RFID E-plate Data based Travel Time Reliability Estimation of Urban Expressway

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Abstract. Travel time distribution shows the aggregation degree of vehicle travel time in road network, and travel time reliability is the key index to measure the aggregation degree of travel time. In order to quantitatively evaluate the fluctuation of travel time of expressway vehicles, it is necessary to establish an estimation method of travel time reliability of expressway. Travel time reliability estimation needs to obtain travel time data of vehicles. Traditional Global Position System (GPS) and video detection methods are easily affected by external factors such as weather and environment, and the description of travel time distribution is not comprehensive under the condition of low permeability. On the other hand, in the evaluation of travel time reliability, although there are lots of travel time probability distribution models, the correlation of vehicle travel time between links is ignored when calculating travel time reliability. In order to estimate travel time reliability more accurately, based on Radio Frequency Identification (RFID) electronic license plate (E-plate) data, this paper proposes a path travel time reliability evaluation model considering travel time correlation between links. First, the RFID readers installed on the gantry of expressway acquires data from the electronic tags deployed on vehicles. Secondly, a percentile travel time estimation method is proposed based on Cornish-Fisher expansion and the skewness of travel time distribution. Finally, considering the reliability estimation of travel time under the correlation of links, the estimated value is closer to the true value. The experimental results show that the travel time reliability estimation method considering the correlation between links improves the accuracy of estimation in the expressway network environment.

1. Introduction

With the rapid development of intelligent transportation system (ITS), advanced travelers information system (ATIS) has gradually become the main functional field of ITS, which is designed to provide more convenience to trips through advanced technologies[1]. "Arriving on-time" has gradually become a consideration of the drivers' travel demand. The urban expressway which providing long distance, reliable transportation in a city, however, gradually shows a trend from "reliable" to "unreliable"[2]. How to provide accurate and reliable travel plans for travelers has become a key issue in ATIS.

Travel time reliability is defined as describing the degree of fluctuation of traveler's travel time with time[3]. In fact, the travel time of vehicles on any road in the road network fluctuates with the passage of time. Therefore, travelers often reserve a certain buffer time in order to arrive at the destination before the planned time.

At present, many evaluation indicators of travel time reliability have been developed. Commonly
used evaluation indicators include: Planning Travel Time, Buffer Index, Frequency of Congestion, Travel Time Budget, Mean-excess Travel Time and Travel Time Reliability Ratio, etc. Almost all of these evaluation indicators are calculated on the basis of percentile travel time[4]. However, most of the research methods on travel time reliability need to fit the travel time distribution first, then calculate the percentile function of travel time through the parameters of the fitting function, so as to finish the calculation of travel time reliability[5-8]. However, these methods based on travel time fitting have three problems that are hard to solve. One is that all the above methods rely on the full sample of single vehicle information. Second, the fitting function changes with the change of distribution, and the portability of the method is low and the calculation is cumbersome. Third, related studies often assume that the travel time of links is independent of each other. On the other hand, it is found that the fourth-order moment method is suitable for scenarios where the distribution is similar to normal distribution and there is no need to fit the distribution. However, there are few literatures used in travel time reliability because of the quality of traffic data[9].

With the development of RFID technology, compared with the traditional detection techniques, RFID has a unique advantage, because it mainly communicates through radio, and has the characteristics of high identification accuracy, strong anti-interference ability, waterproof, dustproof, shockproof, antimagnetic, heat resistance and so on[10].

The motivation of this paper is to improve the estimation accuracy of travel time reliability based on the first four moments of travel time and considering the correlation of travel time between links. The main contributions of this paper are as follows:

- We propose an expressway travel time collection scheme based on RFID E-Plate data, which can obtain complete travel time information and improve the accuracy of reliability estimation.
- We propose a method to estimate the percentile travel time based on the Cornish-Fisher expansion method.
- We propose a travel time reliability estimation method considering the correlation of travel time.

The remainder of this paper is organized as follows. Section 2 introduces the RFID E-plate data under the expressway environment. Section 3 introduces the travel time reliability estimation method based on the first four moments of travel time. Then a large number of experimental results are provided to prove the effectiveness of the model. Finally, we make a summary of this paper and put forward expectations for the future work.

2. RFID E-plate data in urban expressway environment

There are many similarities between urban expressway and highway, such as road structure, traffic conditions, road infrastructure and so on. However, some types of vehicles (such as motorcycles and buses) which are prohibited from running on the highway can still drive on the urban expressway, which leads to more types of vehicles on the highway. On the other hand, in terms of road structure, the urban expressway is built around the city, the traffic density on the urban expressway is also higher, the ramp entrance is denser, and the distance between the basic sections of the urban expressway between the adjacent ramps is shorter. Frequent lane-changing behavior and up-and-down behavior of vehicles are more likely to cause fluctuations in the state of road traffic.

As a new sensor detection technology, RFID technology has been widely used in daily life because of its low cost and convenience[12]. The communication equipment of RFID mainly includes RFID reader, RFID tag and antenna. Because of wireless communication, RFID technology has the advantages of over-the-horizon, long distance, large capacity storage and fast identification, and the data collected is the information of each item with RFID tag[13]. When used in traffic, all-weather, full sample and single vehicle data can be collected, which makes RFID technology for traffic data collection become more detailed. On the other hand, although the amount of RFID readers at each intersection in the city is over 800, its distribution is still relatively sparse. However, it can be determined in expressway environment that there is almost and only one path between adjacent RFID readers to avoid the difference in travel time caused by vehicle detour.
A RFID E-plate data record read by RFID readers roughly contain basic field information such as the E-plate number of the vehicle, the time the vehicle passed through the RFID reader, the IP address of the RFID reader and the type of vehicle, as shown in the example in Table 1.

### Table 1. Example of RFID ERI data field information

| Serial number | Filed name  | Attribute description          | Field name example |
|---------------|-------------|--------------------------------|--------------------|
| 1             | Num         | Record number                  | 675                |
| 2             | RFID_ip     | IP address                     | 10.10.10.03        |
| 3             | Direction   | Vehicle driving direction      | Caiyuanba - Nan’an |
| 4             | EID         | RFID E-plate number            | 325654             |
| 5             | Passtime    | Passing time                   | 2016-03-01 10:30:15|
| 6             | Car_type    | Vehicle type                   | K33                |

### 3. Estimation method of travel time reliability

#### 3.1. The first four moments and percentile travel time of travel time

The first four moments refer to the first-order origin moment, the second-order central moment, the third-order central moment and the fourth-order central moment of a variable. The mean, variance, skewness and kurtosis of travel time are the first four moments of travel time distribution.

When the first four moments of the distribution are known, Cornish-Fisher proposed an expansion method, which establishes the relationship between the arbitrary distribution and the standard normal distribution, so the percentile under arbitrary confidence level can be approximately obtained by using the first four moments of random variables. The estimated percentile travel time after using this expansion is as follows:

\[
P TT ( p ) \approx \mu + \varphi ( p ) \cdot \sigma ^2
\]

Where \( \varphi ( p ) \) is a random variable related to skewness and kurtosis:

\[
\varphi ( p ) = \Phi ^{-1}(p) + \frac{1}{6}(\Phi ^{-1}(p))^2 - 1 ) S + \\
( \frac{1}{24})(\Phi ^{-1}(p))^3 - 3 \Phi ^{-1}(p) K - \frac{1}{36}(2(\Phi ^{-1}(p))^3 - 5\Phi ^{-1}(p)) S^2
\]

Where \( \Phi ^{-1}(\cdot) \) is the inverse function of the cumulative distribution function.

#### 3.2. Logarithmic processing of travel time

In order to calculate the travel time reliability, the concept of valid domain is proposed by Zang[15]. It is found that only the data within the valid domain can use Cornish-Fisher expansion, otherwise it is invalid.

Since the accuracy of calculating percentile travel time by using Cornish-Fisher expansion depends on the similarity between the distribution and the standard normal distribution, and the expansion requires that the derivative of percentile travel time is non-negative, considering that the original travel time distribution has certain skewness and kurtosis characteristics, it is necessary to logarithm the original data.
After logarithmic processing, the original data $TT(T_t^1, T_t^2, \ldots, T_t^i)$ change to $TT_{log}(T_t^1, T_t^2, \ldots, T_t^i)$. Accordingly, the Cornish-Fisher expansion for calculating percentile travel time is also changed to:

$$P_{TT}(p) \approx \exp\left(k_1(T_{log}) + \phi_{log}(p)\sqrt{k_2(T_{log})}\right)$$

(3)

Where $k_1(T_{log})$ and $k_2(T_{log})$ Represent the mean and variance of logarithmic travel time series.

Similarly, in order to ensure the necessary requirements for the increase of the inverse cumulative distribution function, there are the following formulas.

$$\frac{dP_{TT}(p)}{dp} = \exp\left(k_1(T_{log}) + \phi_{log}(p)\sqrt{k_2(T_{log})}\right) \cdot \frac{d\phi_{log}(p)}{dp} \geq 0$$

(4)

For the valid domain, whether it has been logarithmized and which logarithmic method (such as taking the natural base e or 10 as the base) has no change for the interval of the valid field.

$$4S^2 < 3K$$

$$\frac{1}{16} K^2 - \left(\frac{11S^2}{72} + \frac{1}{2}\right) K + \frac{5}{54} S^4 + \frac{7}{9} S^2 \leq 0$$

(5)

Where

$$f(K) = \frac{1}{16} K^2 - \left(\frac{11S^2}{72} + \frac{1}{2}\right) K + \frac{5}{54} S^4 + \frac{7}{9} S^2$$

(6)

Therefore, the formula can be regarded as a quadratic function with respect to K. According to the discriminant, when the travel time skewness is little, the valid domain is:

$$S \in [-6(\sqrt{2} - 1), 6(\sqrt{2} - 1)]$$

(7)

$$K \in \left[4 + \frac{11}{9} S^2 - \frac{1}{81} S^4 - \frac{8}{3} S^2 + 16, 4 + \frac{11}{9} S^2 + \frac{1}{81} S^4 - \frac{8}{3} S^2 + 16\right]$$

(8)

However, when the travel time skewness is large, the skewness can reach infinity in theory. From the actual data, the skewness is less than 20 and the negative value is not less than $-6(\sqrt{2} + 1)$, so the valid domain when the skewness is large is defined as:

$$S \in \left[6(\sqrt{2} + 1), 20\right]$$

(9)

$$K \in \left[4 + \frac{11}{9} S^2 - \frac{1}{81} S^4 - \frac{8}{3} S^2 + 16, 4 + \frac{11}{9} S^2 + \frac{1}{81} S^4 - \frac{8}{3} S^2 + 16\right]$$

(10)

In the logarithmic processing of the original data, although the natural base e can make more data fall into the valid domain, it can not satisfy all the cases, so the logarithmic processing method with base 10 is adopted here.

3.3. Correlation Analysis of Urban Expressway Travel time

3.3.1. Link travel time reliability

In the existing research, in order to quantify the travel time reliability, there are many kinds of related indicators, and there are some differences in the contents described. At present, the calculation expressions of the commonly used evaluation indicators are shown in Table 2.

| Travel time reliability indicator | Expression |
|-------------------------------|------------|
| Travel time budget            | $TTB(p) = \min\{\bar{T} \mid P(T \leq \bar{T}) \geq p\}$ |
| Mean-excess travel time       | $METT = \frac{1}{1-p} \int_{p}^{1} PTT(x)dx$ |
Travel time reliability indicator | Expression
--- | ---
Travel time reliability ratio | $TTRR = \frac{\beta + \gamma \mathbb{E} \left[ \frac{1}{x} \right]}{\alpha} \int_{\beta + \gamma} PTT(x) dx$

Note that $\alpha, \beta, \gamma$ are parameters of driver's preference, $p$ is the confident level and PTT is percentile travel time.

3.3.2. Path travel time reliability

First of all, the path model is simplified, and it is considered that the path is composed of multiple units, because there is no intersection on the urban expressway and there is no influence of traffic lights. At the same time, due to the layout characteristics of RFID readers, there is an upper and lower entrance between adjacent RFID readers. Based on the above situation, this paper assumes that the path is only composed of multiple links, so the travel time of the path can be regarded as the sum of the travel time of all the links on that section.

$$T_{path} = \sum_{i} T_i$$ (11)

Where $T_{path}$ is path travel time, $\sum_{i} T_i$ is the travel time of all links.

According to the relationship between random variables in statistics, similarly, the first-order moment of travel time between two adjacent links can be expressed as follows:

$$E(T_i + T_j) = ET_i + ET_j$$ (12)

It can be seen that the first moment or mean value of travel time is not directly affected by the correlation of links. The second-order moment of travel time between two adjacent links can be expressed as follows:

$$D(T_i + T_j) = DT_i + DT_j + 2Cov(T_i, T_j)$$ (13)

The covariance can quantitatively express the relationship between pairwise random variables, and its calculation formula is:

$$Cov(T_i, T_j) = E(T_iT_j) - ET_i \cdot ET_j = \rho_{T iT j} \cdot \sqrt{DT_i} \cdot \sqrt{DT_j}$$ (14)

Where $\rho_{T iT j}$ is the travel time correlation coefficient between link i and link j.

The existing research on travel time reliability almost only analyzes the stage of the first two moments. The derivation and calculation formula of the third-order moment of travel time, that is, the skewness of path travel time.

$$S(T_i + T_j) = \frac{E(T_i + T_j)^3 - 3E(T_i + T_j) \cdot D(T_i + T_j) - E^3(T_i + T_j)}{D^2(T_i + T_j)}$$ (15)

Similarly, the formula for calculating the fourth moment, that is, the kurtosis of path travel time.

$$K(T_i + T_j) = \frac{E(T_i + T_j)^4 - 4E(T_i + T_j) \cdot \left[ E(T_i + T_j)^3 + E^3(T_i + T_j) \right] + 6E(T_i + T_j)^5 \cdot E^2(T_i + T_j) + E^4(T_i + T_j)}{D^3(T_i + T_j)}$$ (16)

In the case that the high-order moment of the path travel time is known, combined with the expansion of Cornish-Fisher, the percentile travel time on the path can be obtained. Considering METT as the travel time reliability evaluation indicator, the calculation process is as follows:

$$R = METT = \frac{1}{1 - p^2 \phi(p)} \int E(T_i + T_j) + \phi(p) \cdot D(T_i + T_j)$$ (17)
For the problem of determining the value of $\rho_{ijTT}$, it is generally considered to establish a pairwise correlation coefficient matrix for all links in the existing research:

$$\psi=
\begin{pmatrix}
\rho_{iTi_1} & \rho_{iTi_2} & \cdots & \rho_{iTi_m} \\
\rho_{jTi_1} & \rho_{jTi_2} & \cdots & \rho_{jTi_m} \\
\vdots & \vdots & \ddots & \vdots \\
\rho_{mTi_1} & \rho_{mTi_2} & \cdots & \rho_{mTi_m}
\end{pmatrix}
$$

(18)

Because the travel time correlation coefficient $\rho_{ijTT}$ measures the correlation between the travel time series $T_i(t_1, t_2, \ldots, t_n)$ of link $i$ and the travel time series $T_j(t_1, t_2, \ldots, t_n)$ of link $j$, this paper refers to the research status of Seshadri, Chen and others[16], in which Seshadri proposed that the correlation coefficient between adjacent links is 0.75, while that of non-adjacent links is 0. Therefore, when the correlation coefficient between links is considered in this model, the calculation formula is the inverse of the above formula for the travel time correlation coefficient between two links:

$$\rho_{ijTT} = \frac{D(T_i + T_{i+1}) - DT_i - DT_{i+1}}{2\sqrt{DT_i} \cdot \sqrt{DT_{i+1}}}
$$

(19)

For the two non-adjacent links, the average is obtained according to the correlation coefficient between the adjacent links, and the calculation formula is as follows:

$$\rho_{ijTT} = \frac{1}{m} \sum_{i=1}^{m} \rho_{ijTT}
$$

(20)

4. Experimental analysis

4.1. Data description

In order to verify the effectiveness of the above model, this paper uses the measured traffic flow data based on RFID E-plate data in Chongqing. Three long-distance connected expressways from Shimahe to Gaotanyan Interchange in Shapingba inner ring urban expressway of Chongqing are selected. The total length of the expressway is 5.5 km, including the 7-day traffic flow data collected by 4 RFID readers from February 29, 2016 to March 06, 2016, with a total of 777017 data.

4.2. Analysis of experimental results

4.2.1. Logarithmic processing result

Figure 2 shows how the first four moments of the travel time of the original data fall around the valid domain and after logarithmic processing for three links in the past week.
It can be seen that a large number of travel time distribution in the original data will fall outside the valid domain, so that the estimated value of percentile travel time may not be accurate, and after logarithmic processing of the data, the scattered points that originally fell outside the valid domain can fall within the valid domain. On the other hand, it also shows that the valid domain with large skewness in Section 3.2 is not suitable for this study as a basis for discrimination.

Table 3 taking the travel time data of Gaotanyan road within the day of February 29, 2016 as example, 96 groups of travel time distribution data are compared according to the errors at each quantile. Evaluate the error of travel time reliability estimation method based on first four moments of travel time and travel time reliability estimation method based on distribution fitting.

Table 3. The accuracy comparison between the first four moments method of travel time and the common distribution fitting method

| Evaluation indicator | First four moments | Normal | Log-Normal | Burr | Weibull | Gamma |
|----------------------|--------------------|--------|------------|------|---------|-------|
| RMSE                 | **1.38**           | 3.32   | 2.57       | 1.92 | 5.40    | 2.71  |
| MAPE                 | 1.54%              | 4.30%  | 2.65%      | 1.10%| 7.37%   | 3.07% |
| $\chi^2$             | **34.33**          | 434.75 | 120.99     | 102.54| 796.62  | 138.72|
| $R^2$                | 0.97               | 0.81   | 0.89       | 0.94 | **0.47**| 0.88  |

4.2.2. Correlation coefficient of travel time of links

By using the formula (14), due to the small number of links, the correlation coefficient between links obtained by this method can be approximated to the real value, and the correlation coefficient matrix of travel time between links is as follows:

$$
\begin{pmatrix}
1 & 0.651833560450676 & 0.578294745336845 \\
0.651833560450676 & 1 & 0.5351543053989373 \\
0.578294745336845 & 0.5351543053989373 & 1
\end{pmatrix}
$$

(21)

The correlation coefficient matrix of travel time between links calculated by formulas (19) and (20)
is as follows:

\[
\begin{pmatrix}
1 & 0.651833560450676 & 0.593493932924806 \\
0.651833560450676 & 1 & 0.5351543053989373 \\
0.593493932924806 & 0.5351543053989373 & 1
\end{pmatrix}
\] (22)

It can be seen that when calculating the adjacent links, the calculation methods and results of the two methods are actually exactly the same, and the difference lies in the processing of the travel time correlation coefficient between the non-adjacent links. Using the formula (20), the MAPE of the travel time correlation coefficient of the non-adjacent links is 2.63% with the RMSE is 0.0152, and the error is little. This also shows the effectiveness of this method. Later, this method will be used to calculate the path percentile travel time and path travel time reliability.

4.2.3. Path travel time reliability

The comparison is made by using the travel time distribution fitting method, which is obtained by considering the convolution of the distribution when considering the path travel time reliability, and the results are shown in Table 4. It can be seen that after considering the section correlation, the accuracy of the path travel time reliability based on the first four moments are even higher than that of the travel time reliability estimation on the links.

Table 4. The accuracy comparison between the first four moments method of travel time and the common distribution fitting method

| Evaluation indicator | First four moments | Normal | Log-Normal | Burr | Weibull | Gamma |
|----------------------|--------------------|--------|------------|------|---------|-------|
| RMSE                 | 2.84               | 4.75   | 4.33       | 3.14 | 6.07    | 4.01  |
| MAPE                 | 4.12%              | 7.26%  | 6.51%      | 5.16%| 10.23%  | 8.45% |
| \( \chi^2 \)         | 63.19              | 621.28 | 152.04     | 89.45| 841.82  | 179.39|
| \( R^2 \)            | 0.85               | 0.92   | 0.90       | 0.95 | **0.81** | 0.99  |

Therefore, according to formula (17), the METT indicator of path travel time reliability at different confidence levels is shown in Table 5.

Table 5. Path travel time reliability under different confidence levels

| Evaluation indicator | 10%  | 25%  | 50%  | 75%  | 90%  | 95%  |
|----------------------|------|------|------|------|------|------|
| METT                 | 364.96 | 241.93 | 121.89 | 92.14 | 88.24 | 73.48 |

It can be seen that with the increase of the confidence level, the METT gradually decreases. In other words, the lower the confidence level is, the higher risk will driver take; on the contrary, if the driver has lower requirements for "arriving on-time", the corresponding possible buffer time is less.

5. Conclusions

In this study, a travel time reliability estimation scheme based on RFID E-plate data is proposed, and the effectiveness and superiority of this method are verified by using the real traffic big data with 7-day coverage in Chongqing, China. In this paper, the emerging radio frequency identification technology is used to identify vehicles. In the third section, we first introduce the potential problems of travel time reliability estimation, and put forward some solutions. In the fourth section, we find that the accuracy of our proposed model is superior to the traditional travel time fitting method in almost every indicator, and will not overestimate the reliability of travel time. Therefore, the proposed model is sufficient to evaluate the reliability of vehicle travel time in expressway environment. In addition, the model can provide corresponding travel time reliability data according to the different needs of travelers for "arriving on-time", which is of guiding significance for inducing travelers to plan a reasonable departure time and urban traffic managers.
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