ABSTRACT: This research explores a data-driven methodological framework to quantify the effect of rainfall and visibility on travel time reliability (TTR) by considering selected road segments in North Carolina. The framework includes capturing, processing, and integrating weather-related information and travel time data for the selected road segments. Various TTR indices were computed for the selected road segments under different rainfall and visibility ranges by day of the week (DOW) and time of the day (TOD). The TTR indices were computed for one week before and after (same DOW and TOD) under the normal weather condition and compared with those obtained under different intensities of rainfall and visibility. The variability in travel time patterns due to other events is expected to be marginal when considering the same DOW and TOD for comparison purposes. The results indicate that poor visibility with different rainfall intensities has the maximum adverse effect on the TTR. The outcomes from the data-driven methodological framework help the transportation planners in developing weather-responsive traffic management strategies and assessing their effectiveness using TTR indices.

SIGNIFICANCE STATEMENT: Travel time reliability (TTR) generally refers to the level of consistency or dependability in transportation service. It is considered as a measure of road operational performance. Ensuring higher levels of reliability is critical for efficient transportation system management along with mobility and accessibility needs. However, factors such as weather condition have a negative effect on the TTR. A data-driven methodological framework is proposed by integrating weather information and travel time data to quantify the effect of common weather conditions like rainfall and visibility on the TTR. The results indicated that heavy rain and poor visibility have an adverse effect on the TTR. These results are useful for agencies to better manage the traffic under different weather conditions.

KEYWORDS: North America; Rainfall; Transportation meteorology; Visibility

1. Introduction

Rainfall and poor visibility disrupt the operational performance of roads in different ways. The reduction in travel demand and road capacity (Agarwal et al. 2005; Maze et al. 2006; Datla and Sharma 2008), deterioration in safety performance, and the worsening of travel speed or travel time (Agarwal et al. 2005; Koetse and Rietveld 2007) are the significant effects of such weather conditions on the operational performance of roads. Per the National Highway Traffic Safety Administration (NHTSA), 1 235 000 weather-related crashes have occurred in the United States from 2007 to 2016 (U.S. Department of Transportation 2020). Notably, most weather-related crashes happen during rainfall and other wet pavement conditions (Ashley et al. 2015; Black et al. 2017; Tamerius et al. 2016; Tobin et al. 2019). According to Tobin et al. (2020), 8.6% of the vehicle-related fatalities from 2013 to 2017 in the United States occurred during precipitation conditions. Moreover, the crash risk associated with precipitation varies spatially and temporally (Tamerius et al. 2016). Interstates and major highways have higher crash risk than local roads under precipitation conditions (Tamerius et al. 2016).

Per the Highway Capacity Manual (HCM) 2000, the rainfall intensity can adversely affect the average speed on a freeway corridor (Transportation Research Board 2000). Poor visibility and wet pavement surface result in a reduction of travel speed and road capacity. These effects prompted transportation researchers, system managers, and planners to think over the incorporation of weather-related information into the traffic operations to improve the safety and reliability of a transportation system. Ensuring higher levels of reliability and safety are critical for efficient transportation system management along with mobility and accessibility needs.

Current advancements in technologies not only help to assess traffic conditions but also help with communicating such information through advisory and control actions. The weather-related control measures or dynamic signal indicators can be deployed to reduce the effect of rainfall and visibility conditions on road travel time reliability (TTR). The integration of weather-related information and travel time data and analysis of the historical pattern of travel times under varying ranges of weather conditions will improve the efficiency of control strategies to a significant extent. The advancements in probe vehicle technologies made it possible to collect real-time travel time data.
This research is mainly aimed at quantifying the effect of rainfall and visibility on the TTR of freeways and other arterial roads. The objectives of this research are

1) to quantify the effect of rainfall and associated visibility ranges on the TTR of the freeway and arterial roads, and
2) to analyze the probability of a segment being unreliable under different intensities of rainfall and visibility conditions.

Travel time data and weather-related information for 50 selected road segments in North Carolina were used for the analysis. The rainfall intensities were classified into light rain (trace–2.6 mm h⁻¹), moderate rain (2.6–7.6 mm h⁻¹), and heavy rain (over 7.6 mm h⁻¹) as outlined in Table 8-1 of the Federal Meteorological Handbook, No. 1 (Office of the Federal Coordinator for Meteorological Services and Supporting Research 2019). Similarly, the visibility conditions were also classified into good visibility (over 10,000 m), moderate visibility (4000–10,000 m), and poor visibility (less than 4000 m) based on international standards (Cho and Kim 2005). The results help transportation planners in understanding the traffic conditions and predicting the TTR under varying levels of rainfall and visibility on urban freeway and arterial roads.

2. Literature review

The main challenge faced by past researchers when evaluating the effect of rainfall and visibility on traffic conditions is the integration of the weather-related information and the traffic or travel time-related data (Hranac et al. 2007; Sabir et al. 2008). Ibrahim and Hall (1994) analyzed the effect of rainfall and associated intensity on fundamental traffic flow relationships. They concluded the minimal effect of light rain and the maximum effect of heavy rain on free-flow speed and road capacity. Cools et al. (2010) evaluated the effect of weather conditions on traffic intensities in Belgium. The results from their research indicated an increase in traffic volume during high temperature conditions and reduction in traffic volume during snowfall, rainfall, and wind speed conditions. Call (2011) pointed out the reduction in traffic volume during snowfall conditions. Similarly, Kwon et al. (2013) illustrated the effect of snow intensity and visibility on free-flow speed and capacity.

The HCM 2000 states that the light rain condition can cause a reduction of 1.9% in free-flow speed. In heavy rain conditions, a 4.8%–6.4% reduction in free-flow speed is also reported in HCM 2000. According to Smith et al. (2004), rainfall could cause a 5%–6.55% reduction in the operating speed regardless of the intensity of rainfall. Maze et al. (2006) found that heavy rains caused a reduction in speed by 6% while moderate rains caused an average reduction in speed by 4% on urban freeways relative to clear weather conditions. Wang et al. (2006) stated a reduction in average speed by 6.3 km h⁻¹ during heavy rains relative to the case of no rain. They also pointed out that the effect of rainfall varies with road characteristics, such as the route class and the number of lanes. Similarly, Unrau and Andrey (2006) studied the effect of rainfall on traffic speed by considering the urban expressway from Toronto, Canada, as the study area. Their results indicate a 10% reduction in speed during the uncongested daytime condition and light rain.

Stern et al. (2003) studied the effect of weather events on the average travel time (ATT) by considering selected road segments in Washington, DC. The results from their research indicated a 14% increase in the ATT during rainfall conditions. Camacho et al. (2010) studied the effect of rainfall on free-flow speed by considering selected freeway segments from northwestern Spain. Their study results indicated a 5.5 and 7 km h⁻¹ reduction in free-flow speed under the light rain and heavy rain conditions, respectively. Kang et al. (2008) studied the effect of poor visibility on car-following performance. They observed that the distance headway decreased in the densest fog conditions while the root-mean-square velocity error increased with an increase in fog density (Kang et al. 2008).

Nowadays, travel time reliability is considered as a critical performance measure to assess the condition of the freeway and arterial road segments. It is a measure of service quality (Chen et al. 2003). It can be used to quantify the performance of a system from, both, the planners and the user’s perspective (Wakabayashi and Matsumoto 2012). Some of the recent research initiatives illustrated the use of TTR-based measures to quantify the effect of weather conditions on road performance (Chien and Kolluri 2012; Zhao and Chien 2012; Yazici et al. 2013). Chien and Kolluri (2012) assessed the TTR under adverse weather conditions. TTR indices such as planning time (PT), buffer index (BI), and planning time index (PTI) were used for the assessment in their research. Zhao and Chien (2012) used BI to evaluate the effect of adverse weather on the TTR. The BI represents the extra time that travelers must add to their average travel time to avoid late arrival (Zhao and Chien 2012). Yazici et al. (2013) studied the effect of different weather types on travel time variability and concluded that the effects vary with the day of the week (DOW) and time of the day (TOD). Also, a higher effect was observed in less congested periods (Chien and Kolluri 2012). Zhang and Chen (2019) evaluated the effect of rain and snow events on both congestion and travel time reliability. The effect of weather on travel time reliability is more severe than on average delay (Zhang and Chen 2019). The recent version of HCM incorporates measures like PT, travel time index (TTI) and PTI for the freeway and urban streets reliability assessment (Kittelson and Vandehy 2013). PTI indicates the total time a traveler should ensure for the on-time arrival. Wolniak and Mahapatra (2014) stated that PTI could accommodate the effect of events and adverse weather on the TTR. PT, PTI, and TTI can be computed using Eqs. (1), (2), and (3):

\[
PT = 95\text{-percentile travel time}, \quad (1)
\]

\[
PTI = \frac{PT}{\text{Free-flow travel time}}, \quad (2)
\]

Unauthenticated | Downloaded 08/20/24 06:08 AM UTC
\[
\text{TTR} = \frac{\text{Average travel time} \ (\text{ATT})}{\text{Free-flow travel time}} \cdot \text{(3)}
\]

Van Der Loop et al. (2014) identified the main causes of the unreliability of travel times for Netherlands urban roads. They considered factors like traffic, weather condition, road work, and crashes in the assessment process. Sekhar and Asakura (2014) modeled travel time variation by considering supply-side and demand-side of transportation system. They observed that rainfall has a significant influence on travel time variations, and the magnitude of influence is high on weekdays.

Many previous studies quantified the effect of rainfall and visibility on the operational performance of a road using traffic speed or from congestion perspective. A limited number of road segments were used for the analysis in the previous studies. The road characteristics like functional class and the speed limit were neglected in many of the previous studies. Temporal effects of rainfall and different visibility ranges need to be carefully accounted for in the TTR quantification process. Many researchers in the past illustrated varying travel time patterns for a segment by DOW and TOD. This research accounts for the temporal element of the travel times and weather conditions by considering travel times for a relatively large number of road segments for one week before and after (same DOW and TOD) of rainfall and visibility conditions. Also, this research proposes a methodological framework to integrate the travel time data and weather data to compare TTR indices under the normal weather condition with those obtained under different intensities of rainfall and visibility (same DOW and TOD). Such an integrated data-mining framework to assess the effect of weather condition on reliability (TTR) was not explored in the past.

Most of the previous studies considered the average values to examine the effect of rainfall and visibility on a road. It may not give a clear picture of what is happening on a road segment (in general, a link). TTR indices such as PTI and TTI can better capture the effect because reliability thresholds for these measures have already been proposed in the past (Wolniak and Mahapatra 2014). Therefore, comparing PTI and TTI thresholds under varying weather conditions can be considered to be a significant research development. This research also differs from many other past studies on the consideration of different combinations of rainfall intensity and visibility levels to capture the effect of weather on the operational performance of a road.

3. Methodology

The weather and travel time data used in this research were for 2017 and 2018. The methodological framework adopted for this research includes the following steps:

1) selection of weather stations in North Carolina,
2) identification of road segments,
3) data processing,
4) computing TTR indices,
5) comparing the TTR indices under different intensities of rainfall and visibility, and
6) distribution-based quantification of the weather effect on the TTR.

a. Selection of weather stations in North Carolina

In this research, the meteorological data obtained from the Integrated Surface Database (ISD) were used for analysis. The ISD from the National Oceanic and Atmospheric Administration/National Centers for Environmental Information (NOAA/NCEI) contains hourly surface observations for over 20000 locations across the world (Smith et al. 2011). The database includes various weather indicators like visibility, rainfall, dewpoint temperature, and wind speed. In this research, 10 weather stations in North Carolina were considered in the road segment identification process.

b. Identification of road segments

It is assumed that rainfall and visibility data obtained from a weather station would be the same for the segments within a 1.61-km vicinity of the weather station. ArcGIS software was used to identify road segments within a 1.61-km buffer of each selected weather station (Fig. 1). Geo-referencing of the road segments was performed using four coordinates collected from the Regional Integrated Transportation Information System (RITIS) website. A segment was selected if at least 50% of the total length of the segment is inside the 1.61-km buffer around the weather station.

The road network data were obtained in a geospatial format (shapefile) from the North Carolina Department of Transportation (NCDOT). The spatial join feature in the ArcGIS was employed to join the road characteristics into the segment level data. The length of some road segments is less than 0.080 km. Considering these short segments may result in some bias. Therefore, segments with length less than 0.080 km were not considered for the analysis. The final database includes 46 separately identified road segments within the vicinity of the 10 weather stations in North Carolina. The study area is shown in Fig. 1.

c. Data processing

Initially, data processing was carried out separately using the weather-related data and the travel time data for 2017 and 2018. The data one week before and after were used to minimize the effect of other factors (seasonal variations, lighting conditions, changes in traffic patterns due to road construction activities or other events). Also, the data did not include weekends and federal holidays to minimize the effect of special events and holiday travel patterns. Furthermore, the data affected by road crashes identified from the Highway Safety Information System (HSIS) database were removed and excluded from the analysis.

1) Weather data

The weather-related data for all of 2017 and 2018 were obtained from the ISD database. Rainfall and visibility observations were obtained at an hourly time stamp. The weather-
related data were processed based on the time of observation and duration for which the liquid precipitation was measured. The data were processed using Microsoft SQL Server to remove the missing values and values that did not pass the quality checks mentioned in the ISD data documentation (NCEI 2018). For example, the code that denotes the quality status of precipitation data as “erroneous” or “suspect” was removed. In addition, rainfall with snowfall were also excluded from the database. The average value of visibility was estimated using all the reported visibility values within that hour. The processed database contains the weather station identifier (ID), rainfall intensity, visibility, date, and TOD. Further, identified segments with road characteristics were added into the database by relating the weather station ID.

The weather data processing methods/algorithms developed by Duddu et al. (2017), Pulugurtha et al. (2019), and Duddu et al. (2020) were modified and used to accomplish this task.

2) TRAVEL TIME DATA

The raw travel time data were collected from the RITIS website with support from NCDOT, at five-minute intervals. The database contains data corresponding to the date, TOD, average speed, travel time, and reference speed. Data corresponding to each segment were coded with a nine-digit identification code, referred to as the Traffic Message Channel (TMC) code. As rainfall and visibility observations were obtained at an hourly time stamp, travel time data at 5-min intervals were aggregated at 1-h intervals. For example, a weather observation at 1100 LT is paired with TTR indices based on travel time observations from 1001 to 1100 LT.

3) INTEGRATION OF TRAVEL TIME AND WEATHER DATA

The overall process followed in the weather, travel time, and road characteristics data integration is summarized in Fig. 2. The weather database was joined with the travel time database using the related fields such as road segment ID, date, and TOD. The fields in the new database are segment ID, road characteristics, rainfall, visibility, date, TOD, and travel time. Further, travel time data corresponding to one week before (same DOW and TOD) and travel time corresponding to one week after (same DOW and TOD) were added into the database. If normal weather condition was not observed one week before and after, data for two or three weeks before and after were considered for the analysis. Plausibly, comparing travel time data for the same TOD and DOW during normal weather conditions will minimize the variability in travel patterns. Also, it will reduce the effect of other factors beyond the scope of this research. Overall, a total of 28,247 rainfall–visibility conditions were segregated and considered for the analysis. The categorized weather conditions and selected variables for the analysis are summarized in Table 1.

d. Computing TTR indices

The travel time variability patterns may help in determining the peak and off-peak hours of the day. The ATT, 95th-percentile travel or PT, PTI, and TTI were computed for each road segment, for 1-h intervals, by aggregating data by DOW and TOD. The historical free-flow travel time (off-peak free-flow travel time) was used to compute the PTI and TTI to capture the effect of rainfall and visibility conditions on the TTR of the road segment.

The TTI is considered to be an indicator of congestion. It indicates how much longer the road segment travel times are when there is congestion as compared with the normal traffic. The PTI depicts the total travel time required for a traveler to

![Fig. 1. Study area.](image-url)
ensure the on-time arrival at their destination. While looking into the TTR, PTI gives useful indications. For example, a PTI value of 1.5 indicates that total trip time under free-flow conditions should be increased by 50% to ensure the on-time arrival during congested conditions.

e. Comparing the TTR indices under different intensities of rainfall and visibility

The statistical significance of the difference in data from the week before and week after was tested using a paired t test. The t test results indicated that there is no significant variation in the TTR computed for the week before and week after for all the selected cases. The estimated TTR indices during rainfall and visibility conditions were also compared with TTR during normal weather conditions. The statistical significance of the change in TTR was examined using the one-tailed paired t test at a 95% confidence level.

f. Distribution-based quantification of the weather effect on the TTR

Martchouk and Mannering (2009) used the survival function to assess the probability of a trip lasting any specified length of time. It was employed to evaluate the probability of the road segment to be unreliable under any specified value of a selected reliability measure in this research. Empirical survival function plots based on real-world travel time data-based reliability measures and theoretical survival function plots using various distribution fits like lognormal, Weibull, Burr, gamma, and three-parameter lognormal were compared. A Kolmogorov–Smirnov (KS) test was conducted
to identify best theoretical distribution among the selected distributions.

The survival function $S(t)$, which indicates the probability that the TTR is more than a specified value, is estimated using

$$S(t) = \Pr(\text{TTR} > t) = 1 - F(t),$$  \hspace{1cm} (4)$$

where $t$ is the TTR threshold, TTR is the travel time reliability, and $F(t)$ is the cumulative distribution function.

The probability of a segment being unreliable under normal weather condition and under different rainfall and visibility conditions were tested using the survival analysis. In other words, the likelihood of unreliability in normal and adverse weather conditions is evaluated.

4. Results

The results from the analysis are discussed in this section.

a. Effect of rainfall and visibility on urban freeway road segments

Table 2 depicts the percentage of differences in TTR indices for the freeway road segments (functional class 1 and 2) for selected categories of rainfall and visibility relative to the normal weather condition. Eighteen freeway segments were considered in the analysis. The speed limit for the selected segments is 96 or 105 km h$^{-1}$. Hence, all segments are considered together for the analysis.

From Table 2, the poor visibility along with different rainfall intensity have the maximum adverse effect on the TTR. Heavy rain and poor visibility caused a 5.50% increase in the ATT and a 12.24% increase in PTI on urban freeway road segments. Similarly, the moderate rain with poor visibility and light rain with poor visibility also resulted in a 7.55%–13.08% increase in various TTR indices. On the contrary, the effect of heavy rain with moderate and good visibility on the TTR was found to be minimal. Also, most of the cases with heavy rain resulted in poor visibility.

Previous studies have reported different outcomes related to rainfall and visibility effects accounting for the network, traffic, and socioeconomic characteristics of the study area. They showed that the effect of light rain on travel time or operating speed is minimal (Maze et al. 2006; Datla and Sharma 2008; Smith et al. 2004; Tsapakis et al. 2013). Per the findings from this research, light rain can cause a 1.25%–3.06% increase in the TTR without any visibility restraint. However, the effect will be higher under adverse visibility (moderate or poor) conditions.

To check the statistical significance in the change, the paired t test was performed for different weather conditions. A statistically significant change in reliability measures was

### Table 2. TTR indices for freeways under different weather conditions.

<table>
<thead>
<tr>
<th>Weather condition</th>
<th>Intensity</th>
<th>ATT</th>
<th>PT</th>
<th>PTI</th>
<th>TTI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rain</td>
<td>Light</td>
<td>+1.50%</td>
<td>+1.25%</td>
<td>+2.22%</td>
<td>+3.06%</td>
</tr>
<tr>
<td></td>
<td>Moderate</td>
<td>+2.50%</td>
<td>+1.25%</td>
<td>+0.06%</td>
<td>+0.90%</td>
</tr>
<tr>
<td></td>
<td>Heavy</td>
<td>+2.08%</td>
<td>+1.96%</td>
<td>+4.90%</td>
<td>+4.91%</td>
</tr>
<tr>
<td>Rain and visibility</td>
<td>Light rain–moderate visibility</td>
<td>+6.75%</td>
<td>+7.92%</td>
<td>+11.11%</td>
<td>+8.16%</td>
</tr>
<tr>
<td></td>
<td>Light rain–poor visibility</td>
<td>+9.32%</td>
<td>+8.78%</td>
<td>+8.70%</td>
<td>+8.59%</td>
</tr>
<tr>
<td></td>
<td>Moderate rain–poor visibility</td>
<td>-0.27%</td>
<td>-4.30%</td>
<td>-4.22%</td>
<td>+0.96%</td>
</tr>
<tr>
<td></td>
<td>Moderate rain–poor visibility</td>
<td>+7.66%</td>
<td>+13.08%</td>
<td>+8.60%</td>
<td>+7.55%</td>
</tr>
<tr>
<td></td>
<td>Heavy rain–moderate visibility</td>
<td>+1.29%</td>
<td>+2.25%</td>
<td>+0.43%</td>
<td>+0.40%</td>
</tr>
<tr>
<td></td>
<td>Heavy rain–poor visibility</td>
<td>+5.50%</td>
<td>+8.54%</td>
<td>+12.24%</td>
<td>+8.69%</td>
</tr>
</tbody>
</table>
observed in the case of light rain–poor visibility, moderate rain–poor visibility, and heavy rain–poor visibility conditions.

Most of the previous studies evaluated the effect of rainfall and visibility in terms of an average effect, either in terms of a decrease in the average operational speed or an increase in the ATT. The effect will be sporadic based on the condition of traffic. Also, the average based measures may not give a complete picture of the effect as it averages out the overall effect of the weather condition on the TTR. This issue could be addressed by using a distribution-based TTR measure. The HCM suggests PTI and TTI as measures of the TTR. From Table 2, the percentage increase in PTI is more than ATT and TTI in most of the selected weather conditions. When performing a system-level analysis, normalizing the TTR measure is very important to make general conclusions about the effect of weather events on the TTR. Hence, PTI is found to be a better TTR index as it normalizes the 95th-percentile travel time for all the road segments in terms of free-flow travel time.

A scatterplot matrix was created to understand the possible correlation between PTI and other reliability indicators as shown in Fig. 3. Based on the scatterplot, there exists a strong relationship between PTI and TTI. Therefore, further analysis was carried out only using PTI.

First, PTI-based analysis was carried out to find the percentage of reliable conditions and unreliable conditions during different rainfall intensities and associated visibility ranges. The estimated PTI values were compared for rain/visibility and normal weather conditions. A PTI value less than 1.5 is considered as reliable, a PTI value between 1.5 and 2.5 is considered as moderately–highly unreliable, and a PTI value greater than 2.5 is extremely unreliable (Wolniak and Mahapatra 2014). Light rain with poor visibility caused the maximum number of unreliable events: ∼4% of the total samples were extremely unreliable during the light rain–poor visibility condition. In the case of moderate rain and poor visibility, ∼25% of the total samples were moderately–highly unreliable.

As noted previously, the reliability of the segments is lower during the poor visibility condition. To understand the probability of a road segment being unreliable (based on PTI thresholds) under different intensities of rainfall and visibility, survival functions were developed. The parametric approach was adopted as smaller sample sizes associated with some of the selected cases like heavy rain and poor visibility reduced the accuracy of the nonparametric estimates. Similarly, the distributions were not continuous in many cases. Previous studies indicated that lognormal distribution is generally suitable for modeling the travel time data.

As stated previously, the goodness of fit for selected theoretical distributions (lognormal distribution, Weibull distribution, Burr distribution, Gamma distribution, and three-parameter lognormal distribution) were plotted, compared with the empirical survival function, and tested using the KS test to identify the best distribution. As an example, the theoretical survival functions in comparison with the empirical survival function (using the real-
world PTI values) are shown in Fig. 4. The results from the KS test are summarized in Table 3.

From Fig. 4 and the KS test results, three-parameter lognormal distribution was found to be the best survival function to model PTI (not following lognormal). Moreover, Zhang et al. (2016) pointed out the applicability of three-parameter lognormal distribution in travel time modeling. The density function for the three-parameter lognormal distribution is given as follows:

![Comparison of theoretical survival functions with the empirical survival function.](image)

**Fig. 4.** Comparison of theoretical survival functions with the empirical survival function.
\[ f(x) = \frac{1}{(\chi - \gamma)\sqrt{2\pi}\sigma} \exp\left\{ -\frac{1}{2}\left[\frac{\ln(\chi - \gamma) - \mu}{\sigma}\right]^2\right\}, \quad (5) \]

where \(\mu\), \(\sigma\), and \(\gamma\) are the parameters (location, scale, and threshold, respectively) of the three-parameter lognormal distribution.

The survival function plots developed for the freeway segments are shown in Fig. 5. The parameters of the survival function (location, scale, and threshold) are also included in the figure.

Under rain and poor visibility conditions, the survival function shifts to the right, increasing the probability of being unreliable (higher PTI values). In other words, the probability of becoming unreliable is less in the case of normal weather condition. From Fig. 5d, the maximum difference between the curves is between a PTI of 1.15–2.2, which indicates the moderately–highly unreliable traffic condition in the road segments. For example, the probability of reaching moderately–highly unreliable state (PTI > 1.5) is almost 10% higher in the case of heavy rain–poor visibility condition than that of the normal weather condition. Overall, the effect of rainfall and visibility on the TTR is found to be less during the free-flow state and the highly congested state. The shift is minimum in both cases.

The summary related to the survival statistics are provided in Table 4. The probability of observing unreliable conditions is higher in the case of heavy rain–poor visibility condition and the heavy rain–moderate visibility condition.

b. Effect of rainfall and visibility on urban arterial road segments

In the case of urban arterial road segments, functional class 3 and 4 (principal arterial and minor arterial) were considered in the quantification process. A total of 28 arterial segments were evaluated to quantify the effect of rainfall and visibility. Table 5 depicts the percentage of differences in TTR indices for the arterial road segments for selected intensities of rainfall and visibility conditions with respect to the normal weather condition.

From Table 5, heavy rain condition has a maximum effect on the TTR. Under heavy rain condition without any effect on visibility, PTI increased by 6.70%. Similarly, PTI increased by 2.98% in the case of light rain with poor visibility condition while PTI increased by 4.02% in the case of heavy rain with poor visibility condition. A 1.22%–7.91% increase in TTI was

---

**Table 3. Results of goodness-of-fit for the selected theoretical distributions, tested at a 95% confidence level.**

<table>
<thead>
<tr>
<th>Type of distribution</th>
<th>KS test</th>
<th>Result</th>
<th>Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>Three-parameter lognormal</td>
<td>0.030</td>
<td>Accepted</td>
<td>1</td>
</tr>
<tr>
<td>Burr</td>
<td>0.038</td>
<td>Accepted</td>
<td>2</td>
</tr>
<tr>
<td>Lognormal</td>
<td>0.056</td>
<td>Accepted</td>
<td>3</td>
</tr>
<tr>
<td>Gamma</td>
<td>0.083</td>
<td>Rejected</td>
<td>4</td>
</tr>
<tr>
<td>Weibull</td>
<td>0.120</td>
<td>Rejected</td>
<td>5</td>
</tr>
</tbody>
</table>

**Table 5.**

In the case of urban arterial road segments, functional class 3 and 4 (principal arterial and minor arterial) were considered in the quantification process. A total of 28 arterial segments were evaluated to quantify the effect of rainfall and visibility. Table 5 depicts the percentage of differences in TTR indices for the arterial road segments for selected intensities of rainfall and visibility conditions with respect to the normal weather condition.

From Table 5, heavy rain condition has a maximum effect on the TTR. Under heavy rain condition without any effect on visibility, PTI increased by 6.70%. Similarly, PTI increased by 2.98% in the case of light rain with poor visibility condition while PTI increased by 4.02% in the case of heavy rain with poor visibility condition. A 1.22%–7.91% increase in TTI was

---

**Fig. 5.** PTI-based survival function plots for freeway road segments under different weather conditions.
observed in the case of heavy rain condition. However, light and moderate rain conditions do not have much effect on TTR indices. Overall, the effect of TTR on arterial road segments was found to be less than that on the freeway road segments.

Survival functions plots were developed to evaluate the probability of an arterial road segment being unreliable under rainfall and different visibility ranges (Fig. 6). The parameters of the survival function (location, scale, and threshold) are also included in the figure. In majority of the cases, the survival function plots are similar for the normal weather condition and adverse weather condition.

This research estimated the PTI thresholds for urban arterial segments based on the TTI reliability rating guidelines suggested by the National Academies of Sciences, Engineering, and Medicine (2014). A PTI value less than 2.2 is considered as reliable, a PTI value between 2.2 and 3.5 is considered as moderately–highly unreliable, and a PTI value greater than 3.5 is considered as extremely unreliable.

The summary results related to the survival statistics for the urban arterial road segments are provided in Table 6. The effect of rainfall and visibility on the TTR was found to be minimal on the arterial road segments. It can be attributed to the effect of rainfall and visibility on the TTR was found to be less than that on the freeway road segments.

5. Conclusions

One of the main limitations of the previous studies was the disjointed data related to the weather and road operational characteristics. This research extracted the weather and travel time data for the same TOD and DOW and integrated the data for analysis. The effect of other factors (geometric conditions, traffic patterns, and other environmental factors) beyond the scope of this research was minimized by comparing the travel time data for a week before and after rainfall and visibility conditions with the travel time during rainfall and visibility conditions.

Most of the previous studies quantified the effect of rainfall and visibility on road performance by considering operational speed as a measure. In other words, the effect of weather condition on reliability (TTR) of a road segment was not explored previously. However, this research explored TTR indices like PTI and TTI to quantify the effect of rainfall and visibility on the TTR. As various researchers already used PTI and TTI measures to illustrate the reliability or congestion state of a road segment, quantifying the effect of rainfall and visibility and associated intensity on such TTR indices provides better

<table>
<thead>
<tr>
<th>Weather condition</th>
<th>Intensity</th>
<th>Reliable Adverse</th>
<th>Reliable Normal</th>
<th>Moderately–highly unreliable Adverse</th>
<th>Moderately–highly unreliable Normal</th>
<th>Extremely unreliable Adverse</th>
<th>Extremely unreliable Normal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rain</td>
<td>Light</td>
<td>84.50%</td>
<td>88.31%</td>
<td>15.50%</td>
<td>13.72%</td>
<td>0.51%</td>
<td>0.39%</td>
</tr>
<tr>
<td></td>
<td>Moderate</td>
<td>87.02%</td>
<td>90.01%</td>
<td>12.97%</td>
<td>9.99%</td>
<td>0.27%</td>
<td>0.21%</td>
</tr>
<tr>
<td></td>
<td>Heavy</td>
<td>85.84%</td>
<td>94.87%</td>
<td>14.16%</td>
<td>5.13%</td>
<td>3.30%</td>
<td>&lt;0.01%</td>
</tr>
<tr>
<td>Rain and visibility</td>
<td>Light–moderate visibility</td>
<td>78.36%</td>
<td>85.69%</td>
<td>22.64%</td>
<td>14.31%</td>
<td>2.03%</td>
<td>0.38%</td>
</tr>
<tr>
<td></td>
<td>Light–poor visibility</td>
<td>71.17%</td>
<td>79.72%</td>
<td>28.83%</td>
<td>20.28%</td>
<td>3.90%</td>
<td>1.56%</td>
</tr>
<tr>
<td></td>
<td>Moderate–moderate visibility</td>
<td>88.77%</td>
<td>85.32%</td>
<td>11.23%</td>
<td>14.68%</td>
<td>0.15%</td>
<td>0.43%</td>
</tr>
<tr>
<td></td>
<td>Moderate–poor visibility</td>
<td>75.61%</td>
<td>83.09%</td>
<td>24.39%</td>
<td>16.91%</td>
<td>2.45%</td>
<td>0.86%</td>
</tr>
<tr>
<td></td>
<td>Heavy–moderate visibility</td>
<td>91.81%</td>
<td>94.28%</td>
<td>8.19%</td>
<td>5.72%</td>
<td>&lt;0.01%</td>
<td>&lt;0.01%</td>
</tr>
<tr>
<td></td>
<td>Heavy–poor visibility</td>
<td>84.45%</td>
<td>98.84%</td>
<td>15.44%</td>
<td>1.16%</td>
<td>0.41%</td>
<td>&lt;0.01%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Weather condition</th>
<th>Intensity</th>
<th>ATT Change</th>
<th>PT Change</th>
<th>PTI Change</th>
<th>TTI Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rain</td>
<td>Light</td>
<td>+0.04%</td>
<td>−0.30%</td>
<td>−0.12%</td>
<td>+1.01%</td>
</tr>
<tr>
<td></td>
<td>Moderate</td>
<td>+2.70%</td>
<td>−3.21%</td>
<td>−2.91%</td>
<td>4.31%</td>
</tr>
<tr>
<td></td>
<td>Heavy</td>
<td>+1.10%</td>
<td>+8.88%</td>
<td>+6.70%</td>
<td>+7.91%</td>
</tr>
<tr>
<td>Rain and visibility</td>
<td>Light–moderate visibility</td>
<td>+1.21%</td>
<td>−1.68%</td>
<td>−1.53%</td>
<td>+1.50%</td>
</tr>
<tr>
<td></td>
<td>Light–poor visibility</td>
<td>+5.79%</td>
<td>+3.78%</td>
<td>+2.98%</td>
<td>+6.17%</td>
</tr>
<tr>
<td></td>
<td>Moderate–moderate visibility</td>
<td>−1.90%</td>
<td>−4.86%</td>
<td>−5.75%</td>
<td>−0.06%</td>
</tr>
<tr>
<td></td>
<td>Moderate–poor visibility</td>
<td>+6.70%</td>
<td>+6.52%</td>
<td>+1.14%</td>
<td>0.24%</td>
</tr>
<tr>
<td></td>
<td>Heavy–moderate visibility</td>
<td>+4.58%</td>
<td>+3.51%</td>
<td>+0.06%</td>
<td>+2.72%</td>
</tr>
<tr>
<td></td>
<td>Heavy–poor visibility</td>
<td>+3.20%</td>
<td>+3.63%</td>
<td>+4.02%</td>
<td>+1.22%</td>
</tr>
</tbody>
</table>

TABLE 4. Survival analysis summary for freeway segments.

TABLE 5. TTR indices for urban arterials under different weather conditions.
insights into the exact traffic conditions on the road segment under different weather conditions.

The analysis was carried out using data for selected freeway and arterial road segments in North Carolina. Different rainfall intensities with poor visibility have a maximum adverse effect on freeway TTR. Heavy rain and poor visibility caused a 5.50% increase in the ATT and a 12.24% increase in PTI on urban freeway road segments. Similarly, a 7.55% increase in TTI was observed under moderate rain–poor visibility condition on the urban freeway road segments. In the case of arterial road segments, the increase in PTI was 6.70% and 4.02%, respectively under heavy rain–good visibility and heavy rain–poor visibility conditions. Overall, PTI was observed to be a better measure as it normalizes the 95th-percentile travel time for all the road segments in terms of free-flow travel time.

In general, survival function is useful in estimating the probability of reaching an unreliable state under rainfall and visibility conditions. The analysis was performed using data for the freeway and arterial road segments. The probability of a segment being unreliable under a specific PTI value was therefore studied using the survival function. The likelihood of reaching a moderately–highly unreliable condition is 8%–15% higher on urban freeway road segments in the case

<table>
<thead>
<tr>
<th>Weather condition</th>
<th>Intensity</th>
<th>Reliable</th>
<th>Moderately–highly unreliable</th>
<th>Extremely unreliable</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Adverse</td>
<td>Normal</td>
<td>Adverse</td>
</tr>
<tr>
<td>Rain</td>
<td>Light rain</td>
<td>72.10%</td>
<td>70.20%</td>
<td>27.90%</td>
</tr>
<tr>
<td></td>
<td>Moderate rain</td>
<td>79.95%</td>
<td>77.68%</td>
<td>20.05%</td>
</tr>
<tr>
<td></td>
<td>Heavy rain</td>
<td>78.51%</td>
<td>88.67%</td>
<td>21.49%</td>
</tr>
<tr>
<td>Rain and visibility</td>
<td>Light rain–moderate visibility</td>
<td>69.30%</td>
<td>66.53%</td>
<td>30.70%</td>
</tr>
<tr>
<td></td>
<td>Light rain–poor visibility</td>
<td>66.71%</td>
<td>67.72%</td>
<td>33.29%</td>
</tr>
<tr>
<td></td>
<td>Moderate rain–moderate visibility</td>
<td>76.29%</td>
<td>72.61%</td>
<td>23.71%</td>
</tr>
<tr>
<td></td>
<td>Moderate rain–poor visibility</td>
<td>71.60%</td>
<td>70.69%</td>
<td>28.40%</td>
</tr>
<tr>
<td></td>
<td>Heavy rain–moderate visibility</td>
<td>80.63%</td>
<td>80.10%</td>
<td>19.37%</td>
</tr>
<tr>
<td></td>
<td>Heavy rain–poor visibility</td>
<td>75.15%</td>
<td>78.10%</td>
<td>24.85%</td>
</tr>
</tbody>
</table>

Fig. 6. PTI-based survival function plots for arterial road segments under different weather conditions.

Table 6. Survival analysis summary for urban arterials.
of poor visibility conditions relative to the normal weather conditions. However, the survival analysis for arterial road segments indicated the minimal effect of rainfall and visibility conditions on the TTR.

The effect of the weather on TTR was lower in the case of urban arterial road segments when compared with freeway road segments. The maximum effect was observed in the case of heavy rain condition. The data points for the arterial road segment analysis were fewer than for the freeway road segment analysis. The lower operating speed and the interrupted traffic conditions on the arterial road segments may have neutralized the variability in travel times during rain and visibility constraints.

The methodology and results from this research are useful for transportation system managers and planners to manage the traffic under different weather conditions. The methodology described in this research requires weather-related information and travel time of a road segment, which are readily available from various resources. The findings also help improve the functionality of weather-responsive management strategies like variable signs to indicate the change in reliability under rainfall and low visibility conditions. Communicating the travel time information during weather events can also reduce the crash risks associated with weather conditions.

Overall, this research put forth a data-driven approach to quantify the effect of different intensities of rainfall and visibility conditions on the TTR. Also, the effect of only visibility on the TTR was not explored in this research. Conducting similar analysis separately using time-matched rainfall/traffic and visibility/traffic merit an investigation in the future.

Acknowledgments. This paper is prepared from information collected for a research project funded by the U.S. Department of Transportation–Office of the Assistant Secretary for Research and Technology (USDOT/OST-R) University Transportation Centers Program (Grant 69A3551747127). The authors thank the staff of North Carolina Department of Transportation (NCDOT) and Regional Integrated Transportation Information System (RITIS) for their help with data used in this research. The National Performance Management Research Data Set used in this research is based upon work supported by the Federal Highway Administration (FHWA) under Contract DTFH61-17-C-00003. The authors also thank the Integrated Surface Database (ISD) website for providing the data required for this research. This paper is disseminated in the interest of information exchange. The views, opinions, findings, and conclusions reflected in this paper are the responsibility of the authors only and do not represent the official policy or position of any federal, state, regional, or local agency, or the University of North Carolina at Charlotte or other entity. The authors are responsible for the facts and the accuracy of the data presented herein. This paper does not constitute a standard, specification, or regulation.

REFERENCES


Zhao, L., and S. I. J. Chien, 2012: Analysis of weather impact on travel speed and travel time reliability. 12th COTA Int. Conf. of Transportation Professionals, Beijing, China, American Society of Civil Engineers, https://doi.org/10.1061/9780784412442.117.