TRAVEL TIME VARIATION AND TRAVEL TIME RELIABILITY INDEXES

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ABSTRACT

Reliability is an emerging demand for a transportation service under: 1) Increase in the time value, 2) Increased pervasiveness of economic activities related to “Just in Time” production and inventoryless sales, 3) Increased economic efficiency in speed and accuracy related to economic activity, and; 4) Increased demands on people’s time.
This paper includes (1) actual observation of travel time variation, (2) its modeling, and (3) development of travel time reliability indexes for both user and administrator sides, and they will be compared with many indexes proposed so far.

Keywords: travel time reliability, travel time variation

INTRODUCTION

Reliability is an emerging demand for a transportation service under: 1) Increase in the time value, 2) Increased pervasiveness of economic activities related to “Just in Time” production and inventoryless sales, 3) Increased economic efficiency in speed and accuracy related to economic activity, and; 4) Increased demands on people’s time.
This paper includes (1) actual observation of travel time variation, (2) its modeling, and (3) development of travel time reliability indexes for both user and administrator sides, and they will be compared with many indexes proposed so far.
(1) Actual observation of travel time variation

We observed license plates of many vehicles along more than 130 km length on the expressway named “Meishin Expressway”. There are four observation points between the observed length and then the lisence plates on and between three sections are analyzed. Travel time variation and its correlation for adjacent sections are analyzed. Floating survey for the space mean speed is also carried out.

(2) Modeling of travel time variation

Based on the actual travel time variation stated above, the model for travel time variation is developed using probability distribution function (PDF).

(3) Development of travel time reliability index

New indexes for assessing travel time reliability, P(*Tave* + *ATTV*), P(*Tave* - *DTTR*), *TT*80-*TT*20 and *TT*70-*TT*30 are proposed, where *Tave*, *ATTV*, *DTTR*, and *TTxx* are “average travel time”, “acceptable travel time variation”, “desired travel time reduction”, and *xx* percentile travel time”. Travel time reliability indexes, including previously proposed indexes, such as Buffer Time (BT) and Buffer Time Index (BTI), etc., are calculated based on the PDF outcome from the model and then the eleven indexes will be compared and discussed.

ACTUAL OBSERVATION OF TRAVEL TIME VARIATION

Travel time reliability indexes are based on the travel tie variation. Thus, to obtain the actual travel time variation, we observed registration plates of many vehicles along more than 130 km length on the expressway named “Meishin Expressway”. There are four observation points between the observed length and then the registration plates on and between three sections are analyzed. The total distance is 134.2km, and the observation points are Komaki, Imasu, hatasho and Ohtsu. The distances of the three sections between Komaki and Imasu, Imasu and Hatasho, and Hatasho and Ohtsu are 52.9km, 33.6km and 47.7km respectively. These three sections have three Service Area (SA) or Parking Area (PA), respectively.

Japanese vehicle registration plate has five identification information. These are

1) colors that indicate private use and commercial use,

2) registered places of transportation office,

3) three-figure digits for vehicle size and engine displacement.

4) Hiragana character and;

5) four-figure digit.

Travel time variation and its correlation for adjacent sections are analyzed. Floating survey for the space mean speed is also carried out. Using the Automatic register plate identification, the travel time for every vehicle that can be identified between observation points is calculated.

Figure 1 is the one of the "row" histogram for travel time variation per 10km between Hatasho and Ohtsu. Since halting vehicles at SA and PA are not considered, "very slow vehicles" are plotted on the figure. Thus we developed some filtering engine identifying the real moving vehicle, and after several steps of filtering, **Figure 2** is obtained. These research for the actual travel time variation are still being carried out. We will report the detail of these research in the future.

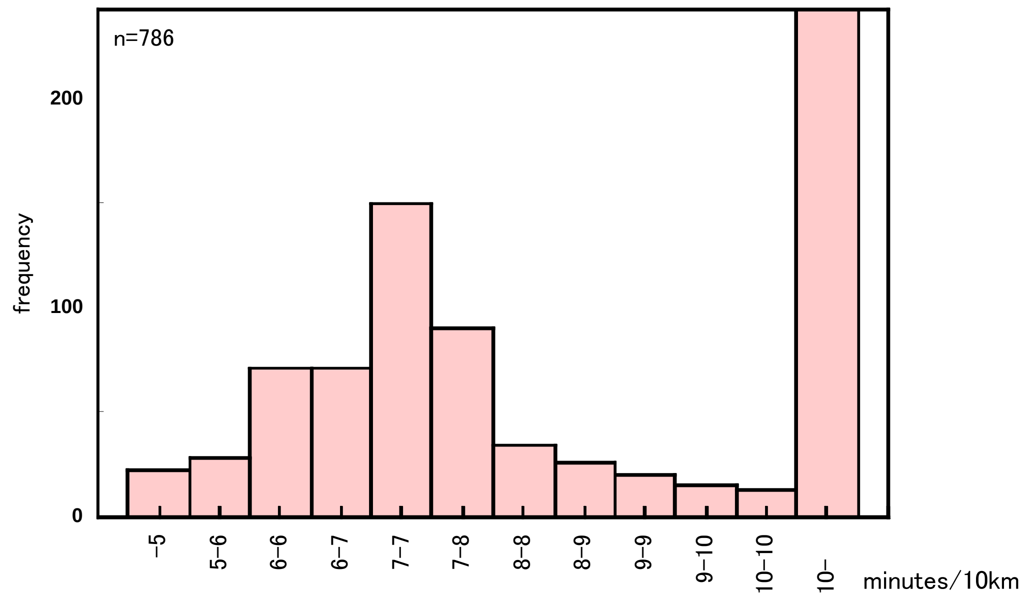

Figure 1. Travel time variation (without filters: between Hatasho and Ohtsu)

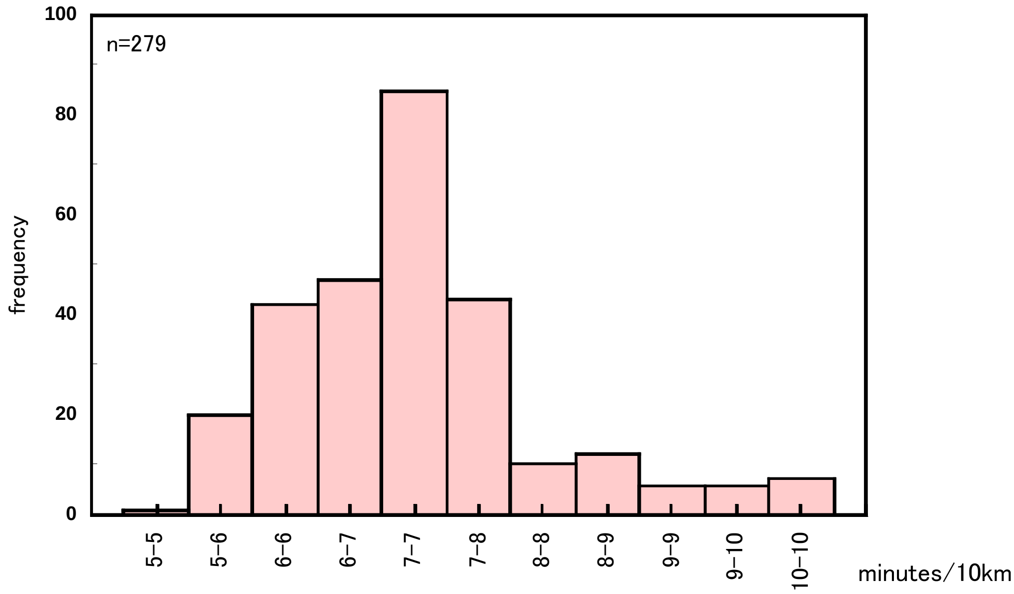

Figure 2. Travel time variation (with filters: between Hatasho and Ohtsu)

TRAVEL TIME RELIABILITY AND ITS MEASURES

DEFINITION OF TRAVEL TIME RELIABILITY

Reliability indexes are used by highway operators and drivers to assess uncertainty. Travel time reliability is defined either as the probability of reaching a destination within a certain travel time, or as the upper- or allowed travel-time limit for a given probability. These indexes indicate the variability and stability of travel time. Travel time reliability provides highway operators with the information necessary for operating highway networks efficiently. It also provides drivers with information that they can use to assess the potential time saving and accuracy of their preferred route using information provided by the highway operator. For example, trips with a high time value, e.g. "Just-in-time production" and trips for which there is a strictly restrictive arrival time e.g. to an airport for an airline connection.

In well-developed arterial highway networks, the measures for evaluating travel time reliability are a very useful and desirable index. This is because drivers are prepared to pay the requisite toll so that they can reduce their travel time and to reach their target destination on time. In addition, since detours should exist within the expressway network, and since there are few such routes in current expressway networks in Japan at present, travel time reliability is more important.

VIEWPOINTS FOR TRAVEL TIME RELIABILITY AND REQUIREMENTS

Operator and User Considerations

Many of the travel time reliability indexes proposed to date are management side indexes. The parties concerned with the operation and management of highway networks are interested in the levels of service that they are providing and what delays are associated with congestion. Consequently, travel time reliability measures reflecting the delay are expressed as Eqs. 1 to 4 below.

From the users' perspective, *i.e.*, drivers, the primary interest lies in how soon they can arrive at their destination, or whether they will arrive on time and how accurate their arrival time estimates are. While users are also interested in potential delays, other than in disaster periods, they are more interested in early arrival (Wakabayashi *et al.*, 2003). Thus, the travel time reliability measures for users are likely to differ slightly from those of operators. The reliability measures should focus on estimated arrival time and the associated probability rather than the travel time within which the majority of drivers complete their trips, *i.e.* the 90- or 95-percentile for travel time.

Comparability with Other Highway Systems

There are two types of travel time reliability indexes, comparable or incomparable with other highway systems Planning Time (*PT*) and Buffer Time (*BT*) indexes are incomparable with other highway systems because they represent a direct measurement of travel time percentile. Conversely, the Planning Time Index (*PTI*) and *BTI* are comparable with other highway systems because they are standardized using minimum or average travel time.

Factors affecting Travel Time Variation

Traffic volume is also an important factor in assessments of travel time reliability indexes because it is the primary factor affecting the level of congestion on highways. When highways, such as on intra-city expressways and urban streets are congested, travel time variation is determined by the traffic volume as drivers are forced to follow the leading vehicles and overtaking is difficult. However, on uncongested highways, travel time variation is determined by the stochastic attributes of individual drivers on the road (their own desired cruising speed, preferred following distance etc.). This perspective is applied to smooth traffic, such as on the inter-city expressway and rural highways.

TRAVEL TIME RELIABILITY MEASURES

Travel time reliability measures are foot lighting measures for evaluating the service levels of highway networks in many countries. In United Kingdom, "Average Delay From the Reference Travel Time for the Last 10% of Trips" is used as an index of congestion.

In the United States, *PT, PTI, BT* and *BTI* indexes have been proposed and used (Lomax *et al*., 2003, FHWA Report, 2006). *PT* and *PTI* can be expressed as follows:

$$PT = The95thPercentileTravelTime = TT95 \;, \tag{1}$$

and

$$PTI = PT / T_{\min} \;, \tag{2}$$

respectively, where *Tmin* is the travel time in free flow and *TTx* is the *x-th* travel time percentile as;

$$TTx = F^{-1}(P/100) \tag{3}$$

where,

$$F(x) = \int_0^x f(t)dt \;, \tag{4}$$

$$P = 100 * F(x) \;, \tag{5}$$

and *P*, $f(t)$ and $F(x)$ are the percentile value, the probability density function of travel time, and the probability distribution function of $f(t)$.

The more widely used *BT* and *BTI* can be expressed as follows:

$$BT = The95thPercentileTravelTime - AverageTravelTime = TT95 - Tave \;, \tag{6}$$

and,

$$BTI = BT / AverageTravelTime = BT / Tave \;. \tag{7}$$

where *Tave* is the average travel time. The use of the " 95-percentile" can be explained as follows:

1) The 95-percentile is 2σ, two times the standard deviation of the normal standard distribution for travel time.
2) The 95-percentile refers to "1 day out of 20 work days" delay. Lomax *et al.* (2003) interpret this as a driver saying, "I can be late to work 1 day a month without getting into to much trouble".

This first point demonstrates that the *BTI* is an operator or management side index for highway networks. Drivers are thus unlikely to use this index since they are interested in either earlier, or on-time, arrivals. The second point is that one driver's behavior in a long time period is replaced by many drivers' behavior in a short time range.

Since a lower travel time variation is desirable, smaller values for both *BT* and *BTI* are desirable. Thus, the highways with relatively smaller *BT* and *BTI* values are reliable for travel time. If the travel time variation, that is, the numerator of Eq. (7) are same for two routes, the *BTI* value for the smaller average travel time is larger than the *BTI* value for the larger average travel time. This one of the problems associated with the *BTI* measure.

To more accurately evaluate travel time variation, van Lint et al. (2004) and Bogers and van Lint (2007) proposed the $\lambda skew$ and $\lambda \, \mathrm{var}$ travel time indexes as:

$$\lambda skew = (TT90 - TT50)/(TT50 - TT10) \text{, and,} \tag{8}$$

$$\lambda \, \mathrm{var} = (TT90 - TT10)/TT50 \, . \tag{9}$$

Tu *et al.* (2007) proposes TTV, Travel Time Variability Index, as

$$\begin{aligned} TTV &= The90thPercentileTravelTime - The10thPercentileTravelTime \\ &= TT90 - TT10 \end{aligned} , \tag{10}$$

also for evaluating the travel time variation.

NEW TRAVEL TIME RELIABILITY MEASURES OF USER SIDE

These indexes are also operator or management side indexes. As stated above in 2.2.1, while the operator side index is still very important, the development for user-friendly travel time index is also needed. Drivers desire to arrive on time, or to arrive relatively quicker using an accurate index; they are also interested in the extent of the delay, but to a lesser degree

(Wakabayashi *et al.*, 2003). Since they may not be interested in the 95-percentile travel time, the travel time reliability measure for users requires average travel time information.

There are several indexes that evaluate travel time reliability around the average travel time. One is the sliding type, which employs a percentile of the average travel time plus/minus the variance. For example, *P*(*Tave* +/- variance), where *P* and *Tave* are the percentile and the average travel time. The other is a proportional type in which ploys a percentile of the average travel time with a specified proportion. For example, *P*(*Tave* +/- *p*ave*), where *p* is the proportion. Generally, when the trip distance is short, the sliding type index is appropriate, and when the trip is very long, the proportion type is appropriate.

Next, we make the following assumptions:
1) Drivers require average travel time.
2) They also require some variation in travel time, adding to the average travel time.

In this paper, the following two new indexes, *P*(*Tave*+*ATTV*), *P*(*Tave*-*DTTR*) are firstly proposed.

1) *P*(*Tave*+*ATTV*) represents the percentile value for which the travel time is *ATTV* (minutes) over the average travel time.
2) *P*(*Tave*-*DTTR*) is the percentile value for which the travel time is *DTTR* (minutes) under the average travel time.

With information of average travel time, drivers can plan a trip to their destination. *P*(*Tave*+*ATTV*), *P*(*Tave*-*DTTR*) are given as:

$$P(Tave + ATTV) = F(Tave + ATTV)\,, \tag{11}$$

$$P(Tave - DTTR) = F(Tave - DTTR)\,. \tag{12}$$

According to allowable errors of travel time information investigated by Matsumoto *et al.* (2008) at expressways around Nagoya City in Japan, the investigation reveals that approximately 80% of drivers can accept +/-10 minutes error of the provided travel time form the real travel time regardless of the absolute travel time. We therefore assume that the 10 minutes is appropriate to the variation of the travel time for the trip length focused on in this paper. Since *ATTV* and *DTTR* are set to be 10 minutes, $P(Tave+10)$ and $P(Tave-10)$ are used in this paper. With this information, drivers are able to determine the likelihood that they will arrive on time of arriving on time.

Next, we propose other travel time reliability indexes. Whereas the previously proposed indexes are 2σ type indexes, 1σ type index is useful for users. Thus we propose the following index as,

$$TT85-TT15 \quad , \tag{13}$$

And we also propose the following indexes for indexes' behavioral checking as:

$$TT80-TT20 \quad , \tag{14}$$

and

$$TT70-TT30 \quad , \tag{15}$$

These indexes can be used not only for users but also operators.
These twelve indexes discussed in this paper are summarized and categorized in **Table 1**.

Table 1. Qualitative Comparison of Travel Time Reliability Indices

	Incomparable with Other Highway	Comparable with Other Highway
Indices for Operator Side	PT BT TTV $\lambda\, skew$ $\lambda\, \mathrm{var}$	PTI BTI
Indices for Operator and User Side	$TT85$-$TT15$ $TT80$-$TT20$ $TT70$-$TT30$	
Indices for User Side	$P(ave+ATTV)$ $P(ave$-$DTTR)$	

MULTI HIERARCHICAL STOCHASTIC MODEL FOR TRAVEL TIME VARIATION

This chapter presents a multi hierarchical stochastic model for estimating travel time variation under the uncertainty of demand and service of bad weather period from observed travel time variation for normal period.

OVERVIEW

This chapter presents an evaluation model for estimating the variation in travel time variation under uncertainty proposed by Wakabayashi (2007). This model is referred to as the Travel Time Variability Assessment Model and considers both variations in demand and service levels under the uncertain environment of snowfall and traffic regulation in the winter season. The framework presented here considers a situation in which a weather forecast affects the implementation of traffic controls, which then impact on travel speed. The output from the model is a probability density function (PDF) for travel time variation along a route with several alternative routes being possible, and for which normal and abnormal weather forecast patterns can be assessed.

The study area is the expressway and high-grade highway network between Nagoya and Osaka in Japan (Figure 5). There are two major routes between Nagoya and Osaka; the Meishin Expressway and the Higashi Meihan Expressway (or Eastern Meishin Expressway). The Meishin Expressway is a logistically important trunk highway in Japan and is also used extensively for commuter traffic, which is expected to be high throughout year. However, it is in a heavy winter snowfall region between Nagoya and Osaka - extremely heavy snowfall occurs approximately one season in every 10 years - and is thus often closed for servicing and snowplow work is undertaken frequently. A Second Meishin Expressway is therefore now under construction and expected to service this area as another trunk highway.

Figure 3 shows the flow of the evaluation model from input to output, with actual weather forecast data used for the input. If there is no snowfall, then no traffic regulation due to snowfall is imposed. Conversely, if there is snowfall, traffic regulation is determined depending on the extent of snowfall.

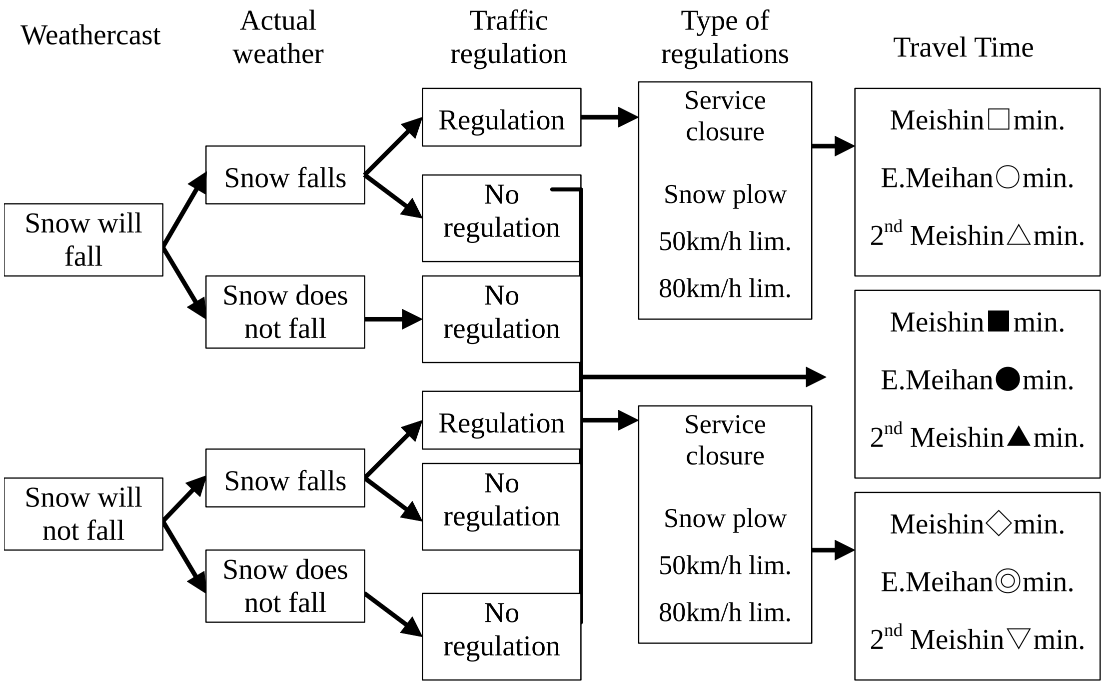

Figure3. Frow from weathercast to travel time

Under conditions of bad weather, such as snowfall or rainfall, traffic on a high-grade road is restricted and traffic regulation can be classified into one of the following four categories: "Road closed", "Snowplow in operation," "50 km/h-limit," or "80 km/h-limit." "Snowplow in operation" is a traffic regulation implemented in 1983 for the Meishin Expressway. Two snowplows form a brigade and remove snow together while traveling slowly; the snowplows also lead the vehicles that are on the road and thus greatly affect driving speed. In this study, "No regulation" was added to the above four levels to give five levels in total:
1) Road closed, 2) Snowplow in operation, 3) 50 km/h-limit, 4) 80 km/h-limit and 5) No regulations in place.

FRAMEWORK FOR DETERMINING TRAVEL TIME RELIABILITY FROM SNOWFALL WEATHERCAST

Weather Forecasts and Traffic Regulation

The reliability of an expressway network under bad weather cannot be sufficiently analyzed by only investigating the traffic regulation (for example, the annual frequency and duration of the traffic regulation should also be analyzed). This is because traffic is only controlled under bad weather conditions. Thus, the probability of regulation due to weather conditions needs to be clarified. Since it is difficult to determine the actual weather conditions along an expressway network, we created a conditional probability model to estimate the level of traffic regulation based on the weather forecast. The following expression is based on weather forecasts and can be used to calculate the conditional probability $p_{a,rj|wi}$ of traffic regulation level:

$$p_{a,rj|wi} = \text{Prob (Regulation level } j \mid \text{Weather forecast level } i \text{ on link } a) \quad , \qquad (16)$$

where r_j is the traffic regulation level and w_i is the weather forecast concentration level (mentioned later). This is combined with the model for estimating the travel time under each regulation level (also mentioned later) to estimate the reliability of the travel time.

Measurement of Space Mean Speed and Travel Time

In this study, the space mean speed in an object road section and the distribution of travel time in a unit section need to be determined. Therefore, the distribution of space speed is measured using a floating survey.

Problem of Dependent Failure

Under the conventional analysis of reliability, fault events have theoretically been constructed based on the assumption of independence because a mathematical formulation is straightforward. Conversely, dependent failures are regarded as "difficult and important subjects" (Kumamoto, 1988). In many cases of dependent failures, results based on independent assumptions have been corrected according to the experiences of engineers.

By reviewing studies of dependent failures, Kumamoto (1988) roughly classified failures under limited conditions into three types: failures attributable to a common cause, inter-system dependent failure, and inter-component dependent failure. Although Kumamoto (1988) further classified the three types of dependent failures into nine types and described their analytical methods, if the different dependent failures attributable to a common cause are described as a single unit, none of the analytical methods differs greatly from independent methodologies and is therefore not suited to the extensive analysis that is typical of dependent failures. Dependencies of the kind that we are investigating at present are also considered "difficult and important subjects (Kumamoto, 1988)".

Therefore, in this study, the following two types of dependency were considered:

1) Dependency of the vehicles' driving status between adjacent sections, and;

2) Dependency of traffic regulations due to a snowfall between adjacent sections.

For the Type 1 dependency, the driving behaviors in each section or per unit distance on an expressway cannot be practically independent. In other words, the driving status of a driver as a certain dependency is maintained throughout all the sections, which needs to be considered in any reliability evaluation. For Type 2, traffic regulations become dependent in adjacent sections of an expressway under bad weather. In other words, the assumption of independency simplifies mathematical formulations and solutions. However, this does not reflect the fact that, if a traffic regulation (*e.g.*, service closure) is applied to a section due to a snowfall, a similar regulation is also necessary in adjacent sections; Type 1 and 2 dependencies therefore need to be considered explicitly.

ESTIMATION MODEL OF TRAVEL TIME VARIATION

This section glances at the estimation model of travel time variation under uncertainty proposed by Wakabayashi (2008). This model is referred to as the Travel Time Variability Assessment Model and considers both variations in demand and service levels under the uncertain environment such as snowfall or heavy rainfall. The output from the model is a probability density function (PDF) for travel time variation along a route with several alternative routes being possible.

The travel time reliability is the probability of traveling between a given OD pair within time t. Since an OD consists of multiple links, the PDF of travel time on the regulation level r_j of each link is $h_{a,rj}(t)$. The regulation level such as road closure, snowplow or speed limit is determined in advance through the weather forecast model. This PDF of travel time is given to the regulation level r_j of each link. Considering the PDF $H_{a,rj}(t)$ of travel time for link a, the PDF of travel time can be expressed as:

$$H_{a,rj}(t) = \int_0^t h_{a,rj}(t)dt \, . \tag{17}$$

This $H_{a,rj}(t)$ on the regulation level r_j gives the travel time variation when the travel time for link a is within t.

In this study, "conservation of cruising speed order" is assumed. Based on this assumption, the travel time reliability for several sections is calculated based on the scheme shown in **Figure 4**. The reverse function of the probability distribution function $H_{a,rj}(t)$ of travel time for link a expressed above in Eq. (13), is discussed next. Here, the travel time t under the cumulative probability p_1 on link a is:

$$t_{p_1,a} = H_{a,rj}{}^{-1}(p_1)\,. \tag{18}$$

The travel time $t_{p1,L}$ between an OD is:

$$t_{p_1,L} = \sum_{a \in L} H_{a,rj}{}^{-1}(p_1)\,, \tag{19}$$

where L is the set of links.

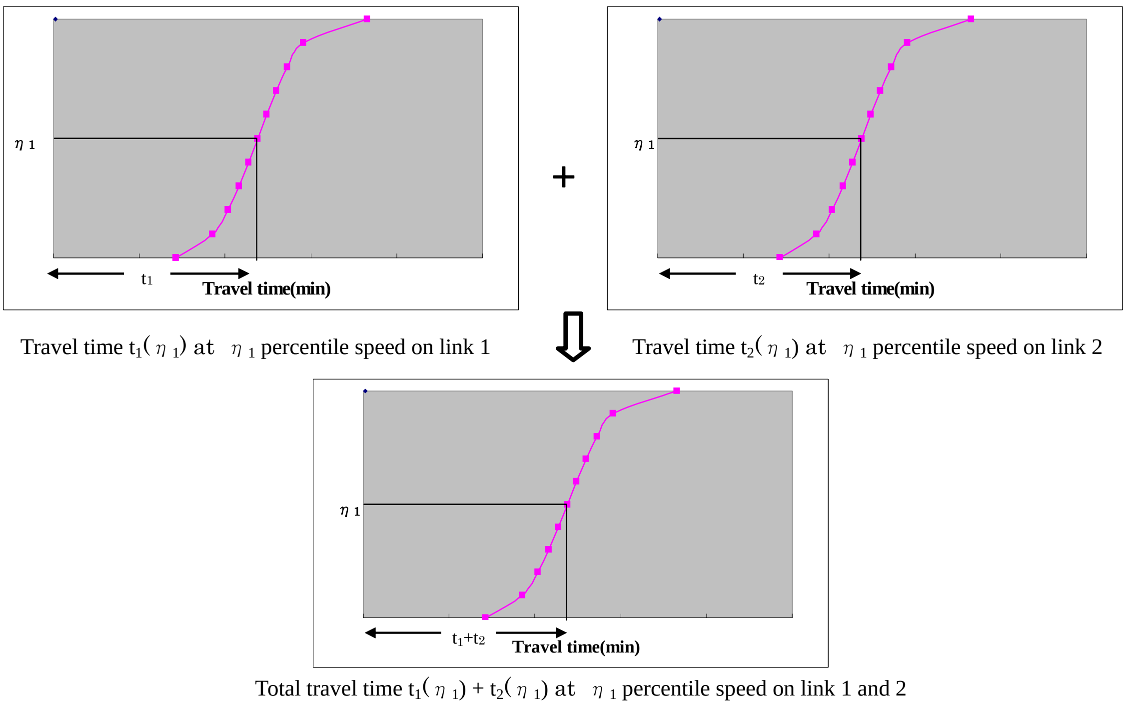

Figure 4. Conservation of Cruising Speed Order

This idea allows the dependency of inter-link driving speed by the same driver to be expressed. If the number of component links between an OD is l, there are 5^l combinations of traffic regulations. Therefore, the travel time reliability for each cumulative probability p_1 between an OD can be calculated from the expected value based on the probability of realization $\prod_{a\in L} p_{a,rj|wi}$ and Equation (15) as

$$\sum_{rj}(\prod_{a\in L} p_{a,rj|wi} t_{p_1,L}) = \sum_{rj}\{\prod_{a\in L} p_{a,rj|wi} \sum_{a\in L} H_{a,rj}^{-1}(p_1)\}. \tag{20}$$

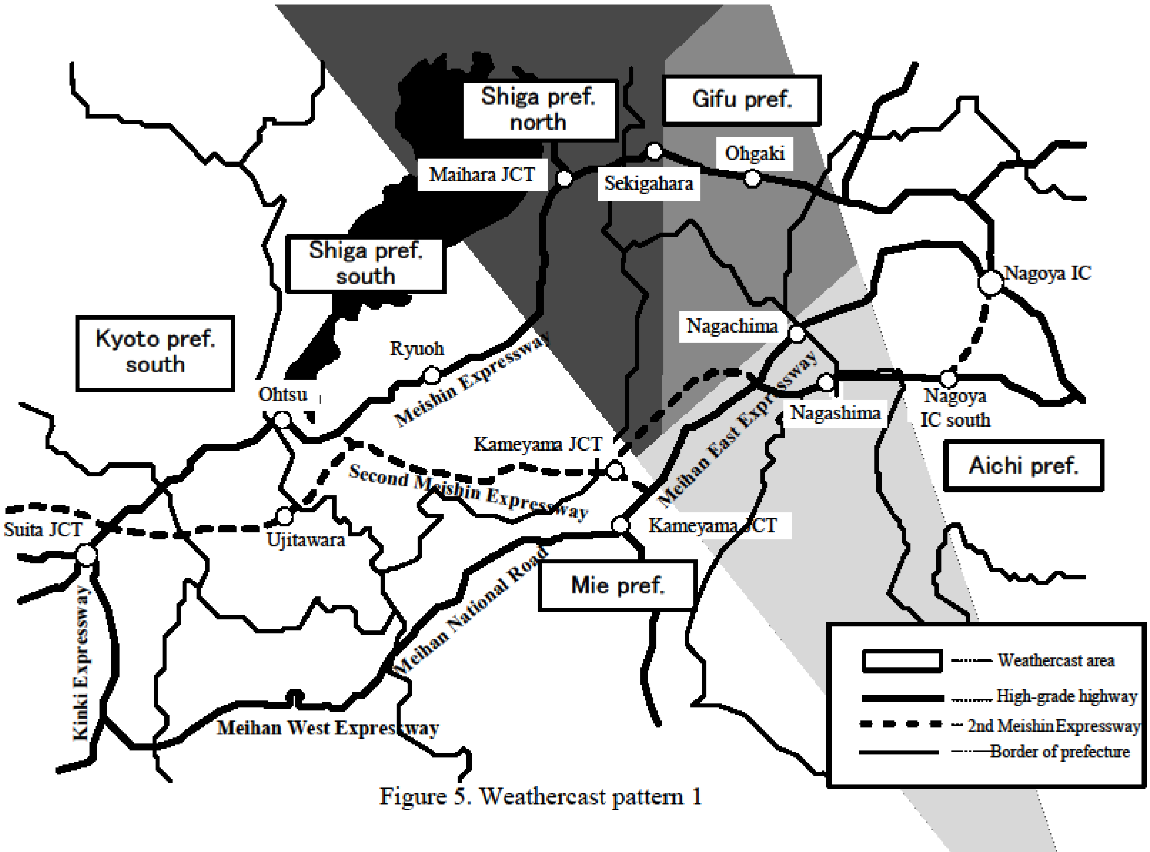

Figure 5. Weathercast pattern 1

STUDY AREA

The study area is as expressway network between Nagoya IC (Inter Change) and Suita JCT (Junction), and there are three routes between the OD pair shown in **Fig. 3**. The main route, *i.e.* New-Meishin Expressway is the shortest route and has less travel time variation. The alternate routes, *i.e.* Meishin Expressway and Higashi-Meihan Expressway are the second and third shortest routes and have rather greater travel time variation. This section lies over Aichi, Gifu, Mie, Shiga and Kyoto prefectures.

CALCULATION RESULTS

First, the travel time variation is analyzed under conditions of no traffic regulations. Then, travel time variation is analyzed under a variety of snowfall scenarios. Here, the travel time variation is calculated from the probability of traffic regulation on each route by assigning different weather forecast patterns to each prefecture. The probability distribution of the travel time obtained is calculated from all potential combinations of traffic regulations under the given weather forecasts.

Figure 5 shows the snowfall areas for the study area. For the Pattern 1 weather forecast shown in **Fig. 3**, the weather concentration level for snowfall probability is 0% to 20% for Aichi prefecture, 30% to 50% for Gifu prefecture, 60% to 100% for northern Shiga prefecture, 0% to 20% for southern Shiga prefecture, 0% to 20% for southern Kyoto prefecture, and 0% to 20% for Mie prefecture. Based on the estimated travel time variations, we calculate *PT, PTI, BT, BTI,* $\lambda skew$, $\lambda \mathrm{var}$, *TTV, P*(*Tave*+10) and *P*(*Tave*-10) values shown in **Table 2** to **Table 4**. Every travel time reliability index is accompanied with a ranking for normal period (upper three rows) and potential snowfall period (lower three rows).

Table 2. Quantitative Comparison of Travel Time Reliability indexes (1)

	Tave	ranking	*PT*	ranking	*PTI*	ranking	*BT*	ranking	*BTI*	ranking
Normal Meishin	119.04	2	164.16	2	2.30465	2	45.12	2	0.37903	3
Normal Higashi-Meihan	145.53	3	190.71	3	1.95725	1	45.18	3	0.31044	1
Normal New-Meishin	93.25	1	128.59	1	2.30448	3	35.34	1	0.37898	2
Expected Value Meishin	140.02	2	183.61	2	1.95658	2	43.59	2	0.31128	2
Expected Value Higashi-Meihan	146.28	3	191.47	3	1.95001	1	45.19	3	0.30890	1
Expected Value New-Meishin	98.48	1	133.77	1	2.18987	3	35.29	1	0.35836	3

Table 3. Quantitative Comparison of Travel Time Reliability indexes (2)

	λskew	ranking	*λvar*	ranking	*TTV*	ranking	P(*Tave* +10)	ranking	P(*Tave* -10)	ranking
Normal Meishin	2.00760	3	0.44355	3	52.80000	2	68.30935	3	31.34650	2
Normal Higashi-Meihan	1.99996	1	0.36338	1	52.88300	3	68.53051	2	31.47101	3
Normal New-Meishin	2.00679	2	0.44354	2	41.36000	1	73.27982	1	26.91406	1
Expected Value Meishin	2.00748	3	0.36416	2	50.99000	2	68.95522	2	30.72356	2
Expected Value Higashi-Meihan	2.00057	1	0.36161	1	52.89700	3	68.52506	3	31.44666	3
Expected Value New-Meishin	2.00731	2	0.41935	3	41.29671	1	72.88500	1	26.88535	1

Table 4. Quantitative Comparison of Travel Time Reliability indexes (3)

	P(*Tave*+10)	ranking	P(*Tave*-10)	ranking	*TT*85-*TT*15	ORDER	*TT*80-*TT*20	ranking	*TT*70-*TT*30	ranking
Normal Meishin	68.30935	3	31.34650	2	43.68000	2	34.56000	2	21.69000	3
Normal Higashi-Meihan	68.53051	2	31.47101	3	43.82650	3	34.77000	3	21.65300	2
Normal New-Meishin	73.27982	1	26.91406	1	34.21500	1	27.07000	1	16.99000	1
Expected Value Meishin	68.95522	2	30.72356	2	42.23000	2	33.47000	2	20.95000	2
Expected Value Higashi-Meihan	68.52506	3	31.44666	3	43.83300	3	34.76900	3	21.63800	3
Expected Value New-Meishin	72.88500	1	26.88535	1	34.18252	1	27.06833	1	16.96912	1

In **Table 2,** the second and third columns are the average travel time. As stated above, for the normal and snowfall periods, the fastest route is the New-Meishin route at 93.25 min and 98.48 min, respectively. The second fastest route for the normal and snowfall periods is the Meishin route at 119.04 min and 140.02 min, respectively, followed by the Higashi-Meihan route at 145.53 min and 146.28 min, respectively.

In **Table 4**, the *P*(*Tave*+10) and *P*(*Tave*-10) travel time reliability indexes are summarized with *TT*85-*TT*15, *TT*80-*TT*20 and *TT*70-*TT*30. For example, one of the *P*(*Tave*+10) values, 68.31, indicates that the 68.31 percentile vehicles travel within the average travel time plus 10 minutes. This information affords drivers the probability of a 10 plus delay from the average travel time. Similarly, one of the *P*(*Tave*-10) values, 31.35, indicates that the 31.35 percentile vehicles travel within the average travel time minus 10 minutes. This information gives drivers the chance of being 10 minutes early arrival to their average travel time. This information is likely to be more useful for drivers rather than operative officials.

In **Table 4**, the larger value in *P*(*Tave*+10) gives more reliable route. Thus the ranking is given in the second column in **Table 4**. In turn, the lower value in *P*(*Tave*-10) gives more reliable route.

COMPARATIVE DISCUSSION OF TRAVEL TIME RELIABILITY MEASURES

Based on the PDF curve, we calculate *PT, PTI, BT, BTI,* $\lambda skew$, $\lambda \mathrm{var}$, *TTV, P*(*Tave*+10), *P*(*Tave*-10) *TT*85-*TT*15, *TT*80-*TT*20 and *TT*70-*TT*30 values shown in Table 3 to Table 5. Every travel time reliability index is accompanied with a ranking for normal period (upper three rows) and potential snowfall period (lower three rows).

In Table 3, the second and third columns are the average travel time. As stated above, for the normal and snowfall periods, the fastest route is the Second-Meishin route at 93.25 min and

98.48 min, respectively. The second fastest route for the normal and snowfall periods is the Meishin route at 119.04 min and 140.02 min, respectively, followed by the Higashi-Meihan route at 145.53 min and 146.28 min, respectively.

In Table 4, the $P(Tave{+}10)$ and $P(Tave{-}10)$ travel time reliability indexes proposed in this paper are summarized. For example, one of the $P(Tave{+}10)$ values, 68.31, indicates that the 68.31 percentile vehicles travel within the average travel time plus 10 minutes. This information affords drivers the probability of a 10 plus delay from the average travel time. Similarly, one of the $P(Tave{-}10)$ values, 31.35, indicates that the 31.35 percentile vehicles travel within the average travel time minus 10 minutes. This information gives drivers the chance of being 10 minutes early arrival to their average travel time. This information is likely to be more useful for drivers rather than administrative officials.

In Table 5, the larger value in $P(Tave{+}10)$ gives more reliable route. Thus the ranking is given in the second column in Table 5. In turn, the lower value in $P(Tave{-}10)$ gives more reliable route. Thus the ranking is given in the 4th column in Table 5.

Based on Tables 3 to 5, the following characteristics of travel time reliability indexes for highway users and operators under uncertain environment are apparent:

(1) *PT* and *PTI*, and *BT* and *BTI* have the quite different ranking. This is because *PTI* and *BTI* are standardized indexes (see Eqs. (2) and (7)).

(2) From Eqs. (6) and (7), *BTI* produces smaller values for more reliable route. Since a smaller travel time variation is desirable, smaller *BTI* values are preferable. However, since *BTI* values are larger for routes with reduced more reliable travel times, which is a disadvantage of *BTI* and is illustrated by the low ranking in Table 3 for the New-Meishin route.

(3) From Tables 3 and 4, $\lambda skew$, $\lambda \mathrm{var}$ and *BTI* all exhibit similar tendencies since they have the same ranking.

(4) $P(Tave{+}10)$ and $P(Tave{-}10)$ have similar ranking tendencies with respect to *Tave* and the gradient of the PDF curves in Figure 4. *TTV* exhibits the same tendency as $P(Tave{+}10)$ and $P(Tave{-}10)$.

(5) $P(Tave{+}10)$ and $P(Tave{-}10)$ are user-side reliability indexes. *BTI*, $\lambda skew$, $\lambda \mathrm{var}$ and *TTV* are operator side reliability indexes, which exhibit different tendencies in their ranking. We

also propose the user- and operator-side reliability indexes, *TT*85-*TT*15, *TT*80-*TT*20 and *TT*70-*TT*30. While *BTI* is a 2σ-type index with respect to the normal standard distribution, *TT*70-*TT*30 is a 1σ-type index. These indexes and their associated rankings are summarized in Table 5. *P*(*Tave*+10), *P*(*Tave*-10), *TT*85-*TT*15, *TT*80-*TT*20, *TT*70-*TT*30 and *TTV* exhibited similar tendencies with respect to their ranking.

CONCLUSIONS

Travel time reliability indexes are emerging evaluation measures of highway network service levels. In this paper, previously proposed travel time reliability indexes were discussed and compared according to the application of two different case studies. Qualitative comparisons from the viewpoints of operator / user sides and comparable / incomparable with other highway systems were shown.

We proposed new indexes of travel time reliability such as *P*(*Tave*+*ATTV*), *P*(*Tave*-*DTTR*), *TT*85-*TT*15, *TT*80-*TT*20, *TT*70-*TT*30. The results showed that the *BTI*, $\lambda skew$ and λvar indexes exhibited similar tendencies, and that *P*(*Tave*+*ATTV*), *P*(*Tave*-*DTTR*), *TT*85-*TT*15, *TT*80-*TT*20, *TT*70-*TT*30 and *TTV* exhibited distinct and similar behavioral tendencies. These results are summarized and compared in **Tables 2**.

We also propose the operator-side reliability indexes, *TT*85-*TT*15, *TT*80-*TT*20 and *TT*70-*TT*30. While *BTI* is a 2σ-type index with respect to the normal standard distribution, these indexes are a 1σ-type index. These indexes and their associated rankings are summarized in **Tables 4**. *P*(*Tave*+*ATTV*), *P*(*Tave*-*DTTR*), *TT*85-*TT*15, *TT*80-*TT*20, *TT*70-*TT*30 and *TTV* exhibited similar tendencies with respect to their ranking. These indexes proposed in this paper give good fitness with PDF curves for travel time variation.

P(*Tave*+*ATTV*) and *P*(*Tave*-*DTTR*) are user-side reliability indexes. *BTI*, $\lambda skew$, λvar and *TTV* are operator side reliability indexes, which exhibit different tendencies in their ranking.

This paper focused on the characteristic differences among travel time reliability indexes. Comparative study demonstrates that every index exhibits its property depending on the route characteristics. This result suggests that the combination of average travel time and appropriate travel time reliability index are very important for assessing truly reliable route in travel time.

Future research will focus on the development of other potential indexes, including a proportional-type index. *P*(*Tave*+*ATTV*), *P*(*Tave*-*DTTR*), *TT*85-*TT*15, *TT*80-*TT*20 and *TT*70-*TT*30 are indexes that are incomparable with other highway systems and development of an index that is comparable index is necessary. Cumulative study is also needed.

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