EVALUATION OF TRAVEL TIME AND OD VARIATION ON THE TOKYO METROPOLITAN EXPRESSWAY USING ETC DATA

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ABSTRACT

This research analyzes the accuracy of travel time estimation and the OD variation on of the Tokyo Metropolitan Expressway (MEX) using Electronic Toll Collection (ETC) data. The ETC data mainly consist of driver ID's and entrance times of the vehicles at on-ramps, which are measured when the vehicles automatically pay the toll at on-ramps. First, travel time between on and off ramps is examined by comparing the estimates from ETC data with one from conventional traffic detector data. Fairly good agreement of two kinds of travel times is observed. Second, the OD variations are examined based on the ETC data. It is found that the variance of a daily OD volume is approximately in proportion to the amount of daily OD volume. And, the difference in OD variations between ETC users and Non-ETC users is examined based of the variation of on-ramp entrance volume. As a result, the OD variation of ETC users may be slightly smaller than that of Non-ETC users.

INTRODUCTION

Electronic Toll Collection (ETC) service on Metropolitan Expressway (MEX) started from March of 2001 at 11 tollgates. Since then, the number of ETC users has been rapidly increasing as ETC devices are being installed at more tollgates. In October 2005, about 60% of MEX trips were paid by the ETC.

When you pay the toll using ETC, the driver ID, the vehicle type, the ramp code, and the passing time at the toll gate are recorded. For the security reason, the driver ID is randomized, but the same driver has always the same ID. Therefore, from the ETC data, we can measure the frequency of MEX trips for individual drivers. Also, we can know how frequently and when each of the on-ramps is used by an individual driver.

Motivated by the information from ETC associated with individual drivers, which cannot be observed by conventional traffic detectors, we have been carrying out several analyses on MEX traffic conditions as well as on MEX user characteristics. Among them, this paper introduces two analyses on the travel time accuracy and the daily OD variations on MEX.

The travel time accuracy of ETC data is validated about possibility of application for travel time provision. Therefore, the travel time measured from the ETC data is analyzed by comparing with estimated travel time from traffic detector data, and the variation of individual vehicle travel times is examined in relation to the trip distance. For the daily OD variation, we examine whether the OD variation measured only for ETC users could be representative for all MEX users including Non-ETC users. If ETC users can be representative for whole of MEX users, we can utilize them for various management schemes.

OUTLINE OF ETC DATA

The ETC data we use here was collected from October 2003 to December 2004 excluding October 2004. The accumulated number of trips recorded reaches more than 100 million trips. During this period, about 25% of MEX trips used the ETC money transaction.

However, the ETC data mentioned above were collected only at on-ramps, but not at off-ramps except at one mainline toll gate at the boundary between Tokyo and Kanagawa regions. Therefore, although we cannot measure travel times between on and off ramps, travel time from an on-ramp to the mainline toll gate was measured. Similarly, the number of trips from each of the on-ramps to the mainline gate was recorded.

ANALYSIS OF TRAVEL TIME

Study Section and Period

The highway section selected for the ETC travel time examination is inbound of Wangan line: from Ichikawa ramp to Wangan-Ukishima mainline gate (see **Figure 1**). Using the ETC data from 1st (Monday) to 7th (Sunday) of March 2004, travel times from each of the on-ramps along Wangan line to the mainline gate are estimated.

Analysis of Travel Time

Correlation between ETC Travel Time and Detector Travel Time

From the ETC data, travel time can be directly measured for individual vehicles as the passing time difference between an on-ramp and the mainline gate. The time axis in discretized for every Δt interval and each interval is denoted as *t.* In this study, we employ 5 minutes for Δt.

Travel time of ETC vehicle *n* from ramp *i* during time interval *t* is defined as $T_i^n(t)$. We call this travel time $T_i^n(t)$ as 'ETC travel time', which is compared to 'Detector travel time' estimated from traffic detector data. Conventionally, travel time has been estimated from traffic detector data, which are normally aggregated for every 5 minutes for each of highway sub-sections of about 300m length. From the aggregated detector data, travel time has been estimated along a hypothetical vehicle trajectory. On the time-space diagram, a hypothetical vehicle is running according to aggregated detector information and the travel time of the hypothetical vehicle is measured in a certain time interval such as 5 minutes.

Figure 2 shows the relationship between ETC travel time and Detector travel time from Ichikawa ramp to the mainline gate for different time periods. Both travel times reasonably agree each other except for smaller travel time. For validating distribution of ETC travel time at smaller Detector travel time, Difference between ETC travel time and Detector travel time from on-ramp *i* during interval *t* is calculated as in Eq.(1).

$$Diff_i^n(t) = T_i^n(t) - T_i^D(t) \qquad \textbf{(1)}$$

where $Diff_i^n(t)$ = Difference between travel time of ETC vehicle *n* and Detector travel time from on-ramp *i* during interval *t*

$T_i^n(t)$ = Travel time of ETC vehicle *n* from ramp *i* during time interval *t*

$T_i^D(t)$ = Detector travel time from on-ramp *i* during interval *t*

Figure 3 shows the frequency of $Diff_i^n(t)$ focusing on Detector travel time from 19 minutes which is minimum value of Detector travel time to 30 minutes within the dotted square in Figure 2. More than 90 % of samples are plotted on the difference from 0 to less than 10 minutes. Therefore, most of ETC travel time is plotted on the 45 degree line of Figure 2.

Root Mean Square Error (RMSE)

RMSE between ETC travel time and Detector travel time for the study hours is calculated from Eq.(2) by vehicle types: small and large vehicle types.

$$RMSE_i = \frac{\sqrt{\sum_t \sum_n^{N_i(t)} (T_i^D(t) - T_i^n(t))^2}}{\sum_t N_i(t)} \qquad \textbf{(2)}$$

where $RMSE_i$ = RMSE of travel time from on-ramp *i* for the study hours

$N_i(t)$ = The number of ETC vehicles from ramp *i* during time interval *t*

Figure 4 shows that RMSE of travel time from each of the on-ramps to the mainline gate during 10:00 to 15:00 by vehicle type. RMSE is less than 1 minute for all sections. And, if the number of samples is large, the accuracy of travel time seems to increase. For instance, since the number of samples from Maihama ramp is the smallest, its RMSE is the largest, especially for large vehicle. Difference of RMSE by vehicle type also can be considered about travel speed. Normally, speed of large vehicle is slower than small vehicle. **Figure 5** shows the different of $Diff_i^n(t)$ between ETC travel time and Detector travel time by vehicle type from Ichikawa on-ramp at time from 10:00 to 15:00. $Diff_i^n(t)$ of large vehicle distribute greater than small vehicle. Therefore, it can be consider that RMSE of large vehicle is also calculated greater than small vehicle.

Travel Time Variation in relation to Section Length

Since travel time of individual vehicle can be measured from the ETC data, we would like to examine the variation of travel time for each of the section above.

In general, the variance of travel time is expected to depend on the section length. Suppose an entire study section of a certain length is divided into several sub-sections of equal length: the entire section is assumed to consist of *K* sub-sections. Let $T_i(t)$ be travel time of sub-section *i* at interval *t* and its expectation and variance are denoted as E($T_i(t)$) and Var($T_i(t)$). If the highway is uniform, the coefficient of variation (= standard deviation / expectation) of travel time for the entire section would be

$$\begin{aligned} CV(T(t)) &= \frac{\sqrt{Var(T(t))}}{E(T(t))} = \frac{\sqrt{\sum_i Var(T_i(t))}}{\sum_i E(T_i(t))} = \frac{\sqrt{K}\cdot\sqrt{Var(T_i(t))}}{K\cdot E(T_i(t))} \\ &= \frac{1}{\sqrt{K}}\cdot\frac{\sqrt{Var(T_i(t))}}{E(T_i(t))} = \frac{1}{\sqrt{K}}\cdot CV(T_i(t)) \end{aligned} \qquad \textbf{(3)}$$

where $T_i(t)$ = averaged ETC travel time from ramp *i* during time interval *t*

T(t) = travel time of the entire section at interval *t*

$$T_i(t) = \frac{\sum_{n}^{N_i(t)} T_i^n(t)}{N_i(t)} \tag{4}$$

$$T(t) = \sum_i T_i(t)$$

$$CV(T(t)) = \frac{\sqrt{Var(T(t))}}{E(T(t))}$$ = coefficient of variation for the entire section at interval *t*

$$CV(T_i(t)) = \frac{\sqrt{Var(T_i(t))}}{E(T_i(t))}$$ = coefficient of variation for a sub-section *i* at interval *t*

The standard deviation relative to the expectation for the entire section, *CV(T(t))*, is smaller than that of a sub-section, $CV(T_i(t))$, by factor of $\sqrt{K}$. This suggests that if the section length gets longer, the standard deviation of travel time gets smaller relatively to its expectation. For the actual highway section, the uniformity may not be satisfied. However, we may expect the similar tendency in the coefficient of variation of travel time.

Figure 6 shows the coefficient of variations for different highway section along Wangan line, i.e. Ichikawa is furthest away and Wagan-kanpachi is nearest on ramps from the mainline gate.

Each of the plots represents $CV(T_i(t))$ estimated from vehicles entering an on-ramp *i* during time interval *t*. Since Δt is equal to 5 minutes, there are 12 x 24 plots for each on-ramp. As we expected, the CV's have monotonically decreasing tendency as the section length gets longer. Therefore, when ETC travel time is used for travel time provision, this tendency should be considered.

Number of Sample for Ensuring the Small Standard Deviation

Let us next examine the number of samples during Δt so that the standard deviation of travel time could stay within the requested range, ΔT. Suppose that the travel time is updated in every Δt interval and the updated travel time value is the average travel time measured during Δt. If a sufficient number of ETC vehicles travel from an on-ramp to the mainline gate, the standard deviation of the average travel time during Δt would be small enough so as to be less than requested range of ΔT.

First of all, the unbiased estimate of the travel time variance from ramp *i* at interval *t* is obtained as follows:

$$Var(T_i^n(t)) = \frac{\sum_{n}^{N_i(t)} (T_i^n(t) - T_i(t))^2}{N_i(t) - 1} \quad , \tag{5}$$

Since ETC travel time from ramp *i* at interval *t*, $T_i(t)$, is the average travel time of ETC vehicles as in Eq.(4), the standard deviation of $T_i(t)$ is calculated as in Eq.(6), which should be less than ΔT.

$$\sqrt{Var(T_i(t))} = \frac{\sqrt{Var(T_i^n(t))}}{\sqrt{N_i(t)}} < \Delta T \tag{6}$$

Therefore, the requested number of samples is

$$N_i\ (t) > \frac{Var(T_i^n(t))}{\Delta T^2} \quad \textbf{(7)}$$

In this research, travel time from Ichikawa on-ramp is analyzed because of the largest sample size. During one week observation period from 1st to 7th of March, there are 309 of 5-minute intervals and, for each interval from 05:00 to 10:00, the standard deviation of ETC travel time, $\sqrt{Var(T_i(t))}$ is estimated.

Figure 7 shows how varies depending on the number of ETC samples during 5 minutes. This figure illustrates that standard deviation $\sqrt{Var(T_i(t))}$ clearly decreases as the number of samples during 5 minutes increases. From the figure it can be seen that if the requested range ΔT is also 5 minutes, at least 6 samples is required.

MEX have carried out the on-line survey for asking the acceptable error range of on-route and pre-trip travel time information to MEX users. From the survey result, about 70% of the survey participants acknowledge that ± 5 minutes as an acceptable level of accuracy (Chung, 2004). Therefore, in case of this research result; i.e. at least 6 samples is required to ensure 5 minutes of standard deviation, at least 6 samples can ensure the acceptable level of accuracy of MEX users.

ANALYSIS OF ORIGIN-DESTINATION VARIATION

This chapter analyzes the variation of daily origin-destination (OD) volumes for ETC users, and the daily OD variation of Non-ETC users is estimated based on several acceptable assumptions.

Study Area and Period

For the analysis on the OD variation, ETC data on weekdays during June and July 2004 are used. The current ETC devices record driver ID's and their passing times only at on-ramps, but not at off-ramps. However, there is one mainline gate at the boundary of Tokyo and Kanagawa sub-regions as shown in **Figure 8**. At the mainline gate, passing times are also recorded. Hence, we can analyze the OD demand as if the mainline gate is an intermediate destination.

Analysis of OD Variation

Since the mainline gate is located at the boundary between Tokyo and Kanagawa sub-regions, we divide the whole metropolitan region into these two sub-regions. The sub-region is denoted as B: B= either Tokyo or Kanagawa sub-region. Several variables for the analysis are first defined as follows:

<Symbols>
y_{ij} = the number of daily trips from ramp i to j observed by regular census (given by OD survey)
$x_{ij}^E(d)$ = the number of ETC trips from ramp i to j during day d
$x_{ij}^N(d)$ = the number of Non-ETC trips from ramp i to j during day d
$x_{ij}(d)$ = the total number of trips from ramp i to j = $x_{ij}^E + x_{ij}^N$ during day d
R_B = a set of off-ramps in sub-region B, B = Tokyo or Kanagawa
$X_i(d)$ = the total number of trips entering at ramp i during day d
$X_{iB}(d)$ = the number of trips from ramp i to R_B during day d
$X_{iB}^E(d)$ = the number of ETC trips from ramp i to R_B during day d

Among above variables, the number of ETC trips from ramp i to R_B, $X_{iB}^E(d)$, can be measured from the ETC data. Suppose one vehicle enters from ramp i in Tokyo sub-region at certain time. If the same driver ID is measured at the mainline gate, we know the vehicle has a destination at an off-ramp in Kanagawa sub-region; on the other hand, if the same ID is not measured, we also know the vehicle has its destination within Tokyo sub-region. Therefore, from the ETC data, we can measure $X_{iB}^E(d)$, but cannot directly measure ramp to ramp OD, $x_{ij}^E(d)$.

OD Variations for ETC users

Using the ETC data during weekdays for June to July 2004, the average daily OD, $\overline{X}_{iB}{}^E$, and the variance, $Var(X_{iB}^E)$, are estimated as shown in **Figure 9**, in which a relationship between $\sqrt{\overline{X}_{iB}{}^E}$ and $\sqrt{Var(X_{iB}{}^E)}$ is illustrated for trips from ramp i to sub-region B for ETC users. The figure also shows the coefficient of variation, $CV(X_{iB}{}^E) = \sqrt{Var(X_{iB}{}^E)} \big/ \overline{X}_{iB}{}^E$, as in the dashed line.

$$\overline{X}_{iB}{}^E = \frac{\sum_{d}^{N_d} X_{iB}{}^E(d)}{N_d}, \tag{8}$$

$$Var(X_{iB}{}^E) = \frac{\sum_{d}^{N_d} (X_{iB}{}^E(d) - \overline{X}_{iB}{}^E)}{N_d - 1}, \tag{9}$$

where N_d = the number of weekdays.

The figure clearly shows that standard deviation $\sqrt{Var(X_{iB}{}^E)}$ is almost monotonically increasing as $\sqrt{\overline{X}_{iB}{}^E}$ increases. For instance, if the OD volume is 10,000 trips ($\sqrt{\overline{X}_{iB}{}^E}$ =100), the standard deviation, $\sqrt{Var(X_{iB}{}^E)}$, is about 500. This means that the standard deviation shares about 5% of the OD volume. On the other hand, if the OD volume is 400 trips ($\sqrt{\overline{X}_{iB}{}^E}$ =20), the standard deviation is about 40; that is, $CV(X_{iB}{}^E)$ is about 10%. In this way, the coefficient of variation sharply increases for the smaller OD volumes.

So far, the daily OD volume from ramp i to sub-region, $X_{iB}{}^E$, is discussed. Although we cannot directly measure individual ramp to ramp OD, $x_{ij}{}^E$, the $x_{ij}{}^E$'s can be roughly estimated assuming that the distribution of OD within a sub-region is proportional to the census OD:

$$x_{ij}{}^E = X_{iB}{}^E \cdot \frac{y_{ij}}{\sum_{k \in R_B} y_{ik}} \tag{10}$$

Figure 10 compares individual ramp to ramp OD volumes $x_{ij}{}^E$ obtained from Eq.(10) with OD census volume, y_{ij}. Obviously, the census OD includes all travellers and hence much larger than $x_{ij}{}^E$. However, there is a clear correlation between these two types of OD volumes. This strong correlation supports the possibility of OD estimation from the ETC data.

Most of estimated x_{ij}^E's are distributed over the range less than 1000 trips; that is, the range of $\sqrt{x_{ij}^E}$ is approximately from 0 to 30 trips. Therefore, if x_{ij}^E could be assumed to have the similar relationship to X_{iB}^E as in Figure 9, the coefficient of variation of x_{ij}^E would be mostly more than 10% because of the smaller number of daily OD volumes between ramps.

Comparison between ETC Users and Non-ETC Users

Using traffic detector data at on-ramps, the number of entry trips at on-ramp *i* , X_i , is observed. **Figure 11** shows how the standard deviation, $\sqrt{Var(X_i)}$, varies in relation to $\sqrt{X_i}$ just as shown in Figure 9. Although the distribution of $\sqrt{Var(X_i)}$ looks similar to Figure 9, $\sqrt{Var(X_i)}$'s seem slightly larger compared to plots in Figure 9 for the same horizontal value. One of the possible reasons would be that Figure 11 includes all travellers while Figure 9 illustrates the tendency of only ETC users. Therefore, examining the discrepancy, we could examine how ETC and Non-ETC users behave differently.

Let us estimate variance $Var(X_i^N)$ and average $\overline{X}_i^N$ of total on-ramp volumes for Non-ETC users as shown below.

$$Var(X_i^N) = Var(X_i) - \sum_B Var(X_{iB}^E) \tag{11}$$

$$\overline{X}_i^N = X_i - \sum_B \overline{X}_{iB}^E \tag{12}$$

Figure 12 superimposes $\sqrt{Var(X_i^N)}$ for Non-ETC users on Figure 11 which shows $\sqrt{Var(X_i)}$ for all users. Standard deviation $\sqrt{Var(X_i^N)}$'s for Non-ETC users look slightly larger than $\sqrt{Var(X_i)}$'s for all users.

CONCLUSION

This research analyses the accuracy of travel time estimation and the day-to-day OD variation on the Tokyo Metropolitan Expressway(MEX) using Electronic Toll Collection(ETC) data. Travel time measured using ETC data was compared with estimated travel time from detector data. Coefficient of variation related to section length and number of samples required to ensure small standard deviation were validated. In addition, OD variation for ETC users was analysed, and traffic characteristics were compared between ETC and Non-ETC users to evaluate whether ETC traffic volume data can be representative of all MEX users.

ETC travel times are in good agreement with detector travel time except when travel time is small. However, we confirmed that most of smaller ETC travel time distributed by less than 10 minutes of error for Detector travel time. Root Mean Square Error(RMSE) is also less than 1 minute for every OD pairs for which travel times were compared. Coefficient of variation has been found to be monotone decreasing as the section length gets longer. The standard deviation gets smaller with increase in number of sample during each 5 minute interval. For instance, at least 6 samples during 5 minutes interval can ensure that standard deviation is less than 5 minutes. Since MEX users acknowledge ±5 minutes as an acceptable level of accuracy, results of this analysis can be used for travel time provision to ETC users.

For OD variation of ETC users, we confirmed that the standard deviation can be approximated as a monotone increasing function of the square root of average traffic volume for ETC users.

And, we also confirmed that its coefficient of variation increases as OD traffic volume become smaller. And, estimated ETC OD traffic volume and the traffic census OD traffic volume have a clear correlation. This result shows possibility to estimate OD traffic volume using ETC data. The characteristics of ETC and Non-ETC users look similar but standard deviations for both groups are different compared to those estimated for all the MEX users.

Future research about ETC travel time will be to explore the possibility of predicting travel time using ETC data and providing it to ETC users. Also with the availability of destination information of ETC users in addition to the origin in the near future, we can analyse the day-to-day OD variation more accurately.

ACKNOWLEDGMENTS

We would like to express Metropolitan Expressway CO., LTD. grateful to provision of ETC data. And we also want to acknowledge to all members of ETC analysis in Kuwahara Laboratory.

REFERENCES

Chung,E., Warita,H., Bajwa,S.I. and Kuwahara,M (2004). Travel Time Prediction: issues and benefits, WCTR 2004 conference, CD-ROM, July, 2004, Istanbul, Turkey

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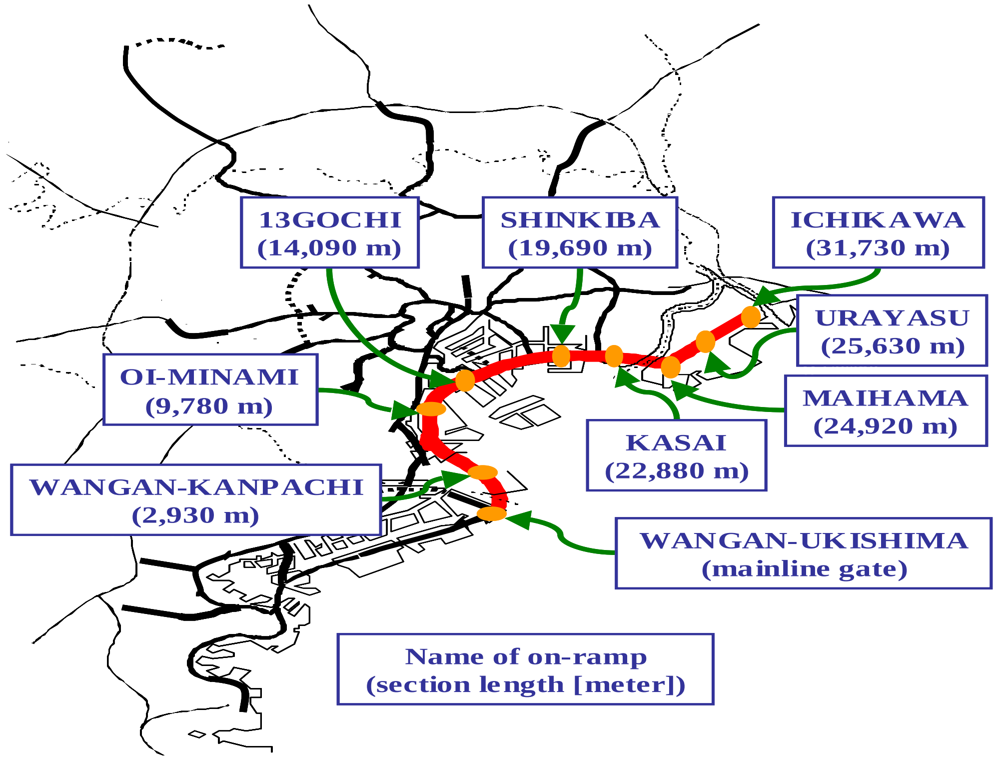


Figure 1: Study section on Wangan Line

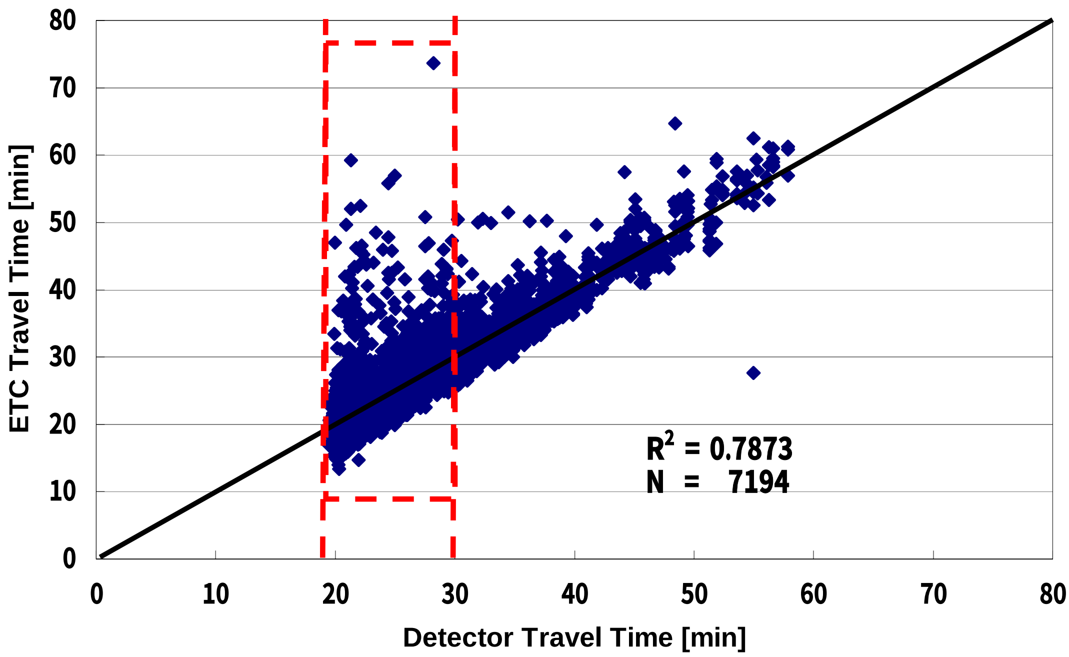


Figure 2: ETC travel time vs. Detector travel time from Ichikawa on-ramp

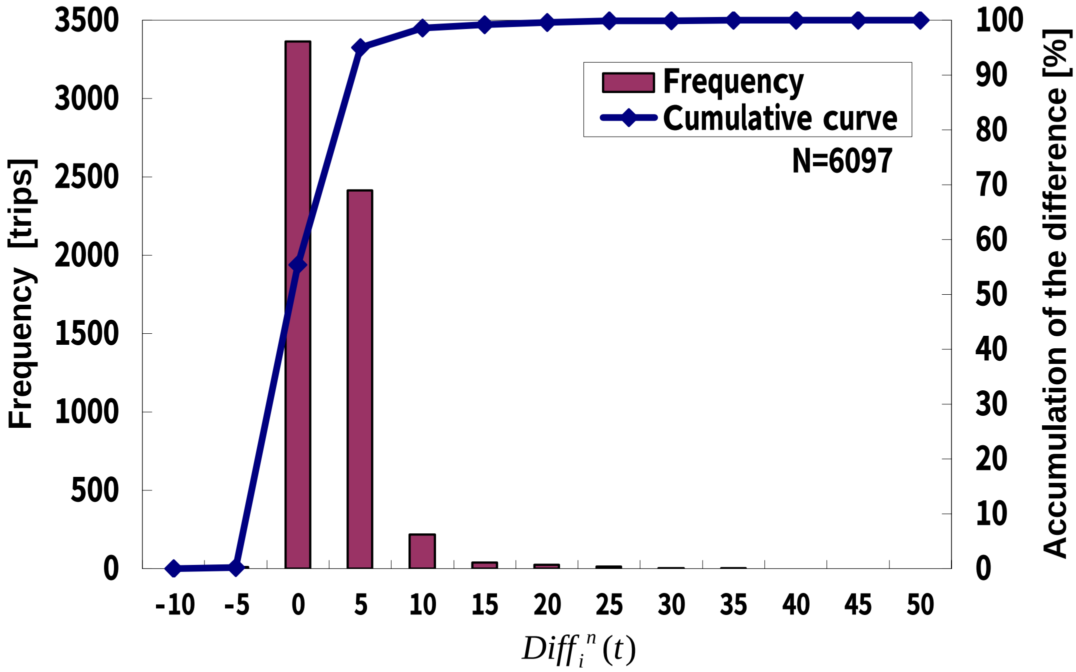
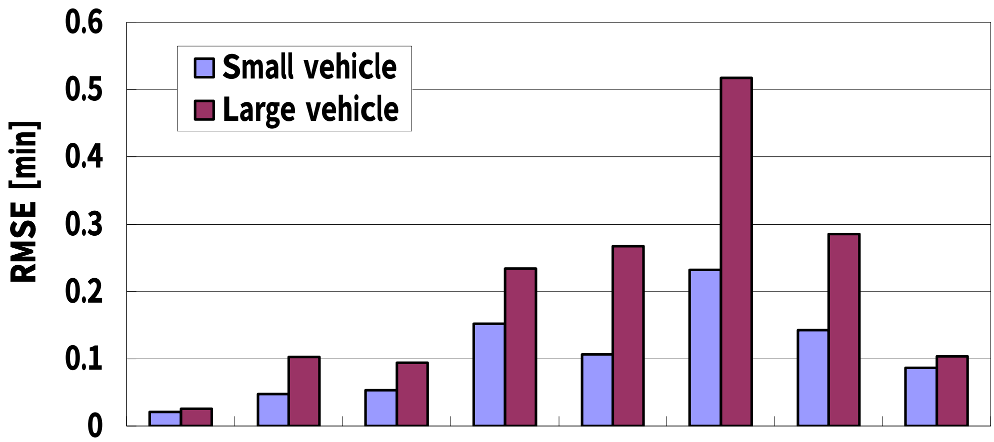


Figure 3: Distribution of $Diff_i^n(t)$ from Ichikawa on-ramp at Detector travel time from 19 minutes to 30 minutes



Number of Sample	Wangan Kanpachi	Oiminami	13Gochi	Shikiba	Kasai	Maihama	Urayasu	Ichiakwa
Small veh	791	398	553	122	354	97	225	1444
Large veh	936	186	313	81	74	32	78	937

Figure 4: RMSE of travel times from on-ramps to the mainline gate

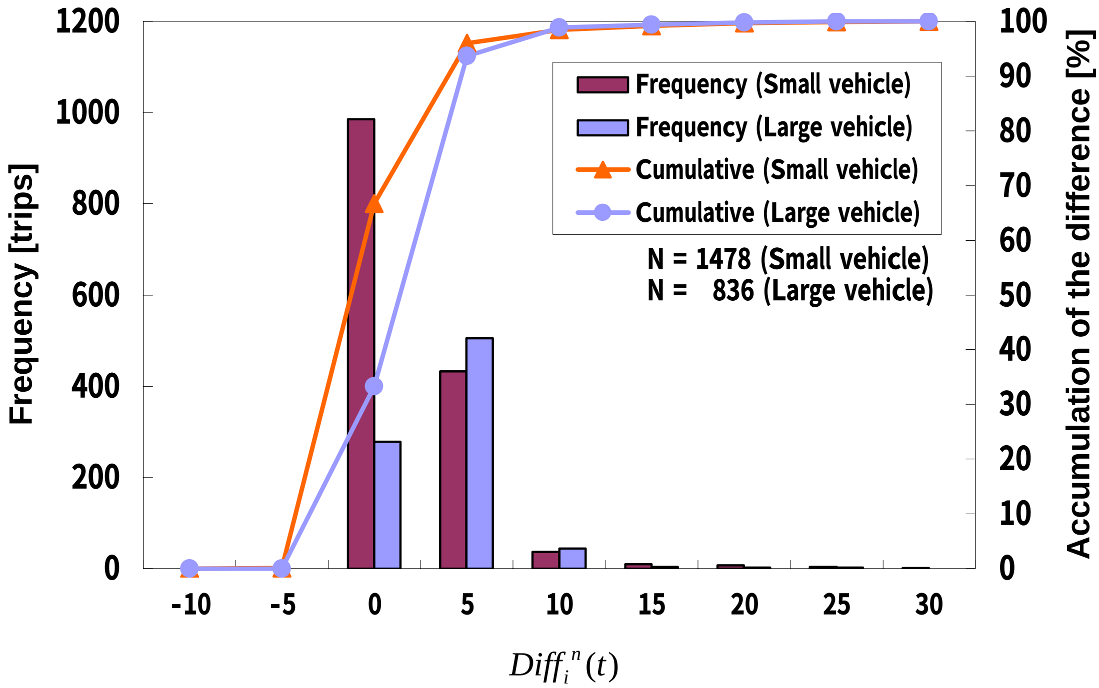


Figure 5: Distribution of $Diff_i^n(t)$ from Ichikawa on-ramp by vehicle type
Time from 10:00 to 15:00

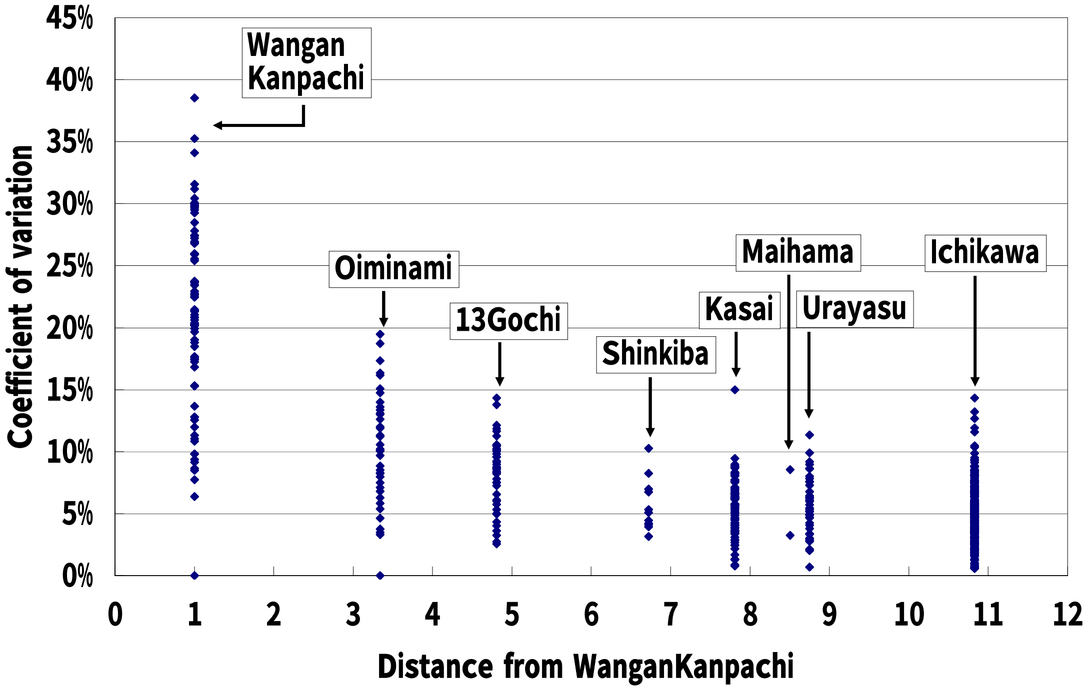


Figure 6: Coefficient of variation of travel time for different trip length

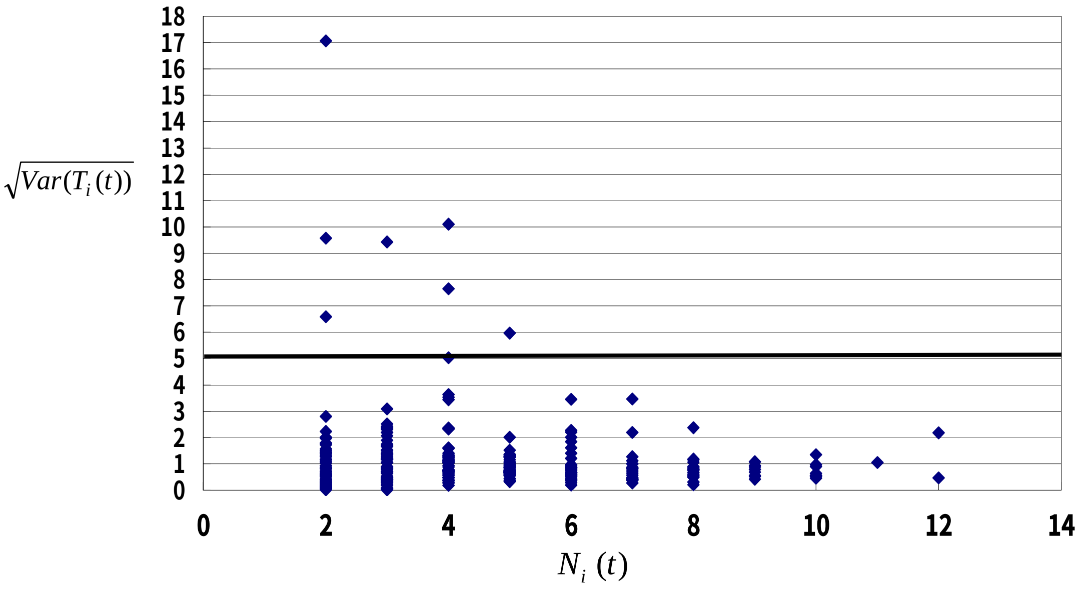


Figure 7: Standard deviation of travel time in relation to the sample size

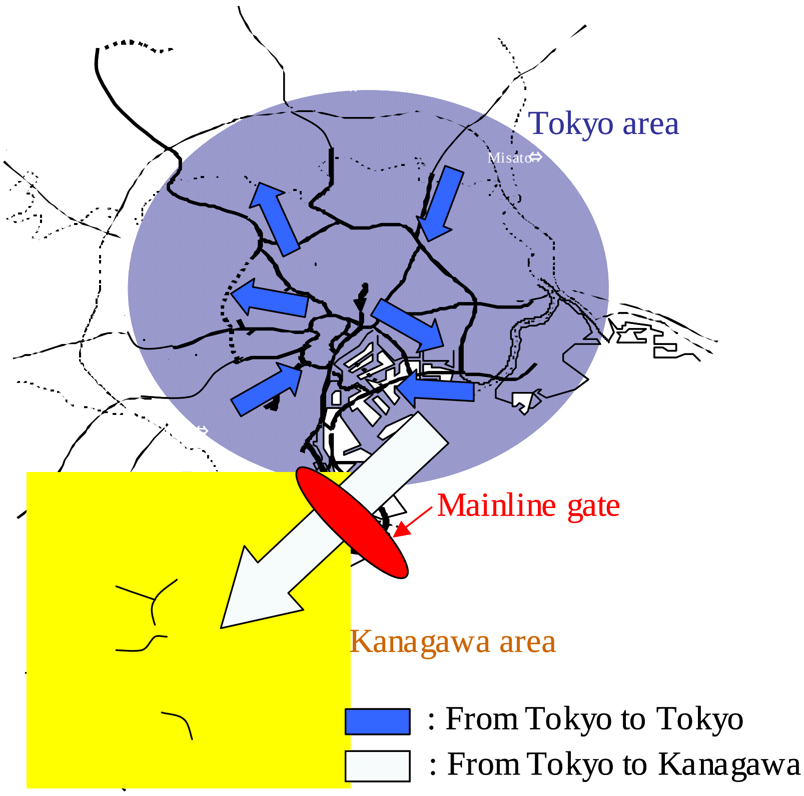


Figure 8: Target direction of OD variation analysis

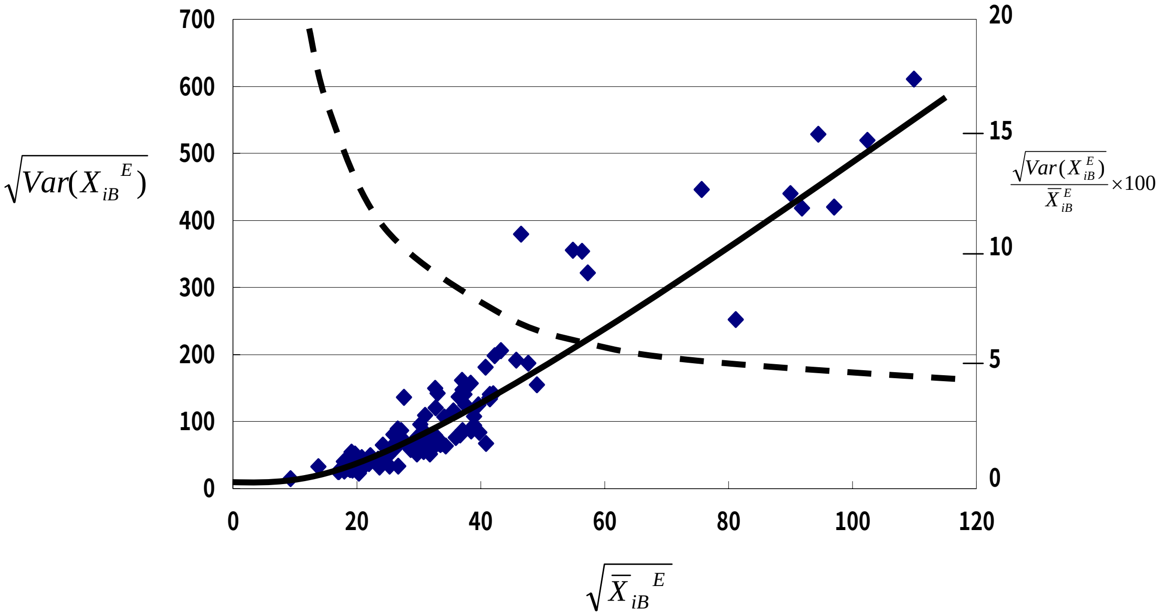


Figure 9: Relationship between $\sqrt{\overline{X}_{iB}{}^{E}}$ *and* $\sqrt{Var(X_{iB}{}^{E})}$

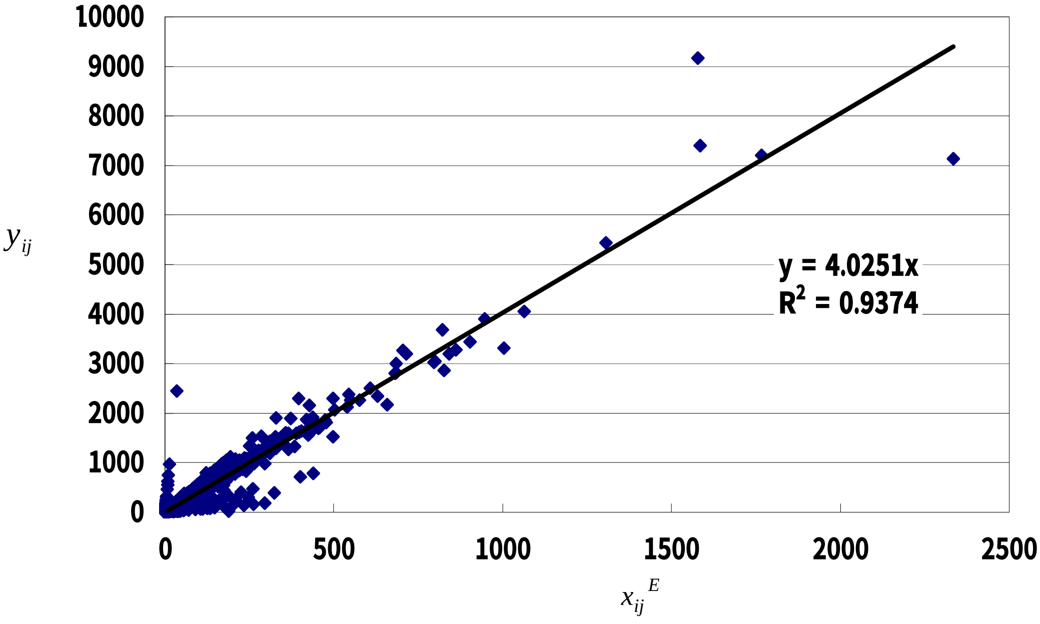


Figure 10: ETC OD traffic volume $x_{ij}{}^{E}$ *vs. OD survey result* y_{ij} *[Tokyo to Tokyo]*

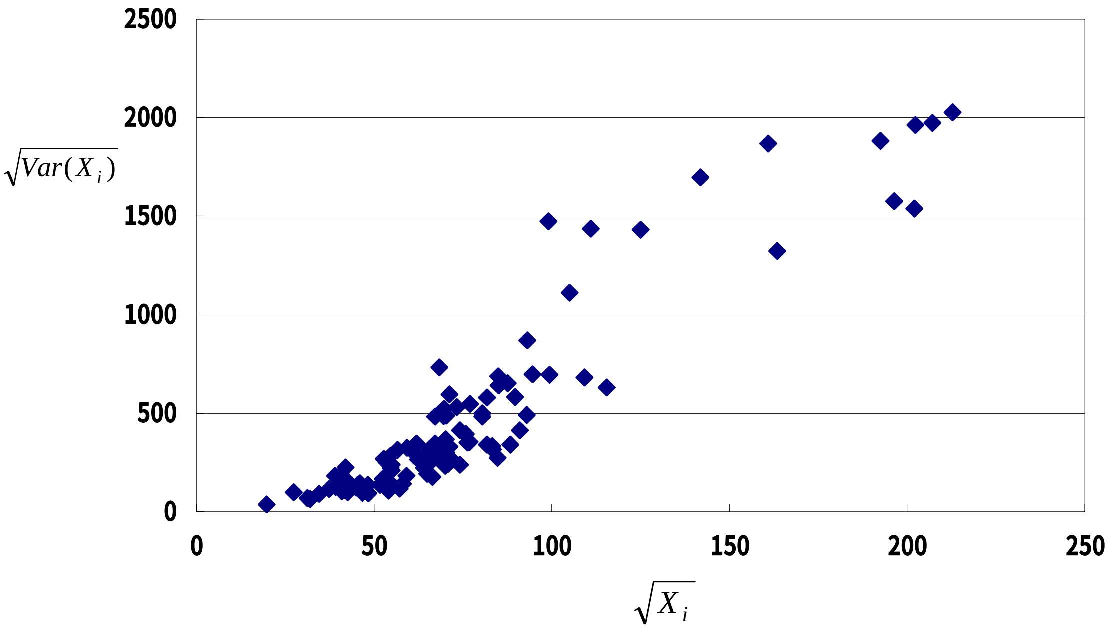


Figure 11: Relationship between $\sqrt{X_i}$ and $\sqrt{Var(X_i)}$ for all users

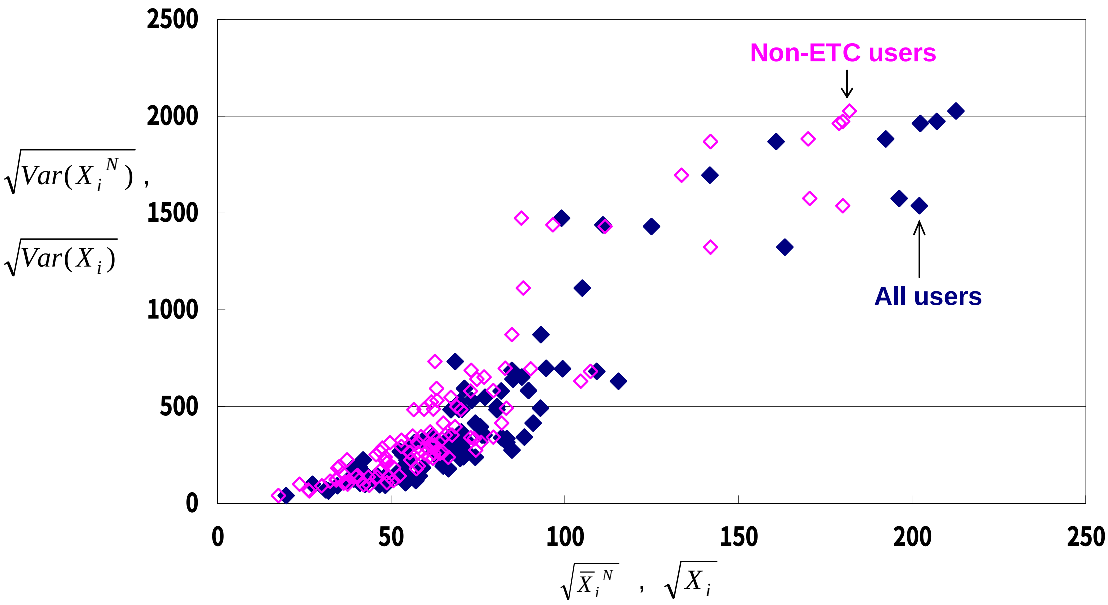


Figure 12: Distribution of standard deviations for all users and for Non-ETC users