Florida’s predictive model to an entire freeway system. ITE Journal, 82(11), 43–47. https://www.fdot.gov/docs/default-source/planning/fmo/mobileity/itepaper14.pdf

Moylan, E., & Rashidi, T. (2017). Latent-segmentation, hazard-based models of travel time. IEEE Transactions on Intelligent Transportation Systems, 18(8), 2174–2180. https://doi.org/10.1109/TITS.2016.2636321

Pu, W. (2011). Analytic relationships between travel time reliability measures. Transportation Research Record: A Journal of the Transportation Research Board, 2254(1), 122–130. https://doi.org/10.3141/2254-13

Pulugurtha, S. S., Duddu, V. R., Puvvala, R., Thokala, V. R., & Imran, M. S. (2015). Commercial Remote Sensing & Spatial Information (CRS & SI) Technologies Program for Reliable Transportation Systems Planning: Volume 2 - Comparative Evaluation of Travel Time Related Performance Measures. Report No. RITARS-12-H-UNCC-2, Prepared for The United States Department of Transportation, Office of the Assistant Secretary for Research and Technology.

Pulugurtha, S. S., Duddu, V. R., & Thokala, V. R. (2016, January 10–14). Travel-time-based performance measures: Examining interrelationships and recommendations for analysis. In Transportation research board 95th annual meeting, compendium of papers.
Pulugurtha, S. S., & Imran, M. S. (2017). Modeling basic freeway section level-of-service based on travel time and reliability. *Case Studies on Transport Policy, 8*(1), 127–134. https://doi.org/10.1016/j.cstp.2017.08.002

Pulugurtha, S. S., & Koilada, K. (2020). Exploring correlations between travel time based measures by year, day-of-the-week, time-of-the-day, week-of-the-year and the posted speed limit. *Urban, Planning and Transport Research.* https://doi.org/10.1080/21650020.2020.1845230

Ramezani, H., & Benekohal, R. (2011). Analysis of queue formation and dissipation in work zones. *Procedia - Social and Behavioral Sciences, 16,* 450–459. https://doi.org/10.1016/j.sbspro.2011.04.466

Singh, V., Gore, N., Chepuri, A., Arkatkar, S., Joshi, G., & Pulugurtha, S. S. (2019). Examining travel time variability and reliability on an urban arterial road using wi-fi detections- A case study. *Journal of Eastern Asia Society for Transportation Studies, 13*(2019), 2390–2411. https://doi.org/10.11175/easts.13.2390

Sisiopiku, V. P., & Islam, M. D. S. (2012). A freeway travel time reliability study. *International Journal of Engineering Research and Development, 3*(10), 83–101. https://www.academia.edu/28832446/A_Freeway_Travel_Time_REliability_Study

Van Lint, J. W., & Van Zuylen, H. J. (2005). Monitoring and predicting freeway travel time reliability: Using width and skew of day-to-day travel time distribution. *Transportation Research Record: A Journal of the Transportation Research Board, 1917*(1), 54–62. https://doi.org/10.1177/0361198105191700107

Wakabayashi, H., & Matsumoto, Y. (2012). Comparative study on travel time reliability indexes for highway users and operators. *Journal of Advanced Transportation, 46*(4), 318–339. https://doi.org/10.1002/atr.1194

Yang, S., & Wu, Y. J. (2016). Mixture models for fitting freeway travel time distributions and measuring travel time reliability. *Transportation Research Record: A Journal of the Transportation Research Board, 2594*(1), 95–106. https://doi.org/10.3141/2594-13

Yesantarao, V. R. S. S., & Pulugurtha, S. S. (2017). Evaluating the influence of a freeway capacity improvement project on travel time based performance measures within its vicinity. In *The 4th Conference of Transportation Research Group of India (CTRG).*

Zheng, F., Liu, X., Van Zuylen, H., Li, J., & Lu, C. (2017). Travel time reliability for urban networks: Modelling and empirics. *Journal of Advanced Transportation, 2017,* 9147356. https://doi.org/10.1155/2017/9147356

Zheng, N., Hegyi, A., Hoogendoorn, S., Van Zuylen, H., & Peters, D. (2011). A comparison of freeway work zone capacity prediction models. *Procedia - Social and Behavioral Sciences, 16,* 419–429. https://doi.org/10.1016/j.sbspro.2011.04.463

Zhong, X., Zou, Y., Dong, Z., Yuan, S., & Ijaz, M. (2020). Finite mixture survival model for examining the variability of urban arterial travel time for buses, passenger cars and taxis. *IET Intelligent Transport Systems, 14*(12), 1524–1533. https://doi.org/10.1049/iet-its.2019.0504

Zou, Y., Zhu, T., Xie, Y., Li, L., & Chen, Y. (2020). Examining the impact of adverse weather on travel time reliability of urban corridors in Shanghai. *Journal of Advanced Transportation, 8860277.* https://doi.org/10.1155/2020/8860277