Origin–Destination-Based Travel Time Reliability

Shu Yang, Chengchuan An, Yao-Jan Wu, and Jingxin Xia

Travel time reliability (TTR) is an important performance indicator for transportation systems. TTR can be generally categorized as either segment based or origin–destination (O-D) based. A primary difference between the two TTR estimations is that route information is implied in segment-based TTR estimations. Segment-based TTR estimations have been widely studied in previous research; however, O-D–based TTR estimations are used infrequently. This paper provides detailed insight into O-D–based TTR estimations and raises three new issues: (*a*) How many routes do travelers usually take and what are the TTR values associated with these routes? (*b*) Do statistical differences exist between route-specific and non-route-specific (NRS) TTR values? (*c*) How can O-D–based TTR information be delivered? Two processes were proposed to address the issues. Three TTR measures—standard deviation, coefficient of variation, and buffer index—were calculated. The bootstrapping technique was used to measure the accuracy of the TTR measures. Approximate confidence intervals were used to investigate statistically the differences between route-specific and NRS TTR measures. A large quantity of taxicab GPS-based data provided data support for estimating O-D–based TTR measures. The results of O-D–based TTR measures showed that no statistically significant differences existed between route-specific and NRS TTR measures for most of the time periods examined. Statistically significant differences could still be found in some time periods. Travelers may take advantage of these differences to choose a more reliable route. Access to both numeric TTR values and route preference, instead of just to TTR information on segments of interest, can be beneficial to travelers in planning an entire trip.

Travel time reliability (TTR) has been receiving increased attention over the past few years. TTR has been listed as an important performance indicator for transportation systems, indicating whether or not transportation authorities and operators are providing service that meets the travelers' expectations. TTR may be defined at different levels on the basis of transportation researchers' and practitioners' understandings or project requirements. For example, Kittelson and Vandehey defined TTR at the facility level or at the trip level (*1*). The concept of TTR and its applications can be extended to the fields of transit operations and transit route planning. For example, Chen et al. used general transit feed specification data to estimate stop-level reliability over the transit network in Tucson, Arizona, and then a new transit trip planner was proposed by jointly applying the reliability information and a chance constrained model (*2*). Most previous studies have defined TTR at the segment level (*3–16*). However, based on the nature of travel time, TTR could be potentially defined at the origin–destination (O-D) level or at the network level. The value of knowing TTR has also been highlighted in previous research studies (*3–6*). TTR measures have been developed to provide travelers the traffic information about the few bad days they've spent in traffic, instead of an average travel time from an entire year or several years. (*7*). It has also been recommended that TTR measures be used for defining level of service on the basis of either travel speed range or travel time index range (*1*). TTR estimations usually apply appropriate TTR measures to travel time data. Many researchers have contributed by mathematically developing TTR measures [e.g., standard deviation (SD), coefficient of variation (CV), buffer index (BI), planning time index, and 90th or 95th percentile travel time] from the perspective of either traffic operations or travelers (*8–16*). Additionally, travel time collection is one of the fundamental tasks in transportation engineering, and many conventional collection approaches, such as probes, test vehicles, or license-plate matching, can be used. Because TTR estimation usually requires a large quantity of travel times (e.g., a year of travel times), those conventional approaches may be unsuitable for TTR estimation.

SEGMENT-BASED AND O-D–BASED TRAVEL TIME

Intelligent transportation systems (ITS) sensors (e.g., loop and radar-based sensors, Bluetooth-enabled sensors, Wi-Fi–enabled sensors, etc.) have been installed nationwide along roadways to collect traffic data. Many previous studies have used the data either to mathematically estimate or to simply calculate travel time by using the data. For example, travel times can be estimated by applying travel time estimation models to data from loop or radar-based sensors (*9*). Fixed-location sensors enabled by Bluetooth or Wi-Fi can collect time stamps, and then travel times can be simply calculated by using start and end time stamps (*17, 18*). Furletti et al. used mobile phone data to estimate mobility flows by estimating O-D travel time and an O-D matrix at the municipality level (*19*). By using a travel time data source, segment-based and O-D–based travel time can generally be identified. Most of the previous studies can be categorized as segment based, because travel times are estimated on segment *s* of interest where fixed location ITS sensors are available.

Using vehicles equipped with GPS-enabled devices (also known as probe vehicles) has become an increasingly popular approach for collecting travel times over the past decades (*20*). Unlike fixed-location ITS sensors, GPS-enabled devices can collect vehicle locations and

S. Yang, Room 324-1, and Y.-J. Wu, Room 324F, Department of Civil Engineering and Engineering Mechanics, College of Engineering, University of Arizona, 1209 East 2nd Street, Tucson, AZ 85721. C. An and J. Xia, Intelligent Transportation System Research Center, Southeast University, Nanjing 210096, China. Corresponding author: J. Xia, xiajingxin@seu.edu.cn.

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time stamps for entire trips. Therefore, the GPS-enabled data can be used for estimating either segment-based or O-D–based travel times regardless of the existence of fixed-location ITS sensors. However, route information may be partially unknown because of the relatively low sampling of GPS-enabled devices.

Segment-Based TTR

Most previous studies used the data collected from fixed-location ITS sensors to first estimate travel times and then estimate TTR measures (*8, 9*). Specific segments must be selected before travel times and TTR measures are estimated. Some studies have also used GPS-based data to conduct both estimations on selected segments (*16*). These TTR estimations are accordingly named segment-based TTR because travel time collection and TTR estimations are conducted after segments have been specified. Estimating segment-based TTR measures has been very popular because of the widespread installation of fixed-location ITS sensors and data availability. Additionally, traffic engineers and professionals prefer to evaluate traffic performance on segments of interest for traffic-monitoring purposes.

Few studies, however, have investigated and explored issues related to and benefits of O-D–based TTR estimations. This study, therefore, aimed to develop and uncover O-D–based TTR estimations. This paper is organized as follows: (*a*) introduction of concept of and issues related to O-D–based TTR, (*b*) proposal of appropriate methods to implement O-D–based TTR measures and to investigate issues, (*c*) description of real-world O-D–based travel times, and (*d*) discussion of findings and recommendations for future work.

O-D–Based TTR

Instead of segments, pairs of origins and destinations must be specified before both O-D–based travel times and TTR measures can be estimated. Therefore, the concept of O-D–based TTR is defined as "how reliable is your trip from an origin to a destination?" Travelers may take different routes to reach their destinations because of traffic conditions or personal preferences. Therefore, O-D–based TTR measures could be intuitively estimated in two ways: (*a*) by evaluating TTR measures for individual routes or (*b*) by evaluating non-route-specific (NRS) TTR measures. Because of the conceptual differences between segment-based and O-D–based TTR, three issues can be identified when O-D–based TTR measures are implemented:

Issue 1. How many routes do travelers usually take, and what are the TTR values associated with these routes?

Issue 2. Do statistical differences exist between route-specific and NRS TTR values?

Issue 3. How should O-D–based TTR information be delivered given that route choice preference is an additional feature for the segment-based TTR?

METHODOLOGY

The three issues noted above were addressed with different methods. Figure 1 shows a flowchart for addressing Issue 1. Assuming that T is the travel time collected for a given O-D pair and that travelers may take N routes to reach the destination so T can be divided into $T_{r1}, T_{r2}, \ldots, T_{rn}$, where T_{rn} is the travel time for taking route n. A copy of T, denoted T_{nrs}, was kept to conduct NRS TTR estimations. In data-driven TTR studies, TTR estimations usually vary with time of day, and 1 h is a popular selections for the time interval (*8, 9, 11, 13, 14, 21*). A half hour was used as the time interval in this study to enable a closer look at changes in TTR with time of day. Therefore, $T_{r1}, T_{r2}, \ldots, T_{rn}$, and T_{nrs} can be further divided into $T_{r1,\text{ti}}, T_{r2,\text{ti}}, \ldots, T_{rn,\text{ti}}$, and $T_{\text{nrs,ti}}$, where ti is the ith time interval. Three popular TTR measures were selected in this study: SD, CV, and BI (*9, 11, 13, 14, 21*). Lognormal mixture models (LMMs) were used to fit travel times and estimate travel time population, and then the three reliability measures could be estimated on the basis of the fitted LMMs. The bootstrapping technique was used to measure the accuracy of the three TTR measures (*22*). The details for the LMM and bootstrapping are provided in the following sections.

Estimation of TTR Measures

The LMM was selected to fit travel times because it has been widely used in TTR estimations (*9–11*). Equations 1 and 2 show the mathematical presentation of the LMM. The LMM consists of k lognormal distributions with parameters of means (μ) and SDs (σ). The value k must be specified before k pairs of both μ and σ are estimated. The criteria for the k selection and the parameter estimation can be found in a previous study, along with estimations for mixture-model–based means, SDs, and BIs (*9*). Equations 3 through 6 are provided below. The mixture-model–based means, SDs, and BIs are different from these three TTR measures derived from raw data (*15, 21*) or derived from estimated single probability distributions (*14*). Previous studies showed the importance of fitting travel time distributions by using mixture probability models [e.g., Guo et al. (*11*)]. Yang and Wu took one step further and comprehensively showed the mathematical presentation of mixture-model–based TTR measures and used large travel time data sets to estimate mixture-model–based TTR measures (*9*).

$$\text{lognormal}(T;\mu,\sigma)=\frac{1}{t\sigma\sqrt{2\pi}}e^{-\frac{(\ln t-\mu)^2}{2\sigma^2}} \tag{1}$$

$$\text{LMM}(T|\mu,\sigma)=\sum_{k=1}^{K}w_k\,\text{lognormal}_k(T|\mu_k,\sigma_k) \tag{2}$$

$$\mu^{(1)}=E[T]=\sum_{k=1}^{K}w_k\mu_k^{(1)} \tag{3}$$

$$\mu^{(2)}=E\left[\left(t-\mu^{(1)}\right)^2\right]=\sum_{k=1}^{K}w_k\left[\left(\mu_k^{(1)}-\mu^{(1)}\right)^2+\mu_k^{(2)}\right] \tag{4}$$

$$\frac{\sqrt{\mu^{(2)}}}{\mu^{(1)}}=\frac{\sqrt{\sum_{k=1}^{K}w_k\left[\left(\mu_k^{(1)}-\mu^{(1)}\right)^2+\mu_k^{(2)}\right]}}{\sum_{k=1}^{K}w_k\mu_k^{(1)}} \tag{5}$$

$$\text{BI}=\frac{\text{90th percentile travel time}-\mu^{(1)}}{\mu^{(1)}} \tag{6}$$

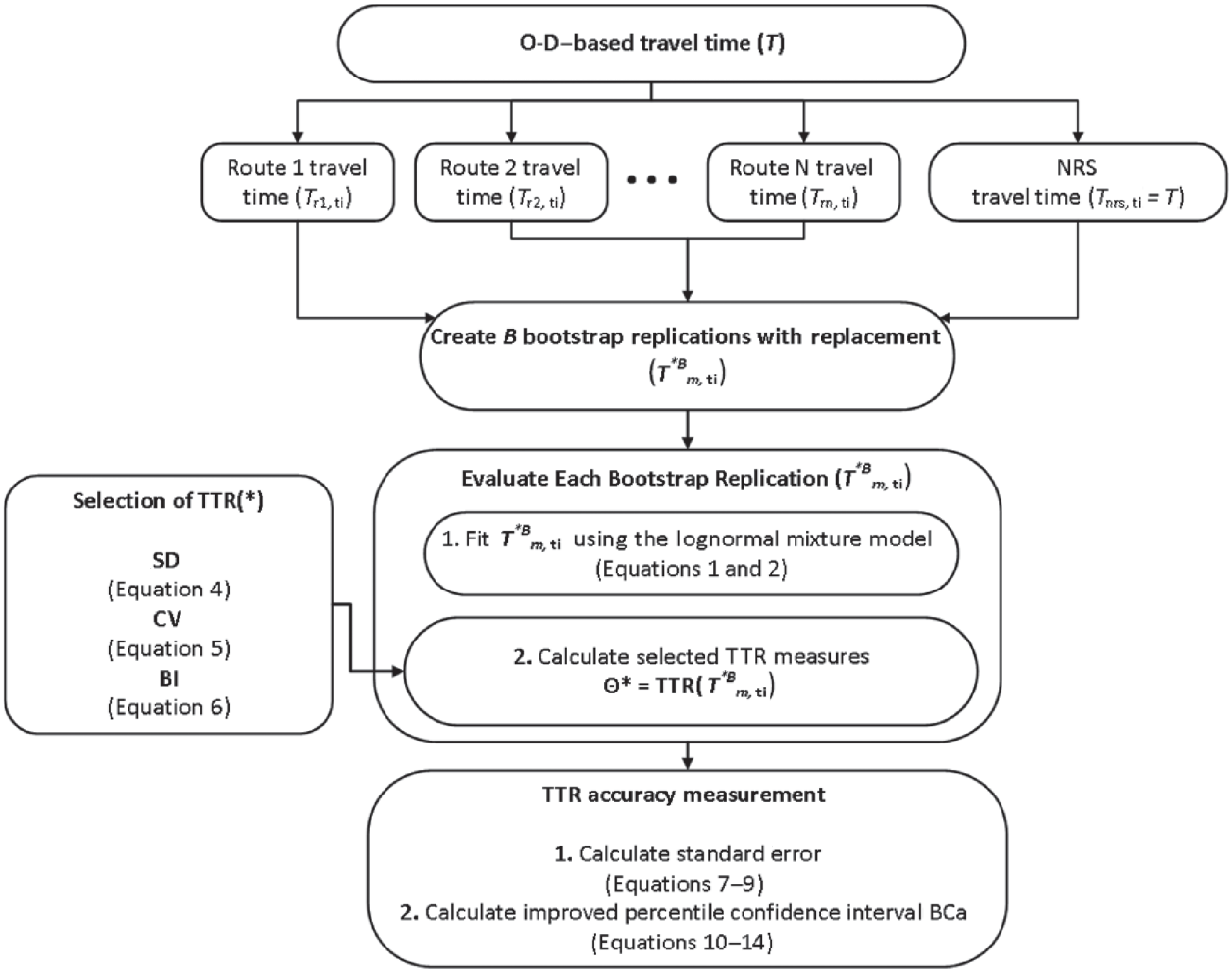


FIGURE 1 Flowchart for estimating O-D–based TTR measures.

where

$$\frac{\sqrt{\mu^{(2)}}}{\mu^{(1)}} = \text{CV}$$

K = number of individual probability distributions in mixture model;
E = expectation;
T = travel time data;
w_k = weight of kth distribution;
μ_k and σ_k = mean and SD of kth lognormal distribution, respectively;
$\mu^{(1)}$ = mean of mixture model; and
$\mu^{(2)}$ = SD of mixture model.

Measurement of TTR Accuracy

Measuring standard errors and measuring confidence intervals are two major approaches for assessing the accuracy of statistics. For example, assuming travel times (t_1, t_2, . . . , t_n) follow a Gaussian distribution with central tendency and SD (G_μ and G_σ), and the unbiased estimators for the two parameters are, respectively,

$$\frac{\sum_{i=1}^{n} t_i}{n}$$

and

$$\sqrt{\frac{(t_i - \mu)^2}{n-1}}$$

The standard error of μ is

$$\sqrt{\frac{(t_i - G_\mu)^2}{n*(n-1)}}$$

and a confidence interval (α) is approximately

$$\left(G_\mu \pm |z_{\alpha/2}| * \sqrt{\frac{(t_i - G_\mu)^2}{n*(n-1)}}\right)$$

where $z(*)$ is a standard normal distribution. The standard error and confidence intervals of G_σ can also be calculated by using conventional statistical theory. The standard errors and confidence

intervals mentioned above of a statistic (e.g., G_μ and G_σ) are derived on the basis of normality and homoscedasticity, indicating that the data should statistically follow a Gaussian distribution. However, travel times may not follow Gaussian distributions. In fact, probability mixture models have been very popular for fitting travel time distributions. Furthermore, explicit equations for measuring standard errors and confidence intervals may not exist for most statistical indicators (e.g., median, *m*th percentile, or complicated measures such as a BI) (*22*). The accuracy of the three TTR measures was measured by using bootstrapping in this study. The bootstrapping technique, which was built through intensive computing and resampling, was developed to provide a general solution for the accuracy measurement. The procedure for bootstrapping is briefly summarized below:

- For the purposes of this study, $t = T_{rn,\text{ti}}$ or $T_{\text{nrs,ti}}$.
- Bootstrap replications (t^{*1}, t^{*2}, . . . , t^{*B}) were created from t by using the resampling technique. B was the number of bootstrap replications. Individual bootstrap replication (t^*) was the same size as t. Confidence intervals were precisely estimated by experimentally selecting B to be 2,000 in this study (*22*).
- The three TTR measures were evaluated by using Equations 3 through 6 for individual bootstrap replication (t^{*i}).
- The unbiased estimation of the TTR measures was calculated by using Equations 8 and 9.
- The standard errors for the three TTR measures were calculated by using Equation 7.
- The bias-corrected and accelerated bootstrap (BCa) confidence interval was used in this study (*22*). Then, the confidence intervals for the three TTR measures were calculated by using Equations 10 through 14.

$$\text{standard error} = \sqrt{\frac{\sum\left(\text{TTR}\left(t^{*i}\right) - \bar{\theta}\right)^2}{B-1}} \tag{7}$$

$$\bar{\theta} = \frac{\sum_{i=1}^{B} \theta^{*i}}{B} \tag{8}$$

$$\theta^{*i} = \text{TTR}\left(t^{*i}\right) \tag{9}$$

where $\bar{\theta}$ is the unbiased estimator of TTR(t^{*i}). TTR(*) can be simply replaced with Equations 4, 5, or 6.

$$\text{BCa} = \left[\theta_{\%,\text{lower}}, \theta_{\%,\text{upper}}\right] = \left[\theta^{*(\alpha_1)}, \theta^{*(\alpha_2)}\right] \tag{10}$$

$$\alpha_1 = \phi\left(\hat{z}_0 + \frac{\hat{z}_0 + z^{(\alpha)}}{1 - \hat{a}\left(\hat{z}_0 + z^{(\alpha)}\right)}\right) \tag{11}$$

$$\alpha_2 = \phi\left(\hat{z}_0 + \frac{\hat{z}_0 + z^{(1-\alpha)}}{1 - \hat{a}\left(\hat{z}_0 + z^{(1-\alpha)}\right)}\right) \tag{12}$$

$$\hat{z}_0 = \phi^{-1}\left(\frac{\#\left\{\theta^* < \bar{\theta}\right\}}{B}\right) \tag{13}$$

$$\hat{a} = \frac{\sum_{i=1}^{n}\left(\bar{\theta} - \theta^{*i}\right)^3}{6\left(\sum_{i=1}^{n}\left(\bar{\theta} - \theta^{*i}\right)^2\right)^{1.5}} \tag{14}$$

where

θ^* = set (θ^{*1}, θ^{*2}, . . . , θ^{*B}),
$\theta^{*(\alpha)}$ = $(1-\alpha)$th percentile of θ^* (95th was applied in this study),
$\theta_{\%,\text{lower}}$ and $\theta_{\%,\text{upper}}$ = lower and upper bounds of confidence intervals with the $(1-\alpha)$th percentile, respectively,
$\phi(*)$ = standard normal cumulative distribution function,
$\phi^{-1}(*)$ = inverse function of standard Gaussian cumulative distribution function,
$z^{(\alpha)}$ = αth percentile of a standard Gaussian distribution, and
= number of data sets.

Statistical Differences Between NRS and Route-Specific TTR

The one-sample *t*-test is widely used to test a population mean (G_μ) against a specific value (say, G_{μ_0}). A hypothesis test is conducted and the *t* value helps to statistically reject or fail to reject the hypothesis. In fact, the *t*-test is to test whether G_{μ_0} is located within $\bar{x} \pm \alpha * s/\sqrt{n}$, where $\bar{x}$ is the average, given n samples; s is the sample SD; and α represents a confidence level. The equation $\alpha * s/\sqrt{n}$ represents the margin of errors, and $\bar{x} \pm \alpha * s/\sqrt{n}$ represents the confidence interval of $\bar{x}$. However, the underlying assumption of the *t*-test is that data should statistically follow normal distributions, indicating that the *t*-test may be unsuitable for investigating the statistical differences between NRS and route-specific TTR measures. Because confidence intervals of the three TTR measures can be calculated by using the bootstrapping technique, the flowchart shown in Figure 2 was proposed on the basis of the idea adopted from the one-sample *t*-test. If an NRS TTR measure is located within a confidence interval of Route *N* TTR measure, the conclusion would be that no statistically significant differences can be found.

STUDY DATA

As stated at the beginning of this paper, GPS-based data can provide O-D information. Therefore, this study used GPS-based data for taxicabs collected from Kunshan, China, a rapidly growing city. Approximately 1,500 daily active taxicabs provided services for almost 24 h a day and 7 days a week, covering the city and surrounding suburban areas. Every operational taxicab has a GPS enabled device, which primarily records latitude, longitude, time stamp, and occupancy status. The sampling rate hard coded in the GPS-enabled devices was approximately one sample per 30 s. Figure 3*a* shows an example of GPS-based data from a single taxicab. Seventeen samples were recorded over a period of 8 min, approximately one sample per 30 s. The occupancy status shows a complete trip with a passenger (or passengers) from 4:02:31 to 4:08:16 p.m. on December 25, 2015. The corresponding longitude and latitude information indicates the origin and destination of the trip. Detailed GPS-based data collected from December 1, 2015, to May 30, 2016, were used in this study

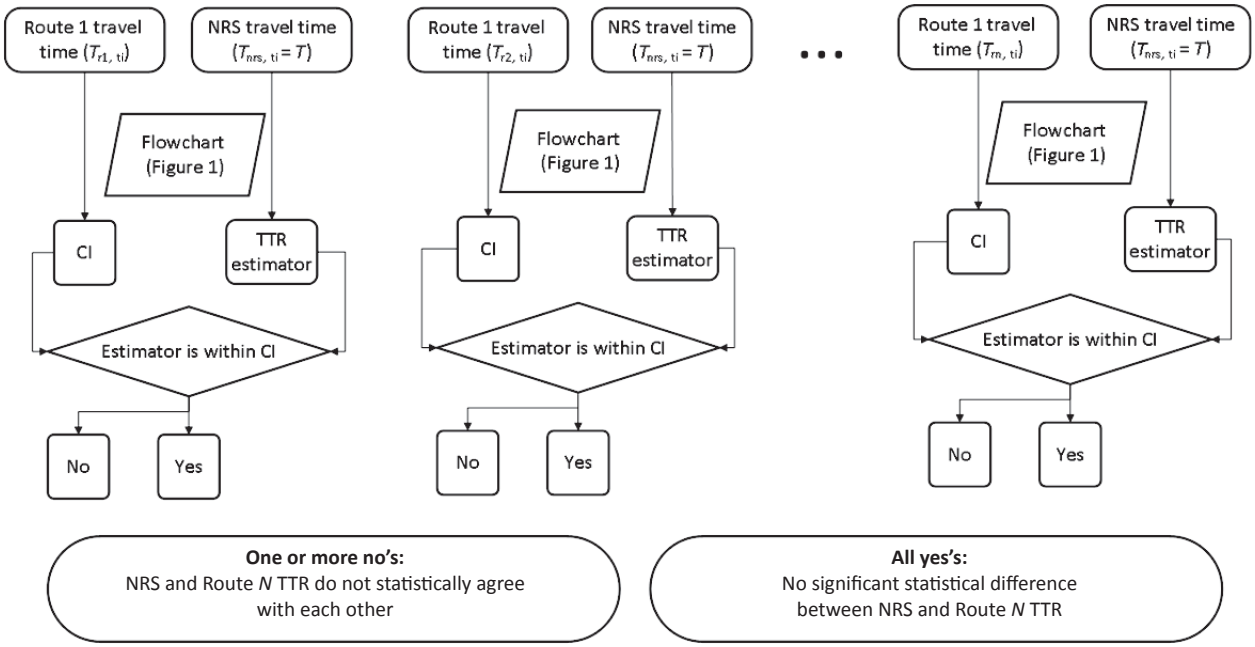
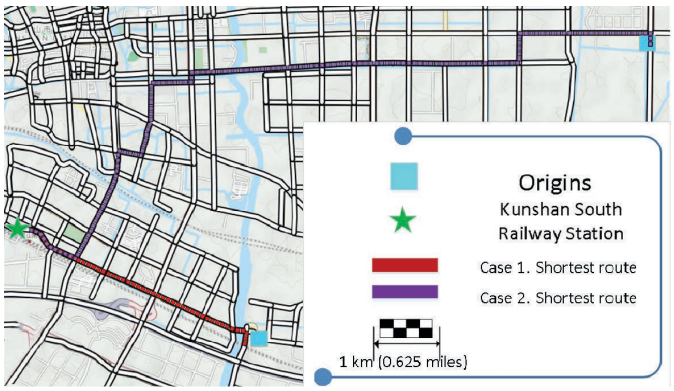


FIGURE 2 Flowchart for investigating statistical differences between NRS and route-specific TTR.

Time Stamp	Status	Longitude	Latitude
2015-12-25 16:01:15.000	0	120.9202960	31.4027000
2015-12-25 16:01:17.000	0	120.9202960	31.4027000
2015-12-25 16:01:35.000	0	120.9202960	31.4027000
2015-12-25 16:01:55.000	0	120.9202960	31.4027000
2015-12-25 16:02:15.000	0	120.9202960	31.4027000
2015-12-25 16:02:31.000	1	120.9202960	31.4027000
2015-12-25 16:03:16.000	1	120.9202960	31.4027000
2015-12-25 16:04:16.000	1	120.9202960	31.4027000
2015-12-25 16:05:15.000	1	120.9207100	31.4072990
2015-12-25 16:05:57.000	1	120.9251900	31.4068980
2015-12-25 16:06:15.000	1	120.9251900	31.4068980
2015-12-25 16:06:23.000	1	120.9251900	31.4068980
2015-12-25 16:08:16.000	1	120.9399000	31.4061000
2015-12-25 16:08:42.000	0	120.9424000	31.4060000
2015-12-25 16:08:44.000	0	120.9424000	31.4060000
2015-12-25 16:09:04.000	0	120.9424000	31.4060000
2015-12-25 16:09:24.000	0	120.9437940	31.4060000

(a)



(b)

FIGURE 3 Study data and O-D: (*a*) example of single taxicab trajectory and occupancy status and (*b*) two pairs of O-D and their shortest routes.

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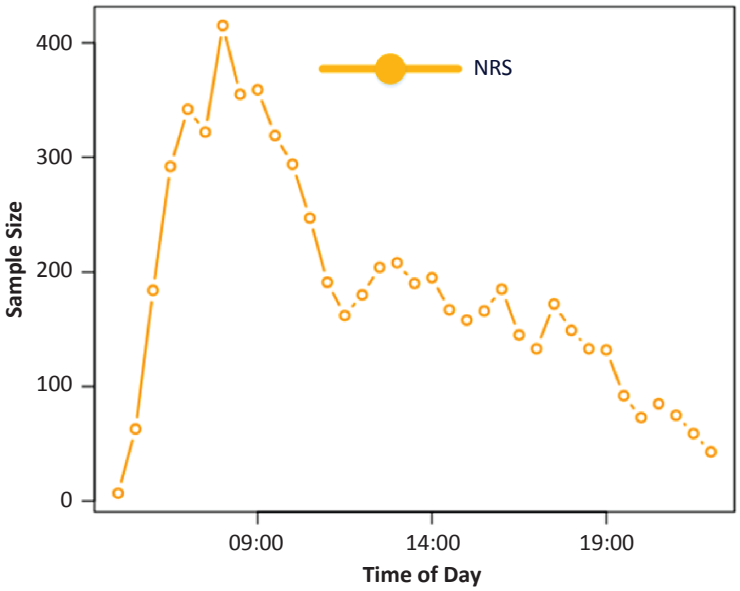
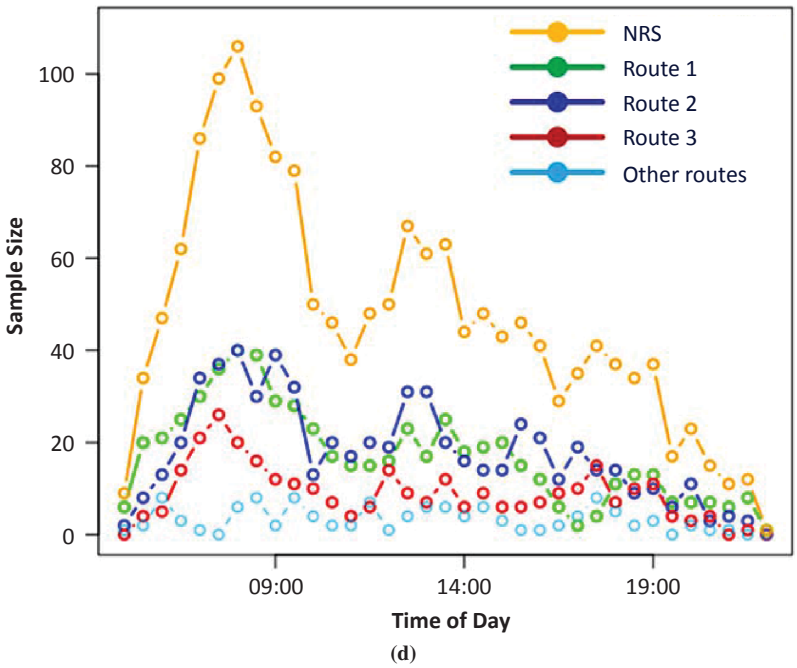


(c)



(d)

FIGURE 3 *(continued)* Study data and O-D: average number of taxicab trips for (*c*) Case 1 and (*d*) Case 2.

to conduct O-D–based TTR estimations. Approximately 10 million GPS-based records were collected per month, and around 1.6 million trips per month occurred in the Kunshan area. Trip travel times could easily be calculated by knowing the differences between start and end times.

Two origins and a destination were selected and are marked in Figure 3*b.* The destination was the Kunshan South Railway Station with a daily throughput of 15.7 thousand travelers. Taxicabs are one of the most popular ways to reach the station. A high demand for taxicabs was expected because large living communities are located in the two origins. Figure 3, *c* and *d*, shows the average number of taxicab trips by time of day. Because of the relatively low demand early in the morning and late at night, the period selected for the study was from 5:00 a.m. to 10:30 p.m. Figure 3*b* also shows the shortest paths from the two origins to the station. The shortest paths were calculated by using Dijkstra's algorithm, and the criterion in the algorithm was to look for the paths with the shortest distance. The shortest paths were 4.3 km (2.7 mi) and 13.7 km (8.5 mi) in Cases 1 and 2, respectively. The paths show preferences for route choice, because travelers may likely take the shortest paths.

RESULTS

In this section, Issue 1 is addressed by first identifying taxicab drivers' preferred routes for both cases, then by applying the flowchart in Figure 1 to the study data and, finally, by estimating the three TTR measures and the corresponding accuracy. Issue 2 is addressed by investigating statistical differences. A discussion of Issue 3 is also presented.

Preferred Routes

Microsoft SQL Server 2012 provides powerful spatial data storage and spatial query functions. This study used the tool both to transfer GPS-based data and roadway geometric information into the database and to identify trajectories based on taxicab routes by finding the nearest roadway, spatially, to a given taxicab longitude–latitude point. Then, the preferred routes were identified on the basis of the frequency of taxicab visits. Figure 4 shows the preferred routes for both cases. The specific findings are summarized as follows:

- The preferred route in Case 1, shown in Figure 4*a*, is the same as the shortest path in Figure 3*b.* This preferred route is reasonable because the origin and the destination are on the same road, and other routes very likely have detours, which might increase both traveling distance and travel time
- Three preferred routes can still be identified in Case 2:
  - Route 1, which is spatially close to the shortest path shown in Figure 3*b* with a traveling distance of 13.8 km (8.6 mi) (0.1 km longer than the shortest path). Most of the roadways in Route 1 are in an urban environment with traffic signals.
  - Route 2, which has a traveling distance (14.3 km, or 8.9 mi) that is a little longer than that of Route 1, was selected as an alternate by taxicab drivers. One of the obvious reasons for this choice is that most roadways in Route 2 were less congested than those in Route 1. Most of the roadways in Route 2 are also in an urban environment with traffic signals.
  - Route 3, which has a traveling distance of 21.1 km (13.1 mi), is approximately 50% longer than both Routes 1 and 2. However, the major roadways in Route 3 are expressways without traffic signals. Taxicab cost was determined at the time by traveling distance, so taking Route 3 would result in a cost that was approximately 50% greater than the cost for taking Routes 1 and 2. The higher cost implies that travelers might still prefer to take either Route 1 or 2.
- Any routes that differed from the three primary, preferred routes are identified as "others." Figure 3*d* shows that only a few travelers took other routes to the station.

Estimations of TTR Measures and Accuracy

Case 1. Single Preferred Route

Because a single preferred route was identified in Case 1, only the NRS TTR was measured. Figure 5, *a* through *d*, shows the average travel times, SDs, CVs, and BIs by time of day. The corresponding confidence intervals are also shown to align with those measures. Below is the summary of findings:

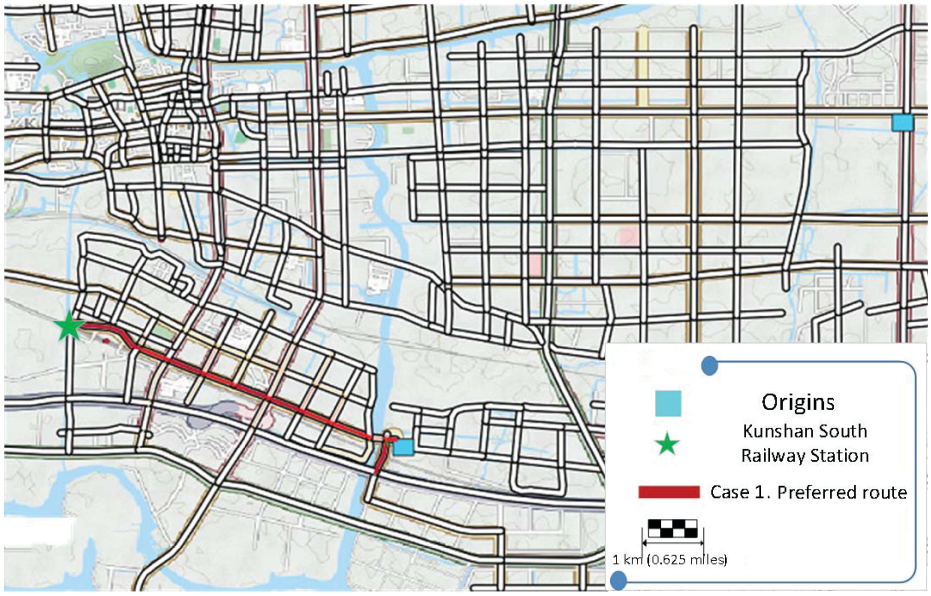
- A peak time period, around 5:00 to 6:00 p.m., can be identified. Travel times during non–peak hours were approximately 10 min, while an additional 5 min might be required to reach the station during the peak hour.
- The three TTR measures performed stably during non–peak hours, but a significant increase can be observed during the peak hour.
- The distance was 4.3 km (2.7 mi), but BIs were around 0.2 even during non–peak hours, indicating that 20% more time (i.e., 2 to 3 min) should be planned for the trip to ensure that 90% of trips arrive on time. On the basis of the authors' experience, one of the explanations for this additional time could be that a long taxicab arrival and loading queue could often be observed on the roadways approaching the station.
- The confidence intervals were close to the estimated TTR measures, suggesting that the estimated measures are statistically accurate.

Case 2. Three Preferred Routes

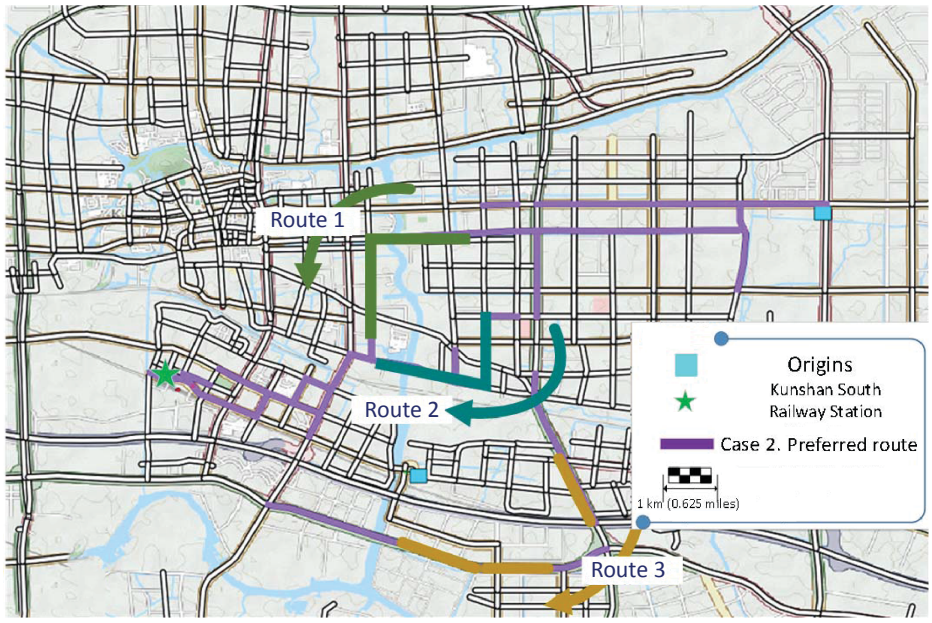
Figure 6 gives a first impression of average time-of-day travel times by the three routes, the NRS route, and other routes. Clearly, average travel times on the three routes were similar; however, travelers experienced long travel times (as much as 70 min) when they took other routes. These long travel times on other routes imply that taxicabs may have often taken detours. One explanation for this finding is that taxicabs had to pick up or drop off other passengers during trips.

Not only was a visualization of average travel times created, but the details for the TTR measures were also summarized and partially tabulated, as shown in Table 1. The complete summary for the three TTR measures by route is provided in Table A-1 in Appendix A. Specific findings are summarized below:

- Overall, no statistically significant differences were found between route-specific and NRS TTR values for most of the time periods. For example, from 5:30 to 6:00 a.m., the NRS SD, CV, and BI were located within the corresponding confidence intervals

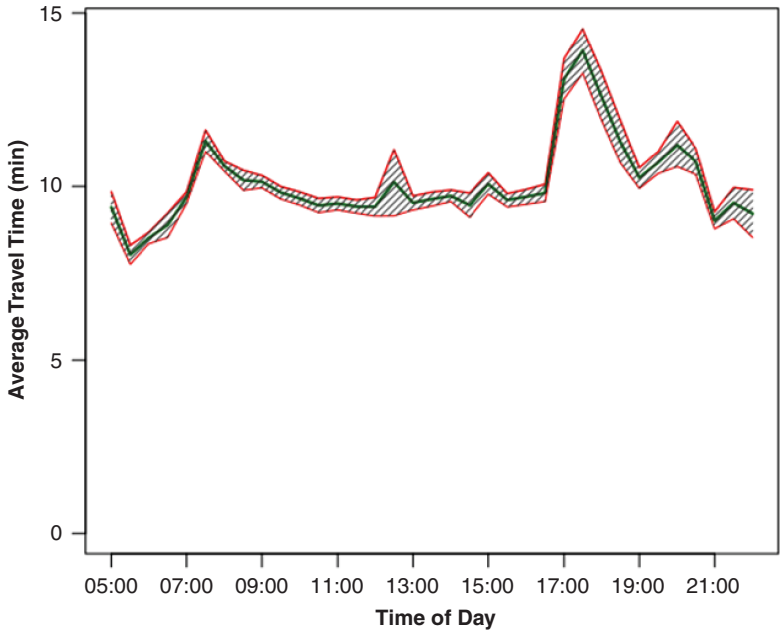


(a)

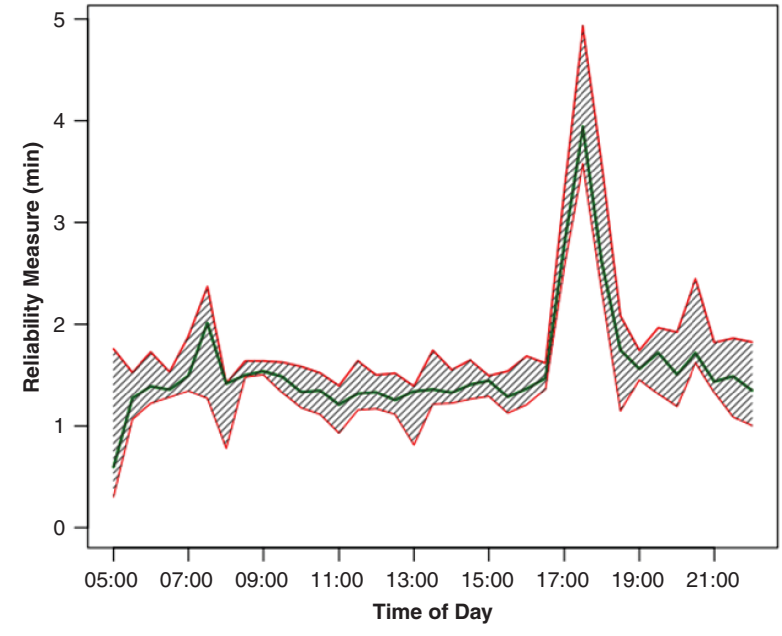


(b)

FIGURE 4 Preferred routes: (*a*) Case 1 and (*b*) Case 2.



(a)



(b)

FIGURE 5 TTR measures and corresponding 95th confidence intervals for Case 1: (*a*) average travel times and (*b*) SDs.

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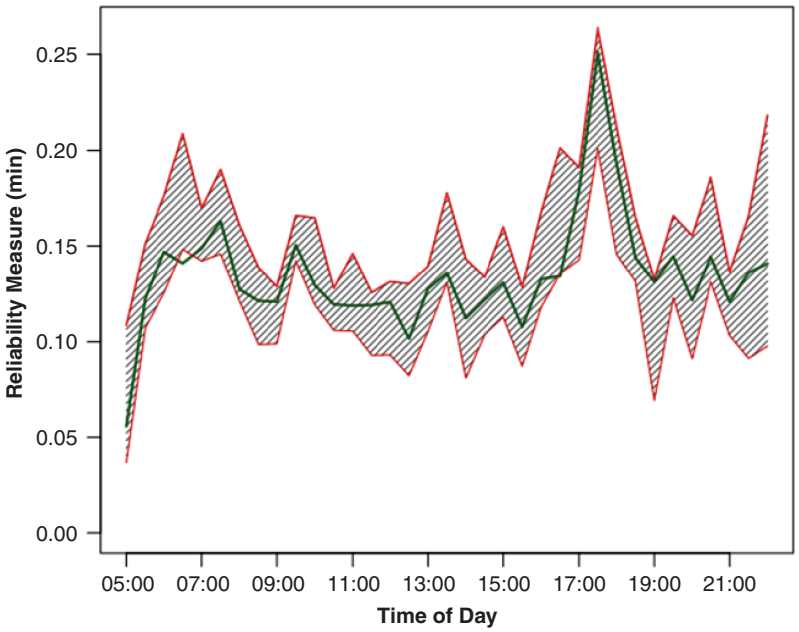
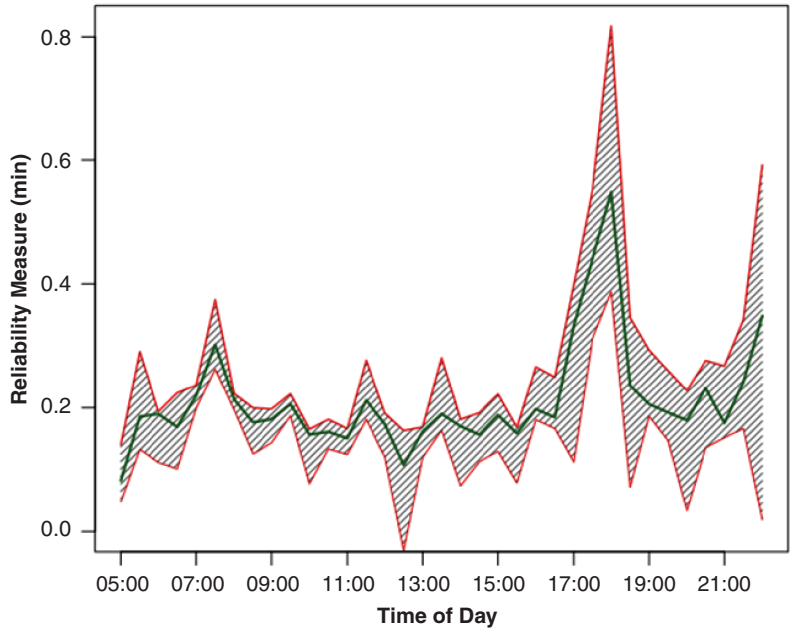


(c)



(d)

FIGURE 5 *(continued)* TTR measures and corresponding 95th confidence intervals for Case 1: (*c*) CVs, and (*d*) BIs.

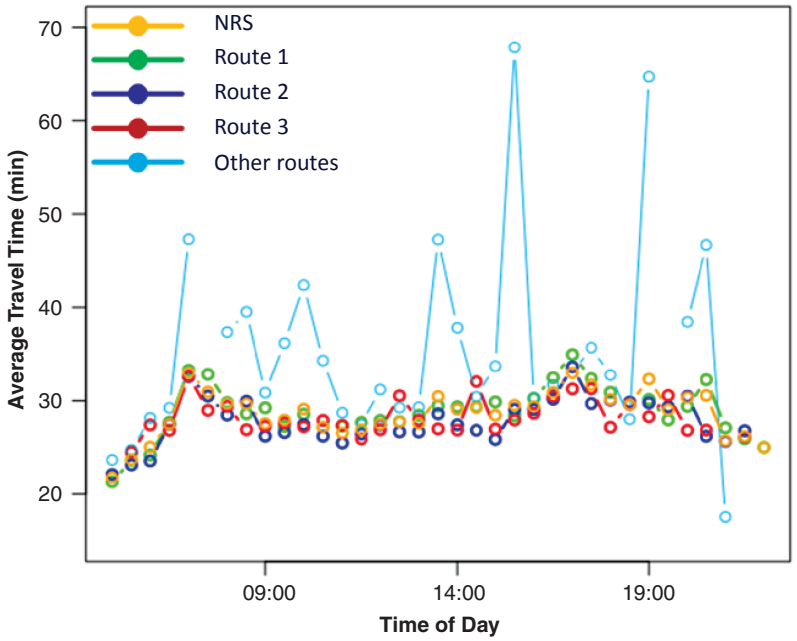


FIGURE 6 Average travel times by preferred route for Case 2.

TABLE 1 TTR Measures and Corresponding Accuracy Measures: Case 2

Route	Sample (percentage)	SD				CV				BI			
		Value (SE)	1[a]	2[b]	3[c]	Value (SE)	1[a]	2[b]	3[c]	Value (SE)	1[a]	2[b]	3[c]
5:30–6:00 a.m.													
1	20 (58.8)	2.27 (0.73)	1.10 3.51	Y	Y	0.08 (0.02)	0.05 0.13	Y	Y	0.14 (0.08)	–0.02 0.26	Y	Y
2	8 (23.5)	1.88 (0.95)	0.36 3.49	Y		0.07 (0.03)	0.07 0.16	Y		0.09 (0.03)	0.04 0.13	Y	
3	4 (11.8)	0.86 (0.68)	0.33 2.58	Y		0.03 (0.02)	0.01 0.08	Y		0.05 (0.02)	0.05 0.12	Y	
Others	2 (5.9)	1.70 (1.69)	2.29 7.86			0.03 (0.03)	0.04 0.13			0.04 (0.04)	0.05 0.17		
NRS	34 (100)	2.18 (0.59)	0.89 2.84			0.08 (0.02)	0.06 0.12			0.12 (0.04)	0.07 0.19		
6:00–6:30 a.m.													
1	21 (44.7)	2.21 (0.82)	1.33 4.03	Y	Y	0.08 (0.02)	0.02 0.10	Y	Y	0.13 (0.06)	0.03 0.21	Y	N
2	13 (27.7)	2.69 (1.41)	0.13 4.77	Y		0.11 (0.03)	0.08 0.17	Y		0.13 (0.05)	–0.02 0.16	N	
3	5 (10.6)	2.66 (1.90)	1.53 7.78	Y		0.09 (0.04)	0.06 0.20	Y		0.11 (0.04)	0.08 0.22	Y	
Others	8 (17.0)	2.47 (1.89)	–1.03 5.17			0.09 (0.06)	–0.01 0.17			0.19 (0.09)	0.08 0.38		
NRS	47 (100)	2.75 (0.93)	1.01 4.06			0.10 (0.02)	0.05 0.11			0.19 (0.04)	0.14 0.27		

(continued on next page)

TABLE 1 *(continued)* **TTR Measures and Corresponding Accuracy Measures: Case 2**

Route	Sample (percentage)	SD				CV				BI			
		Value (SE)	1[a]	2[b]	3[c]	Value (SE)	1[a]	2[b]	3[c]	Value (SE)	1[a]	2[b]	3[c]
2:00–2:30 p.m.													
1	18 (40.9)	1.68 (0.60)	0.66 2.64	N	N	0.06 (0.02)	0.01 0.08	N	N	0.06 (0.02)	0.03 0.08	N	N
2	16 (36.4)	2.12 (0.79)	1.20 3.80	Y		0.07 (0.02)	0.03 0.10	Y		0.14 (0.10)	–0.09 0.23	Y	
3	6 (13.6)	1.39 (1.20)	–1.22 2.74	N		0.05 (0.04)	–0.04 0.08	N		0.10 (0.05)	0.04 0.21	Y	
Others	4 (9.1)	3.84 (2.94)	6.27 15.95			0.09 (0.04)	0.10 0.24			0.12 (0.05)	0.13 0.29		
NRS	44 (100)	3.48 (0.55)	3.05 4.86			0.10 (0.01)	0.09 0.13			0.16 (0.08)	–0.04 0.22		
4:30–5:00 p.m.													
1	6 (20.7)	3.31 (2.25)	1.41 8.82	Y	Y	0.10 (0.05)	0.00 0.18	Y	Y	0.16 (0.07)	0.10 0.33	Y	Y
2	12 (41.4)	3.18 (1.44)	0.57 5.29	Y		0.09 (0.03)	0.04 0.14	Y		0.13 (0.05)	0.03 0.18	Y	
3	9 (31.0)	1.85 (0.87)	0.63 3.48	Y		0.05 (0.02)	0.02 0.09	Y		0.07 (0.02)	0.02 0.10	N	
Others	2 (6.9)	6.66 (6.57)	8.82 30.45			0.09 (0.09)	0.11 0.40			0.11 (0.11)	0.15 0.51		
NRS	29 (100.0)	3.30 (0.82)	1.59 4.27			0.09 (0.02)	0.07 0.14			0.16 (0.06)	–0.02 0.19		
5:00–5:30 p.m.													
1	2 (5.7)	1.53 (1.54)	2.09 7.15	Y	Y	0.02 (0.02)	0.02 0.08	N	Y	0.02 (0.02)	0.03 0.11	N	Y
2	19 (54.3)	5.03 (1.52)	4.02 9.04	Y		0.12 (0.03)	0.07 0.16	Y		0.20 (0.06)	0.15 0.34	Y	
3	10 (28.6)	2.25 (1.14)	0.93 4.69	Y		0.06 (0.02)	0.02 0.11	Y		0.09 (0.03)	0.09 0.20	Y	
Others	4 (11.4)	3.23 (2.78)	1.52 10.66			0.09 (0.05)	0.01 0.18			0.12 (0.06)	0.11 0.31		
NRS	35 (100.0)	4.13 (1.02)	2.99 6.35			0.11 (0.02)	0.08 0.15			0.19 (0.05)	0.12 0.29		
5:30–6:00 p.m.													
1	4 (9.8)	3.35 (3.47)	–1.88 9.52	Y	Y	0.10 (0.06)	0.00 0.20	Y	Y	0.15 (0.08)	0.15 0.40	Y	Y
2	14 (34.1)	3.85 (1.58)	2.55 7.74	Y		0.12 (0.06)	0.03 0.21	Y		0.18 (0.08)	–0.04 0.23	Y	
3	15 (36.6)	3.58 (1.70)	0.10 5.69	Y		0.09 (0.03)	0.05 0.13	Y		0.15 (0.06)	0.09 0.28	Y	
Others	8 (19.5)	3.58 (2.32)	–0.75 6.88			0.09 (0.05)	0.01 0.16			0.15 (0.08)	0.01 0.26		
NRS	41 (100.0)	4.29 (1.03)	3.20 6.60			0.12 (0.02)	0.07 0.15			0.21 (0.06)	0.11 0.30		

NOTE: SE = standard error; Y = yes; N = no.
[a]Corresponding 95th percentile intervals.
[b]Whether NRS TTR measures are located within specific route TTR confidence intervals.
[c]Whether statistically significant differences can be found between NRS and route TTR measures.

of the TTR measures for Routes 1, 2, and 3. This finding suggests that no statistically significant differences can be found between route-specific and NRS TTR measures, and the NRS TTR measures can serve as alternatives for route-specific TTR measures. Therefore, the effort required for estimating route-specific TTR measures could be saved.

- Significant differences can still be found in some cases. For example, from 2:00 to 2:30 p.m., the NRS TTR measures were statistically different from the route-specific TTR measures. The route-specific TTR measures were either statistically larger or smaller than the NRS TTR measures. Smaller TTR measures suggest that taking this preferred route may have advantages in terms of TTR, because the average travel times were similar (Figure 6). For example, the SDs of Routes 1 and 3 were 1.68 and 1.39, respectively, while the SD of Route 2 was 2.12. Travelers might use this information to choose Routes 1 and 3 as the most reliable routes.
- The statistically significant differences derived from the three TTR measures did not always agree with each other. For example, from 6:00 to 6:30 a.m., the SD and CV suggest the NRS TTR measures were statistically identical to route-specific TTR measures. However, the NRS BI was not located within any of the confidence intervals of the route-specific TTR measures.

Delivery of O-D–Based TTR Information

Most segment-based TTR measures may be user-friendly for traffic professionals who use these measures to monitor traffic operations on segments of interest, and TTR measures usually provide numbers only because route information is implied. However, O-D–based TTR measures could provide both numbers and route choice preferences for travelers. The two case studies primarily showed the following:

- Distance-based shortest paths can be preferred routes,
- Average travel times by preferred route may differ slightly, and
- TTR measures by preferred route may be statistically different.

Therefore, two ways of delivering O-D–based information can be adopted: (*a*) both numeric TTR values and route preferences can be jointly published and (*b*) if preferred routes cannot be identified, NRS TTR measures can alternatively represent route-specific TTR measures, and distance-based shortest paths could serve as the references for preferred routes. The two case studies showed that O-D–based TTR measures and preferred routes may naturally serve as guidance for travelers in the planning of entire trips.

CONCLUSION

TTR has been an important performance indicator for transportation systems, revealing whether or not transportation authorities and operators are providing service that meets the travelers' expectations. TTR estimations usually rely on a large quantity of travel times. Because the type of travel time can be generally categorized as either segment based or O-D based, TTR can also be categorized as segment based or O-D based. The primary difference between the two TTR estimations is that route information is implied in segment-based TTR estimations. Segment-based TTR estimations have been widely studied in previous research because of the widely available ITS sensors. However, O-D–based TTR estimations have barely been mentioned. This study defined the concept of O-D–based TTR estimations, and three issues were raised because of the primary difference between the two types of estimations, including the following: (*a*) How many routes do travelers usually take, and what are the TTR values associated with these routes? (*b*) Do statistical differences exist between route-specific and NRS TTR values? and (*c*) How should O-D–based TTR information be delivered? These three issues were addressed by proposing two flowcharts to estimate O-D–based TTR measures, measure the accuracy of O-D–based TTR measures, and investigate statistical differences between route-specific and NRS TTR measures. LMMs were used to fit O-D–based travel time, and the three TTR measures (i.e., SD, CV, and BI) were calculated on the basis of the fitted LMMs. Because of the application of the LMM, classical statistical approaches based on normality and homoscedasticity may be unsuitable for measuring the accuracy of the three TTR measures. The bootstrapping technique that is based on intensive computing was used to determine the accuracy of the TTR measures. Confidence intervals, one of the products of bootstrapping, were used to statistically investigate the differences between route-specific and NRS TTR measures. Additionally, distance-based shortest paths were calculated by using Dijkstra's algorithm, and the preferred routes were identified and visualized on the basis of the frequency of vehicles' use of those routes. Much of the GPS-based data from taxicabs provided data support for calculating O-D–based travel times, and then O-D–based TTR measures were estimated by using the proposed flowcharts. The O-D–based TTR measures showed that there were no statistically significant differences between route-specific and NRS TTR measures for most of the time periods, meaning that NRS TTR measures can alternatively represent route-specific TTR measures. Statistically significant differences can still be found in some time periods. Travelers may take advantage of these differences to choose more reliable routes. The success in addressing the first two issues led to the recommendation for Issue 3: both numeric TTR values and route preferences can be jointly published. Travelers may benefit from this recommendation for planning an entire trip instead of having TTR information for segments of interest only.

This research provided detailed insight into O-D–based TTR estimations. The general public may find that access to average travel time, TTR, and preferred routes, made possible by this research, are useful when they are planning trips. Future research could focus on automatic identification of preferred routes and development of information delivery systems that are traveler friendly, as well as discussion of other dimensions of TTR, such as demand surges, incidents, and weather.

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APPENDIX A

The complete summary of the three TTR measures by route is provided in Table A-1.

TABLE A-1 TTR Reliability Measures and Measures of Accuracy by Time of Day

Route	Sample (percentage)	SD				CV				BI			
		Value (SE)	1[a]	2[b]	3[c]	Value (SE)	1[a]	2[b]	3[c]	Value (SE)	1[a]	2[b]	3[c]
5:00–5:30 a.m.													
1	6 (66.7)	1.37 (0.97)	0.17 3.36	Y	Y	0.06 (0.03)	0.01 0.10	Y	Y	0.09 (0.03)	0.05 0.16	Y	Y
2	2 (22.2)	0.75 (0.78)	1.08 3.64	Y		0.01 (0.01)	0.02 0.07	Y		0.02 (0.02)	0.03 0.09	Y	
3	0 (0.0)	NA	NA NA			NA	NA NA			NA	NA NA		
Others	1 (11.1)	NA	NA NA			NA	NA NA			NA	NA NA		
NRS	9 (100.0)	1.78 (0.86)	0.81 3.64			0.06 (0.03)	0.04 0.13			0.09 (0.03)	0.06 0.15		
5:30–6:00 a.m.													
1	20 (58.8)	2.27 (0.73)	1.10 3.51	Y	Y	0.08 (0.02)	0.05 0.13	Y	Y	0.14 (0.08)	–0.02 0.26	Y	Y
2	8 (23.5)	1.88 (0.95)	0.36 3.49	Y		0.07 (0.03)	0.07 0.16	Y		0.09 (0.03)	0.04 0.13	Y	
3	4 (11.8)	0.86 (0.68)	0.33 2.58	Y		0.03 (0.02)	0.01 0.08	Y		0.05 (0.02)	0.05 0.12	Y	
Others	2 (5.9)	1.70 (1.69)	2.29 7.86			0.03 (0.03)	0.04 0.13			0.04 (0.04)	0.05 0.17		
NRS	34 (100.0)	2.18 (0.59)	0.89 2.84			0.08 (0.02)	0.06 0.12			0.12 (0.04)	0.07 0.19		
6:00–6:30 a.m.													
1	21 (44.7)	2.21 (0.82)	1.33 4.03	Y	Y	0.08 (0.02)	0.02 0.10	Y	Y	0.13 (0.06)	0.03 0.21	Y	
2	13 (27.7)	2.69 (1.41)	0.13 4.77	Y		0.11 (0.03)	0.08 0.17	Y		0.13 (0.05)	–0.02 0.16	N	
3	5 (10.6)	2.66 (1.90)	1.53 7.78	Y		0.09 (0.04)	0.06 0.20	Y		0.11 (0.04)	0.08 0.22	Y	
Others	8 (17.0)	2.47 (1.89)	–1.03 5.17	Y		0.09 (0.06)	–0.01 0.17			0.19 (0.09)	0.08 0.38		
NRS	47 (100.0)	2.75 (0.93)	1.01 4.06			0.10 (0.02)	0.05 0.11			0.19 (0.04)	0.14 0.27		
6:30–7:00 a.m.													
1	25 (40.3)	4.09 (1.51)	2.17 7.14	Y	Y	0.12 (0.03)	0.11 0.22	Y	Y	0.16 (0.03)	0.09 0.20	Y	Y
2	20 (32.3)	2.23 (0.98)	0.58 3.81	Y		0.08 (0.03)	0.03 0.12	Y		0.16 (0.05)	0.03 0.20	Y	
3	14 (22.6)	2.55 (1.27)	2.48 6.65	Y		0.09 (0.03)	0.02 0.13	Y		0.20 (0.17)	–0.32 0.24	Y	
Others	3 (4.8)	0.03 (0.05)	0.14 0.30			0.01 (0.01)	0.01 0.04			0.02 (0.01)	0.01 0.04		
NRS	62 (100.0)	3.47 (0.68)	2.46 4.69			0.11 (0.02)	0.09 0.14			0.16 (0.03)	0.10 0.21		
7:00–7:30 a.m.													
1	30 (34.9)	4.99 (1.06)	3.92 7.40	Y	N	0.13 (0.03)	0.08 0.17	Y	Y	0.18 (0.04)	0.09 0.23	Y	Y
2	34 (39.5)	4.01 (0.82)	2.57 5.27	Y		0.11 (0.02)	0.08 0.16	Y		0.15 (0.09)	–0.04 0.24	Y	
3	21 (24.4)	2.85 (0.97)	0.78 3.98	N		0.08 (0.03)	0.03 0.13	Y		0.19 (0.34)	–0.62 0.49	Y	
Others	1 (1.2)	NA	NA NA			NA	NA NA			NA	NA NA		
NRS	86 (100.0)	4.81 (0.64)	3.67 5.79			0.13 (0.01)	0.09 0.13			0.18 (0.04)	0.08 0.22		

(continued)

TABLE A-1 *(continued)* **TTR Reliability Measures and Measures of Accuracy by Time of Day**

Route	Sample (percentage)	SD				CV				BI			
		Value (SE)	1[a]	2[b]	3[c]	Value (SE)	1[a]	2[b]	3[c]	Value (SE)	1[a]	2[b]	3[c]
7:30–8:00 a.m.													
1	36 (36.4)	4.60 (1.17)	3.06 6.91	Y	Y	0.13 (0.03)	0.11 0.19	Y	Y	0.18 (0.05)	0.08 0.24	Y	N
2	37 (37.4)	3.38 (0.70)	2.04 4.35	Y		0.09 (0.02)	0.08 0.13	Y		0.16 (0.03)	0.15 0.25	Y	
3	26 (26.3)	3.25 (0.94)	2.50 5.58	Y		0.11 (0.02)	0.09 0.17	Y		0.11 (0.03)	0.05 0.14	N	
Others	0 (0.0)	NA	NA NA			NA	NA NA			NA	NA NA		
NRS	99 (100.0)	4.06 (0.55)	3.64 5.45			0.11 (0.01)	0.08 0.12			0.18 (0.02)	0.14 0.20		
8:00–8:30 a.m.													
1	40 (37.7)	3.13 (0.62)	1.96 3.99	Y	Y	0.10 (0.02)	0.07 0.15	Y	Y	0.12 (0.02)	0.06 0.16	Y	Y
2	40 (37.7)	2.76 (0.68)	2.06 4.29	Y		0.08 (0.02)	0.04 0.10	Y		0.15 (0.03)	0.10 0.22	Y	
3	20 (18.9)	3.34 (1.14)	1.06 4.81	Y		0.09 (0.03)	0.02 0.12	Y		0.18 (0.05)	0.12 0.29	Y	
Others	6 (5.7)	4.71 (4.40)	10.32 24.78			0.16 (0.07)	0.13 0.36			0.21 (0.07)	0.15 0.40		
NRS	106 (100.0)	3.38 (0.56)	2.29 4.13			0.10 (0.01)	0.08 0.13			0.16 (0.02)	0.15 0.23		
8:30–9:00 a.m.													
1	39 (41.9)	3.01 (0.68)	2.63 4.88	Y	Y	0.09 (0.02)	0.06 0.11	Y	Y	0.12 (0.02)	0.08 0.14	Y	Y
2	30 (32.3)	2.73 (0.88)	1.29 4.17	Y		0.09 (0.03)	0.04 0.12	Y		0.18 (0.16)	–0.25 0.27	Y	
3	16 (17.2)	3.11 (1.09)	1.26 4.83	Y		0.10 (0.03)	0.07 0.16	Y		0.15 (0.05)	0.07 0.22	Y	
Others	8 (8.6)	7.32 (6.98)	–7.92 15.03			0.22 (0.13)	–0.02 0.40			0.49 (0.24)	0.21 1.00		
NRS	93 (100.0)	3.13 (0.48)	2.25 3.84			0.10 (0.01)	0.10 0.14			0.12 (0.05)	0.00 0.16		
9:00–9:30 a.m.													
1	29 (35.4)	2.90 (0.72)	1.99 4.36	Y	Y	0.08 (0.02)	0.04 0.11	Y	Y	0.15 (0.04)	0.07 0.20	Y	Y
2	39 (47.6)	2.65 (0.66)	1.60 3.77	Y		0.09 (0.02)	0.06 0.11	Y		0.13 (0.02)	0.11 0.16	Y	
3	12 (14.6)	2.78 (1.00)	1.65 4.94	Y		0.08 (0.02)	0.05 0.12	Y		0.12 (0.04)	0.06 0.20	Y	
Others	2 (2.4)	0.02 (0.02)	0.03 0.09			NA	NA NA			NA	NA NA		
NRS	82 (100.0)	3.21 (0.37)	3.03 4.24			0.09 (0.01)	0.08 0.11			0.14 (0.02)	0.08 0.15		
9:30–10:00 a.m.													
1	28 (35.4)	2.03 (0.54)	0.90 2.66	Y	Y	0.06 (0.01)	0.04 0.08	Y	Y	0.11 (0.05)	0.03 0.18	Y	Y
2	32 (40.5)	2.68 (0.48)	2.33 3.92	Y		0.08 (0.01)	0.06 0.10	Y		0.13 (0.06)	0.01 0.21	Y	
3	11 (13.9)	1.71 (0.85)	0.55 3.35	Y		0.06 (0.02)	0.01 0.09	Y		0.07 (0.02)	0.05 0.12	Y	
Others	8 (10.1)	6.08 (5.57)	–4.91 13.41			0.20 (0.12)	–0.02 0.36			0.42 (0.19)	0.41 1.03		
NRS	79 (100.0)	2.49 (0.43)	1.65 3.05			0.08 (0.01)	0.08 0.11			0.11 (0.04)	0.03 0.17		

(continued on next page)

TABLE A-1 *(continued)* **TTR Reliability Measures and Measures of Accuracy by Time of Day**

Route	Sample (percentage)	SD				CV				BI			
		Value (SE)	1[a]	2[b]	3[c]	Value (SE)	1[a]	2[b]	3[c]	Value (SE)	1[a]	2[b]	3[c]
10:00–10:30 a.m.													
1	23 (46.0)	2.57 (0.84)	1.04 3.80	Y	Y	0.08 (0.02)	0.04 0.11	Y	Y	0.13 (0.03)	0.06 0.17	Y	Y
2	13 (26.0)	2.99 (1.33)	2.18 6.56	Y		0.10 (0.03)	0.04 0.15	Y		0.14 (0.08)	–0.09 0.17	Y	
3	10 (20.0)	2.38 (0.97)	1.87 5.07	Y		0.08 (0.02)	0.06 0.13	Y		0.09 (0.03)	0.07 0.15	Y	
Others	4 (8.0)	12.37 (12.18)	–7.51 32.58			0.27 (0.13)	0.11 0.56			0.39 (0.20)	0.44 1.09		
NRS	50 (100.0)	3.05 (0.72)	0.67 3.03			0.10 (0.02)	0.06 0.12			0.13 (0.04)	0.01 0.16		
10:30–11:00 a.m.													
1	17 (37.0)	2.79 (1.17)	1.96 5.80	Y	Y	0.08 (0.02)	0.03 0.11	Y	Y	0.12 (0.04)	0.06 0.18	Y	Y
2	20 (43.5)	2.48 (0.81)	0.72 3.38	Y		0.08 (0.03)	0.02 0.11	Y		0.12 (0.04)	0.03 0.19	Y	
3	7 (15.2)	3.10 (1.87)	0.58 6.75	Y		0.10 (0.04)	0.07 0.21	Y		0.16 (0.05)	0.14 0.31	Y	
Others	2 (4.3)	0.99 (0.98)	1.31 4.52			0.01 (0.01)	0.02 0.05			0.02 (0.02)	0.02 0.07		
NRS	46 (100.0)	3.10 (0.61)	2.30 4.30			0.09 (0.02)	0.07 0.13			0.18 (0.03)	0.15 0.26		
11:00–11:30 a.m.													
1	15 (39.5)	2.71 (0.85)	1.57 4.37	Y	Y	0.08 (0.02)	0.05 0.12	Y	Y	0.12 (0.02)	0.10 0.17	Y	Y
2	17 (44.7)	2.25 (1.04)	2.32 5.73	Y		0.07 (0.02)	0.06 0.11	Y		0.11 (0.08)	–0.12 0.14	Y	
3	4 (10.5)	1.17 (0.81)	1.45 4.12	Y		0.04 (0.02)	0.03 0.09	Y		0.05 (0.02)	0.05 0.15	Y	
Others	2 (5.3)	1.51 (1.51)	2.05 7.03			0.02 (0.02)	0.03 0.10			0.03 (0.03)	0.04 0.13		
NRS	38 (100.0)	2.76 (0.65)	2.17 4.32			0.08 (0.02)	0.04 0.10			0.14 (0.02)	0.13 0.21		
11:30 a.m.–12:00 p.m.													
1	15 (31.3)	2.93 (1.07)	2.40 6.13	Y	Y	0.09 (0.02)	0.07 0.15	Y	Y	0.14 (0.04)	0.06 0.20	Y	Y
2	20 (41.7)	2.70 (0.87)	1.57 4.44	Y		0.08 (0.02)	0.02 0.11	Y		0.13 (0.03)	0.11 0.22	Y	
3	6 (12.5)	1.40 (0.97)	–0.35 2.83	Y		0.05 (0.02)	0.00 0.08	Y		0.07 (0.03)	0.04 0.12	N	
Others	7 (14.6)	1.48 (1.23)	–0.83 3.21			0.05 (0.03)	–0.02 0.07			0.09 (0.04)	0.02 0.17		
NRS	48 (100.0)	2.49 (0.62)	1.83 3.86			0.08 (0.02)	0.05 0.10			0.14 (0.02)	0.12 0.18		
12:00–12:30 p.m.													
1	16 (32.0)	4.72 (1.30)	4.04 8.32	N	N	0.14 (0.03)	0.11 0.21	N	N	0.19 (0.04)	0.14 0.27	Y	N
2	19 (38.0)	2.55 (0.80)	1.47 4.10	Y		0.08 (0.02)	0.05 0.11	Y		0.13 (0.10)	–0.11 0.22	Y	
3	14 (28.0)	1.50 (0.54)	0.31 2.08	N		0.05 (0.01)	0.04 0.08	N		0.07 (0.03)	0.01 0.11	N	
Others	1 (2.0)	NA	NA NA			NA	NA NA			NA	NA NA		
NRS	50 (100.0)	2.74 (0.55)	1.70 3.50			0.09 (0.02)	0.03 0.09			0.15 (0.03)	0.08 0.18		

(continued)

TABLE A-1 *(continued)* **TTR Reliability Measures and Measures of Accuracy by Time of Day**

Route	Sample (percentage)	SD				CV				BI			
		Value (SE)	1[a]	2[b]	3[c]	Value (SE)	1[a]	2[b]	3[c]	Value (SE)	1[a]	2[b]	3[c]
12:30–1:00 p.m.													
1	23 (34.3)	3.47 (0.88)	2.89 5.83	Y	N	0.10 (0.02)	0.08 0.14	Y	Y	0.14 (0.03)	0.11 0.20	Y	Y
2	31 (46.3)	1.70 (0.53)	0.59 2.33	N		0.06 (0.02)	0.05 0.10	Y		0.11 (0.04)	0.07 0.19	Y	
3	9 (13.4)	3.67 (1.88)	1.73 7.93	Y		0.10 (0.05)	0.03 0.18	Y		0.19 (0.10)	–0.01 0.33	Y	
Others	4 (6.0)	2.83 (2.36)	0.75 8.52			0.09 (0.05)	0.03 0.19			0.13 (0.06)	0.13 0.32		
NRS	67 (100.0)	2.90 (0.57)	2.10 3.96			0.09 (0.01)	0.07 0.12			0.15 (0.02)	0.12 0.19		
1:00–1:30 p.m.													
1	17 (27.9)	1.90 (0.91)	–0.43 2.96	Y	Y	0.06 (0.02)	0.03 0.11	Y	Y	0.14 (0.08)	–0.05 0.21	Y	Y
2	31 (50.8)	2.50 (0.63)	2.20 4.26	Y		0.08 (0.02)	0.05 0.10	Y		0.13 (0.02)	0.09 0.16	Y	
3	7 (11.5)	2.36 (1.41)	0.56 5.21	Y		0.07 (0.03)	0.06 0.16	Y		0.09 (0.03)	0.05 0.15	Y	
Others	6 (9.8)	3.39 (2.27)	–0.39 7.09			0.10 (0.05)	0.00 0.17			0.14 (0.05)	0.11 0.28		
NRS	61 (100.0)	2.87 (0.51)	2.17 3.84			0.09 (0.01)	0.07 0.12			0.13 (0.02)	0.07 0.15		
1:30–2:00 p.m.													
1	25 (39.7)	2.78 (0.80)	1.64 4.26	Y	Y	0.08 (0.02)	0.05 0.10	Y	Y	0.13 (0.06)	0.02 0.21	Y	Y
2	20 (31.7)	2.22 (1.15)	0.05 3.82	Y		0.07 (0.03)	0.01 0.10	Y		0.16 (0.11)	–0.08 0.29	Y	
3	12 (19.0)	2.31 (1.01)	1.46 4.80	Y		0.08 (0.02)	0.04 0.12	Y		0.12 (0.03)	0.09 0.21	Y	
Others	6 (9.5)	7.16 (15.42)	–23.84 26.87			0.21 (0.23)	–0.36 0.38			0.60 (0.37)	0.37 1.57		
NRS	63 (100.0)	3.28 (0.49)	3.18 4.78			0.09 (0.01)	0.09 0.13			0.11 (0.07)	–0.02 0.19		
2:00–2:30 p.m.													
1	18 (40.9)	1.68 (0.60)	0.66 2.64	N	N	0.06 (0.02)	0.01 0.08	N	N	0.06 (0.02)	0.03 0.08	N	N
2	16 (36.4)	2.12 (0.79)	1.20 3.80	Y		0.07 (0.02)	0.03 0.10	Y		0.14 (0.10)	–0.09 0.23	Y	
3	6 (13.6)	1.39 (1.20)	–1.22 2.74	N		0.05 (0.04)	–0.04 0.08	N		0.10 (0.05)	0.04 0.21	Y	
Others	4 (9.1)	3.84 (2.94)	6.27 15.95			0.09 (0.04)	0.10 0.24			0.12 (0.05)	0.13 0.29		
NRS	44 (100.0)	3.48 (0.55)	3.05 4.86			0.10 (0.01)	0.09 0.13			0.16 (0.08)	–0.04 0.22		
2:30–3:00 p.m.													
1	19 (39.6)	4.68 (1.33)	3.02 7.39	Y	N	0.13 (0.03)	0.10 0.19	Y	N	0.19 (0.04)	0.12 0.26	Y	N
2	14 (29.2)	2.35 (0.95)	0.49 3.61	N		0.07 (0.02)	0.04 0.11	N		0.12 (0.04)	0.11 0.23	N	
3	9 (18.8)	5.37 (3.88)	–2.27 10.50	Y		0.16 (0.09)	–0.03 0.25	Y		0.32 (0.13)	0.33 0.75	Y	
Others	6 (12.5)	4.62 (3.83)	–1.18 11.41			0.16 (0.08)	0.10 0.38			0.26 (0.09)	0.30 0.59		
NRS	48 (100.0)	4.00 (0.88)	2.43 5.33			0.13 (0.02)	0.10 0.17			0.26 (0.08)	0.10 0.36		

(continued on next page)

TABLE A-1 *(continued)* **TTR Reliability Measures and Measures of Accuracy by Time of Day**

Route	Sample (percentage)	SD				CV				BI			
		Value (SE)	1[a]	2[b]	3[c]	Value (SE)	1[a]	2[b]	3[c]	Value (SE)	1[a]	2[b]	3[c]
3:00–3:30 p.m.													
1	20 (46.5)	2.57 (0.75)	1.71 4.18	Y	N	0.07 (0.02)	0.04 0.10	Y	N	0.14 (0.07)	0.02 0.25	Y	Y
2	14 (32.6)	1.13 (0.64)	0.53 2.65	N		0.04 (0.02)	0.00 0.08	N		0.11 (0.09)	–0.08 0.20	Y	
3	6 (14.0)	1.38 (1.15)	–0.26 3.53	Y		0.05 (0.03)	0.01 0.11	Y		0.09 (0.04)	0.09 0.20	Y	
Others	3 (7.0)	0.38 (0.70)	1.78 4.08			0.04 (0.02)	0.03 0.11			0.06 (0.04)	0.07 0.19		
NRS	43 (100.0)	3.47 (0.78)	2.65 5.23			0.10 (0.02)	0.08 0.13			0.17 (0.04)	0.11 0.25		
3:30–4:00 p.m.													
1	15 (32.6)	2.23 (0.99)	1.62 4.89	Y	Y	0.06 (0.02)	0.03 0.09	Y	Y	0.12 (0.04)	0.08 0.21	Y	Y
2	24 (52.2)	2.46 (0.90)	0.83 3.79	Y		0.08 (0.02)	0.03 0.11	Y		0.21 (0.12)	–0.09 0.30	Y	
3	6 (13.0)	1.40 (1.47)	–2.36 2.48	Y		0.05 (0.04)	–0.06 0.07	Y		0.10 (0.05)	0.03 0.20	Y	
Others	1 (2.2)	NA	NA NA			NA	NA NA			NA	NA NA		
NRS	46 (100.0)	2.40 (0.56)	2.02 3.85			0.07 (0.02)	0.04 0.10			0.17 (0.09)	–0.01 0.27		
4:00–4:30 p.m.													
1	12 (29.3)	2.59 (1.13)	0.43 4.17	Y	Y	0.07 (0.03)	0.01 0.11	Y	Y	0.15 (0.12)	–0.13 0.26	Y	Y
2	21 (51.2)	3.48 (0.84)	2.70 5.47	Y		0.10 (0.02)	0.08 0.15	Y		0.14 (0.06)	0.04 0.22	Y	
3	7 (17.1)	2.28 (1.61)	0.15 5.46	Y		0.12 (0.06)	0.10 0.31	Y		0.12 (0.05)	0.04 0.22	Y	
Others	1 (2.4)	NA	NA NA			NA	NA NA			NA	NA NA		
NRS	41 (100.0)	3.27 (0.67)	2.31 4.51			0.10 (0.02)	0.06 0.12			0.13 (0.04)	0.04 0.18		
4:30–5:00 p.m.													
1	6 (20.7)	3.31 (2.25)	1.41 8.82	Y	Y	0.10 (0.05)	0.00 0.18	Y	Y	0.16 (0.07)	0.10 0.33	Y	Y
2	12 (41.4)	3.18 (1.44)	0.57 5.29	Y		0.09 (0.03)	0.04 0.14	Y		0.13 (0.05)	0.03 0.18	Y	
3	9 (31.0)	1.85 (0.87)	0.63 3.48	Y		0.05 (0.02)	0.02 0.09	Y		0.07 (0.02)	0.02 0.10	N	
Others	2 (6.9)	6.66 (6.57)	8.82 30.45			0.09 (0.09)	0.11 0.40			0.11 (0.11)	0.15 0.51		
NRS	29 (100.0)	3.30 (0.82)	1.59 4.27			0.09 (0.02)	0.07 0.14			0.16 (0.06)	–0.02 0.19		
5:00–5:30 p.m.													
1	2 (5.7)	1.53 (1.54)	2.09 7.15	Y	Y	0.02 (0.02)	0.02 0.08	N	Y	0.02 (0.02)	0.03 0.11	N	Y
2	19 (54.3)	5.03 (1.52)	4.02 9.04	Y		0.12 (0.03)	0.07 0.16	Y		0.20 (0.06)	0.15 0.34	Y	
3	10 (28.6)	2.25 (1.14)	0.93 4.69	Y		0.06 (0.02)	0.02 0.11	Y		0.09 (0.03)	0.09 0.20	Y	
Others	4 (11.4)	3.23 (2.78)	1.52 10.66			0.09 (0.05)	0.01 0.18			0.12 (0.06)	0.11 0.31		
NRS	35 (100.0)	4.13 (1.02)	2.99 6.35			0.11 (0.02)	0.08 0.15			0.19 (0.05)	0.12 0.29		

(continued)

TABLE A-1 *(continued)* **TTR Reliability Measures and Measures of Accuracy by Time of Day**

Route	Sample (percentage)	SD				CV				BI			
		Value (SE)	1[a]	2[b]	3[c]	Value (SE)	1[a]	2[b]	3[c]	Value (SE)	1[a]	2[b]	3[c]
5:30–6:00 p.m.													
1	4	3.35	−1.88	Y	Y	0.10	0.00	Y	Y	0.15	0.15	Y	Y
	(9.8)	(3.47)	9.52			(0.06)	0.20			(0.08)	0.40		
2	14	3.85	2.55	Y		0.12	0.03	Y		0.18	−0.04	Y	
	(34.1)	(1.58)	7.74			(0.06)	0.21			(0.08)	0.23		
3	15	3.58	0.10	Y		0.09	0.05	Y		0.15	0.09	Y	
	(36.6)	(1.70)	5.69			(0.03)	0.13			(0.06)	0.28		
Others	8	3.58	−0.75			0.09	0.01			0.15	0.01		
	(19.5)	(2.32)	6.88			(0.05)	0.16			(0.08)	0.26		
NRS	41	4.29	3.20			0.12	0.07			0.21	0.11		
	(100.0)	(1.03)	6.60			(0.02)	0.15			(0.06)	0.30		
6:00–6:30 p.m.													
1	11	3.60	2.25	Y	Y	0.10	0.07	Y	Y	0.13	0.07	Y	Y
	(29.7)	(1.50)	7.17			(0.03)	0.17			(0.04)	0.20		
2	14	3.96	1.78	Y		0.12	0.10	Y		0.16	−0.05	Y	
	(37.8)	(1.41)	6.42			(0.03)	0.19			(0.08)	0.20		
3	7	2.92	3.33	Y		0.09	0.06	Y		0.14	0.14	Y	
	(18.9)	(1.85)	9.41			(0.04)	0.18			(0.04)	0.28		
Others	5	2.62	−6.92			0.09	−0.08			0.14	0.09		
	(13.5)	(4.21)	6.91			(0.06)	0.14			(0.07)	0.31		
NRS	37	4.22	3.07			0.13	0.12			0.17	0.01		
	(100.0)	(0.94)	6.17			(0.01)	0.17			(0.06)	0.21		
6:30–7:00 p.m.													
1	13	3.32	2.96	Y	Y	0.10	0.05	Y	Y	0.17	0.13	Y	Y
	(38.2)	(1.38)	7.49			(0.04)	0.18			(0.04)	0.28		
2	9	3.46	4.34	N		0.11	0.06	Y		0.13	0.13	Y	
	(26.5)	(2.23)	11.68			(0.04)	0.19			(0.04)	0.26		
3	10	3.29	3.14	Y		0.10	0.05	Y		0.18	−0.14	Y	
	(29.4)	(1.67)	8.62			(0.04)	0.19			(0.12)	0.25		
Others	2	0.49	0.68			0.01	0.01			0.01	0.01		
	(5.9)	(0.50)	2.33			(0.01)	0.03			(0.01)	0.04		
NRS	34	3.90	3.06			0.11	0.07			0.18	0.13		
	(100.0)	(0.88)	5.95			(0.02)	0.14			(0.04)	0.26		
7:00–7:30 p.m.													
1	13	3.79	2.80	Y	Y	0.10	0.06	Y	Y	0.15	0.09	Y	Y
	(35.1)	(1.49)	7.71			(0.03)	0.15			(0.05)	0.24		
2	10	3.01	1.46	Y		0.09	0.00	Y		0.19	0.04	Y	
	(27.0)	(1.67)	6.94			(0.05)	0.15			(0.11)	0.39		
3	11	2.24	0.65	Y		0.08	−0.02	Y		0.16	0.14	Y	
	(29.7)	(1.24)	4.75			(0.04)	0.12			(0.08)	0.42		
Others	3	1.56	7.94			0.24	0.25			0.35	0.45		
	(8.1)	(2.96)	17.70			(0.16)	0.77			(0.25)	1.27		
NRS	37	4.27	2.54			0.12	0.10			0.17	−0.17		
	(100.0)	(1.06)	6.01			(0.03)	0.18			(0.16)	0.36		
7:30–8:00 p.m.													
1	7	2.92	2.79	Y	Y	0.09	0.08	Y	Y	0.12	0.10	Y	Y
	(41.2)	(1.69)	8.36			(0.03)	0.19			(0.04)	0.21		
2	6	2.32	1.15	Y		0.08	0.00	Y		0.14	0.10	Y	
	(35.3)	(1.70)	6.72			(0.05)	0.15			(0.06)	0.29		
3	4	0.71	0.70	N		0.02	0.01	N		0.03	0.02	N	
	(3.5)	(0.49)	2.32			(0.01)	0.05			(0.01)	0.06		
Others	0	NA	NA			NA	NA			NA	NA		
	(0.0)		NA				NA				NA		
NRS	17	3.13	0.95			0.09	0.05			0.13	0.02		
	(100.0)	(1.06)	4.45			(0.02)	0.12			(0.05)	0.18		

(continued on next page)

TABLE A-1 *(continued)* **TTR Reliability Measures and Measures of Accuracy by Time of Day**

Route	Sample (percentage)	SD				CV				BI			
		Value (SE)	1[a]	2[b]	3[c]	Value (SE)	1[a]	2[b]	3[c]	Value (SE)	1[a]	2[b]	3[c]
8:00–8:30 p.m.													
1	7 (30.4)	3.43 (2.29)	–0.37 7.16	Y	Y	0.10 (0.04)	0.05 0.18	Y	Y	0.14 (0.05)	0.09 0.26	Y	Y
2	11 (47.8)	4.80 (2.26)	–0.02 7.41	Y		0.12 (0.04)	0.07 0.21	Y		0.20 (0.07)	0.10 0.33	Y	
3	3 (13.0)	1.05 (1.96)	5.17 11.62	N		0.07 (0.04)	0.07 0.19	Y		0.09 (0.05)	0.11 0.28	Y	
Others	2 (8.7)	3.94 (3.95)	5.36 18.34			0.04 (0.04)	0.06 0.20			0.06 (0.06)	0.07 0.26		
NRS	23 (100.0)	5.17 (1.64)	2.03 7.41			0.14 (0.03)	0.09 0.19			0.23 (0.06)	0.10 0.31		
8:30–9:00 p.m.													
1	7 (46.7)	1.65 (0.96)	0.43 3.58	N	N	0.05 (0.02)	0.05 0.11	N	N	0.06 (0.02)	0.03 0.10	N	N
2	3 (20.0)	0.87 (1.69)	4.66 10.21	N		0.06 (0.03)	0.07 0.17	Y		0.08 (0.04)	0.07 0.21	Y	
3	4 (26.7)	2.19 (2.24)	4.47 11.85	N		0.08 (0.04)	0.11 0.25	Y		0.10 (0.04)	0.10 0.25	Y	
Others	1 (6.7)	NA	NA NA			NA	NA NA			NA	NA NA		
NRS	15 (100.0)	4.12 (1.74)	2.41 8.12			0.13 (0.05)	0.10 0.26			0.19 (0.10)	–0.11 0.23		
9:00–9:30 p.m.													
1	6 (54.5)	2.44 (1.60)	0.59 5.85	Y	Y	0.08 (0.04)	0.00 0.14	Y	Y	0.13 (0.05)	0.10 0.26	Y	Y
2	4 (36.4)	1.05 (0.91)	0.47 3.46	Y		0.04 (0.02)	0.01 0.08	N		0.05 (0.02)	0.03 0.16	Y	
3	0 (0.0)	NA	NA NA			NA	NA NA			NA	NA NA		
Others	1 (9.1)	NA	NA NA			NA	NA NA			NA	NA NA		
NRS	11 (100.0)	2.75 (1.44)	0.92 5.64			0.10 (0.05)	0.00 0.15			0.15 (0.08)	–0.05 0.22		
9:30–10:00 p.m.													
1	8 (66.7)	1.04 (0.74)	–0.54 1.91	Y	Y	0.04 (0.02)	–0.01 0.06	Y	Y	0.07 (0.03)	0.07 0.16	Y	Y
2	3 (25.0)	0.31 (0.59)	1.54 3.47	N		0.02 (0.01)	0.02 0.06	Y		0.02 (0.01)	0.03 0.07	Y	
3	1 (8.3)	NA	NA NA			NA	NA NA			NA	NA NA		
Others	0 (0.0)	NA	NA NA			NA	NA NA			NA	NA NA		
NSR	12 (100.0)	1.15 (0.63)	–0.01 2.05			0.04 (0.02)	0.02 0.07			0.07 (0.02)	0.05 0.11		
10:00–10:30 p.m.													
1	1 (100.0)	NA	NA NA			NA	NA NA			NA	NA NA		
2	0 (0.0)	NA	NA NA			NA	NA NA			NA	NA NA		
3	0 (0.0)	NA	NA NA			NA	NA NA			NA	NA NA		
Others	0 (0.0)	NA	NA NA			NA	NA NA			NA	NA NA		
NSR	1 (100.0)	NA	NA NA			NA	NA NA			NA	NA NA		

NOTE: NA = not available.
[a]Corresponding 95th percentile intervals.
[b]Whether NRS TTR measures are located within specific route TTR confidence intervals.
[c]Whether statistically significant differences can be found between NRS and route TTR measures.

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