TRAVEL TIME RELIABILITY ANALYSIS IN MIXED TRAFFIC NETWORK UNDER PROVISION OF ADVANCED TRAVELER INFORMATION SYSTEM *

by Phyrum KOV**, Yasuhiro HIROBATA***, and Yasuyuki NAKAHIRA****

1. Introduction

Recently, transportation network reliability has attracted more attention from many researchers and planners along with the increasing need of the society for a more reliable transportation system which is very important for people's daily commute. In urban network, unreliable travel time is one of the major disturbances for commuters, since it is the main source of uncertainty in arriving at the destination within an acceptable travel time so that it is difficult for travelers to schedule their trip. This problem gives rise to the study of travel time reliability.

It has been argued by previous studies that, under normal day-to-day operation of transportation network, travel time variation or unreliability is caused by daily fluctuation of supply side or non-recurrent congestion[1]; and day-to-day variation of demand side[2]. While the former is related to the unexpected change in link capacity attributed to some minor disruptions along roadway such as illegal parking, traffic accidents, or road works etc., the latter corresponds to the change in travel demand including trip making decision, trip distribution, mode choice, and trip assignment. Considering demand side variation, the change in trip generation and distribution on daily basis induces a so-called day-to-day OD demand change. Now that this change occurs in an unknown and unpredictable manner, OD travel demand can be considered as random variable whose realized value is the OD demand on each day. Therefore, although network capacity is relatively fixed on normal operation of transportation network, stochastic OD demand becomes a major factor contributing to unreliable travel time on network; and it is the essence of this study that we incorporate this stochasticity in assessing the travel time reliability. In this framework, Clark and Watling[2] appeared to be the first authors who attempted to estimate probability distribution of total network travel time considering day-to-day fluctuation of travel demand by proposing an analytical method to determine moments of network travel time. Yet, their study is limited to single-mode network while actual network is composed of various types of vehicle (e.g. large and small, or slow and fast vehicles) having different performance functions and interacting on each other in different way. Therefore, their study may provide a misleading interpretation in real world application, especially when network exhibits many modes having strongly different performance (e.g. car and motorbike).

Within this context, Kov *et al.*[3] proposed an analytical model to estimate first and second order moments of link travel time by incorporating two types of vehicle on each link of the network while OD demand is day-to-day stochastic. It is, however, arguable that the model formulated in their study is applicable only for a two-mode network, and the link flow moments which are the most important inputs of the model are obtained from collection of link flow statistics over time. In addition, the method used to derive link flow on each day is based on equilibrium assignment model which lacks of behavioral consistence such that traveler's ability to build up their memory over time is ignored. In this sense, the first objective of this paper is to extend the analytical approach for modeling the moments of travel time proposed by Kov *et al.*[3] by incorporating multiple vehicle types in the formulation along with theoretical method of determining link flow moments, and by taking into account traveler's day-to-day learning.

The second objective is to evaluate the travel time reliability using travel time moments obtained from the analytically formulated model. In this way, travel time reliability can be analyzed by properly taking into consideration flow of mixed traffic whose interaction is appropriately tackled. At this point, it is worth noting that even though numerous studies on travel time reliability have been conducted, none of them considered mixed types of vehicle in their studies.

Now turning attention to the information technology (IT), it is believed that IT can play critical role in

* Keywords: travel time reliability, mixed traffic network, ATIS

** Graduate Student, Dept. of Architecture and Civil Engineering, Toyohashi University of Technology,
(1-1, Hibarigaoka, Tempaku-cho, Toyohashi city, 441-8580 Japan, TEL 0532-44-5625, FAX 0532-44-6831)
*** Member of JSCE, Dr. Eng., Dept. of Architecture and Civil Engineering, Toyohashi University of Technology,
(1-1, Hibarigaoka, Tempaku-cho, Toyohashi city, 441-8580 Japan, TEL 0532-44-6833, FAX 0532-44-6831)
****Member of JSCE, M. Eng., Dept. of Civil Engineering, Kinki University Technical College,
(Arima-cho 2800, Kumano city, Mie 519-4395 Japan, TEL 0597-89-2011, FAX 0597-89-1018)

bettering network performance. Given that travel time unreliability is becoming more and more serious in this modern society drivers may try to seek any possible mean that might help them to improve their travel time reliability. With advanced development of technology and emerging Intelligent Transportation System (ITS), some drivers try to get access to Advanced Traveler Information System (ATIS), which provides predictive information or the information on current network condition at pre-trip stage, in the expectation that it will help them to make their trip more reliable and predictable. However, whether ATIS can really help to improve the travel time reliability of equipped drivers is very questionable; and not so many researches have devoted in this field. To our knowledge, Lam *et al.*[4] are the first authors who analyze the reliability in terms of generalized travel cost under provision of predictive information while traffic flow is subject to random day-to-day fluctuation.

In similar fashion to Lam *et al.*[4], this paper will also investigate the impacts of ATIS on travel time reliability, which is the final objective of this study. It should be noted that this paper will firstly propose analytical model to estimate travel time moments in mixed traffic network under stochastic OD demand, then calculate travel time reliability, and finally analyze the effects of ATIS on travel time reliability.

2. Notations and Assumptions

For the sake of simplicity, the notations that will be used throughout the paper are defined as follows: q_{od} is the mean OD demand (given by OD matrix) corresponding to random variable Q_{od} (person trips/hr). σ_{od}^2 is the variance of OD demand distribution. q^i_{od} is the mean OD demand of mode i corresponding to random variable $Q^i_{od}(i = 1, 2, \ldots, n)$ measured in person trips per hour. σ_{od}^{ij} is the covariance between OD demand by mode i and mode j. $p_{i|od}$ is the probability of choosing mode i for a given OD pair. R_{od} represents the index set of paths connecting the pair OD. $p_{r|i}^{od}$ is the probability or fraction that the driver of mode i chooses path r ($r \in R_{od}$) to travel from O to D. λ_i^{od} is the vehicle occupancy of mode i for a given OD pair (passengers/vehicle). f_{ri}^{od} is the mean flow of mode i on path r ($r \in R_{od}$). v_{ai} is the realized flow of mode i on link a ($a = 1, 2, \ldots, A$). μ_{ai} is the mean flow of mode i on link a. σ_a^{ij} is the covariance between flow of mode i and mode j on link a. α_{ij} is the flow converting factor of mode i to mode j which is equal to 1 if $i = j$. C_{ai} is the capacity of link a for mode i (vehicle/hr). t_{0ai} and t_{ai} is the free-flow travel time and realized travel time of mode i on link a. $\mu_{T_{ai}}, \sigma^2_{T_{ai}}$ are the mean and variance respectively of travel time on link a for mode i. $c_{r|i}^{od}$ is the realized travel time on path r for mode i traveling from O to D. $\mu_{C^{od}_{r|i}}, \sigma^2_{C^{od}_{r|i}}$ are respectively the mean and variance of travel time on path r for mode i. $\mu_{i,od}, \sigma^2_{i,od}$ are the mean and variance of OD travel time for mode i corresponding to random variable $T_{i,od}$. δ_{ar}^{od} is link-path incidence index for a pair OD being equal to 1 if link a is part of path r and 0 otherwise. V_{ai}, $C_{r|i}^{od}$, T_{ai} are random variables of v_{ai}, $c_{r|i}^{od}$, t_{ai}.

In the study of day-to-day dynamics, the period that is considered to analyze the system variation can be part of the day (e.g. morning rush hour) or the whole day. Hereafter in this paper the term *reference period* and *day* will be used interchangeably to refer to the period under study. The reference period is further divided into *intervals* since it is more relevant in the framework of providing pre-trip information to drivers.

Before proceeding, the following assumptions should be adopted throughout this study:

i) The actual demand for each OD pair is randomly distributed in the day-to-day context; and all OD demand on each day is statistically independent across OD pairs. The OD demand is inelastic with network level of service.

ii) For each OD demand of any one day, travelers choose independently between alternative modes i (i = 1, 2, ..., n) with constant probabilities $p_{i|od}$. Over time, these probabilities remain unchanged regardless of network travel time.

iii) Conditional on OD demand realized on any one day, driver on a given mode i is assumed to choose independently between alternative paths $r \in R_{od}$ with constant probability (route choice fraction) $p_{r|i}^{od}$.

iv) The departure rate is uniformly distributed within the reference period, i.e. the same number of travelers departs at each interval; and the duration of each interval is large enough so that usual definition of link-path incidence maintains its significance. Moreover, travelers are assumed not to have incentive to change their departure time from one day to another so that route choice is the only decision open to them.

v) All drivers have the knowledge of travel time history for the time they depart through their own experience for the routes they used and via the information provided by media for the unused routes. Additionally, the drivers equipped with ATIS can have the knowledge about network travel time in the previous intervals of the same day through information supplied by ATIS.

vi) The pre-trip information about the current network condition is provided at every interval of the reference period.

3. Model Formulation

(1) Determination of link flow moments

Given the relationship $Q^i_{od} = p_{i|od}\, Q_{od}$, the mean, variance and covariance of modal OD demand can be determined by $q^i_{od} = p_{i|od}\, q_{od}$, $\sigma^{ii}_{od} = p^2_{i|od}\, \sigma^2_{od}$, and $\sigma^{ij}_{od} = p_{i|od}\, p_{j|od}\, \sigma^2_{od}$ respectively. Therefore, link flow which is related to OD demand via relation $V_{ai} = \sum_{od}\sum_{r\in R_{od}} (1/\lambda^{od}_i)\delta^{od}_{ar}\, p^{od}_{r|i}\, Q^i_{od}$, can be deduced as follows:

Mean $$\mu_{ai} = \sum_{od}\sum_{r\in R_{od}} (1/\lambda^{od}_i)\delta^{od}_{ar}\, p^{od}_{r|i}\, q^i_{od} = \sum_{od}\sum_{r\in R_{od}} (1/\lambda^{od}_i)\delta^{od}_{ar}\, p^{od}_{r|i}\, p_{i|od}\, q_{od} \tag{1}$$

Variance $$\sigma^{ii}_a = \sum_{od} (1/\lambda^{od2}_i)\left(\sum_{r\in R_{od}} \delta^{od}_{ar}\, p^{od}_{r|i}\right)^2 \sigma^{ii}_{od} = \sum_{od} (1/\lambda^{od2}_i)\left(\sum_{r\in R_{od}} \delta^{od}_{ar}\, p^{od}_{r|i}\right)^2 p^2_{i|od}\, \sigma^2_{od} \tag{2}$$

Covariance $$\sigma^{ij}_a = \sum_{od}\sum_{r\in R_{od}}\sum_{r'\in R_{od}} (1/\lambda^{od}_i\lambda^{od}_j)\delta^{od}_{ar}\delta^{od}_{ar'}\, p^{od}_{r|i}\, p^{od}_{r'|j}\, p_{i|od}\, p_{j|od}\, \sigma^2_{od} \tag{3}$$

Equation (3) can be demonstrated by the following arguments:

$$\sigma^{ij}_a = Cov(V_{ai}, V_{aj}) = Cov\left(\sum_{od}\sum_{r\in R_{od}} (1/\lambda^{od}_i)\delta^{od}_{ar}\, p^{od}_{r|i}\, Q^i_{od}, \sum_{o'd'}\sum_{r'\in R_{o'd'}} (1/\lambda^{o'd'}_j)\delta^{o'd'}_{ar'}\, p^{o'd'}_{r'|j}\, Q^j_{o'd'}\right)$$
$$= \sum_{od}\sum_{o'd'}\sum_{r\in R_{od}}\sum_{r'\in R_{o'd'}} (1/\lambda^{od}_i\lambda^{o'd'}_j)\delta^{od}_{ar}\delta^{o'd'}_{ar'}\, p^{od}_{r|i}\, p^{o'd'}_{r'|j}\, Cov(Q^i_{od}, Q^j_{o'd'})$$

where, $Cov(Q^i_{od}, Q^j_{o'd'}) = p_{i|od}\, p_{j|o'd'}\, Cov(Q_{od}, Q_{o'd'})$

According to the assumptions above, the random OD demand of different OD pairs are mutually independent, implying that $Cov(Q_{od}, Q_{o'd'})=0$. Therefore, $Cov(Q^i_{od}, Q^j_{o'd'})=0$ and $Cov(Q^i_{od}, Q^j_{od})=\sigma_{od}^{ij}$ from which the above equation can be reduced to $\sigma^{ij}_a = \sum_{od}\sum_{r\in R_{od}}\sum_{r'\in R_{od}} (1/\lambda^{od}_i\lambda^{od}_j)\delta^{od}_{ar}\delta^{od}_{ar'}\, p^{od}_{r|i}\, p^{od}_{r'|j}\, \sigma^{ij}_{od}$, which is equivalent to (3).

It is worth noting that random link flow which is obtained by taking summation of random route flow over routes and OD pairs can be approximated to follow multivariate Normal distribution by Central Limit Theorem. This approximation becomes more realistic with the larger size of network in the sense that large number of OD pairs and paths pass through a link a. In such case, link flow moments given in (1), (2), and (3) are approximately the moments of multivariate Normal V_{ai}. The multivariate Normal approximation of link flow in this section will be later seen useful in the formulation of travel time moments below.

It is also important to note that in the above formulation route choice fraction $p_{r|i}{}^{od}$ is assumed to be constant, and it is referred to as base route choice fraction. In this study, we adopt route choice fraction that is derived from the stationary probability distribution of the stochastic process (SP) proposed by Cascetta[5] based on mean OD demand. This method is seen to be relevant for traffic assignment in the context of temporal evolution of the transportation system. In SP approach, the state occupied by the system at any day t is dependent on the system states occurred in previous epochs i.e. t-1, t-2, …, t-n etc. Therefore, it may reflect some behavioral characteristics of travelers in the sense that travelers usually make choice or decision at any day t based on previous experiences that they have undergone in the previous times. In this case, SP method can well incorporate the driver's ability to build up their memory over time, i.e. learning over day-to-day, which is quite realistic in real world. Moreover, the reason that SP model is adopted in our multi-modal assignment is due to its powerful results in route choices and flows when the system state evolves over time. It has been proved that the temporal evolution of the transportation system is dynamically stable and ergodic under some mild conditions regardless of link performance function, i.e. it admits steady-state probabilities from which mean and moments of link flows can be deduced analytically. The sufficient conditions of stability and ergodicity of the system are: firstly, route choice probability is time homogenous which means that it is invariant under temporal translation of same sets of system states, secondly route choice probability is positive which can be easily obtained through traditional route choice model, and thirdly the memory of drivers on network condition over time is limited to a finite number of days.

In addition, the stationarity and ergodicity of the system still hold when drivers update network travel time up to their departure interval based on travel time that occurred in the previous intervals of the same reference period, which can be accomplished only by provision of pre-trip information[6]. From the computational point of view, although the stationary probability distribution can be calculated analytically, Monte Carlo simulation approach exhibits more advantages in large network problem[5),6)] for its tractability, so that it is adopted in this paper.

Based on fixed mean OD demand, the simulation procedure of determining the base route choice fraction $p_{r|i}^{od}$ can be described as follows:

Step 1: Initialize day $t = 0$, and initialize updated past travel time

Step 2: Set next day $t = t + 1$, initialize interval $h = 0$, and initialize travel time supplied by ATIS

Step 3: Set next interval $h = h + 1$

Step 4: Based on the departure rate of the current interval, perform traffic assignment of *non-equipped drivers* using updated past travel time, and *equipped drivers* using combination of updated past travel time and travel time supplied by ATIS

Step 5: Calculate travel time and flow for current interval. If the reference period ends, go to step 6. Otherwise, update travel time provided by ATIS and go to step 3

Step 6: Perform stationarity test. If satisfied, calculate stationary mean route flow for each interval by averaging flow over days and discarding some initial days, and stop. Otherwise, update past travel time up to day t and go to step 2

Once the stationary mean route flow is obtained, base route choice fraction can be calculated accordingly by dividing mean route flow by mean OD demand.

(2) Calculation of link travel time moments

For the sake of simplicity, the index a will be dropped from the formulation below. Then, since there are n modes on a link, the travel time of any one mode is affected by flows of the others. So, the performance function of mode j can be expressed by:

$$T_j = t_{0j}\left(1+\gamma_j\left(\sum_{i=1}^{n}\alpha_{ij}V_i/C_j\right)^{\beta_j}\right) \tag{4}$$

where γ_j is non-negative constant, and β_j is non-negative integer.

Then, mean travel time: $\mu_{T_j} = t_{0j} + \left(\gamma_j t_{0j}/C_j^{\beta_j}\right)E\left[\left(\sum_{i=1}^{n}\alpha_{ij}V_i\right)^{\beta_j}\right]$, and

variance of travel time: $\sigma_{T_j}^2 = \left(\gamma_j^2 t_{0j}^2/C_j^{2\beta_j}\right)\left\{E\left[\left(\sum_{i=1}^{n}\alpha_{ij}V_i\right)^{2\beta_j}\right] - E^2\left[\left(\sum_{i=1}^{n}\alpha_{ij}V_i\right)^{\beta_j}\right]\right\}$

So, we need to calculate $S_j = E\left[\left(\sum_{i=1}^{n}\alpha_{ij}V_i\right)^{\beta_j}\right]$ and $S_j' = E\left[\left(\sum_{i=1}^{n}\alpha_{ij}V_i\right)^{2\beta_j}\right]$ by using Multinomial series.

Firstly, define a set $A(n,\beta_j)$ of n-dimensional non-negative integers a_i, where

$$A(n,\beta_j) = \left\{a_i : i = 1,2,\ldots,n \text{ and } \sum_{i=1}^{n}a_i = \beta_j\right\}$$

By Multinomial expansion, S_j can be written as:

$$S_j = \sum_{a_i\in A(n,\beta_j)}\frac{\beta_j!}{\prod_{i=1}^{n}a_i!}E\left[\prod_{i=1}^{n}\alpha_{ij}^{a_i}V_i^{a_i}\right] = \sum_{a_i\in A(n,\beta_j)}\frac{\beta_j!}{\prod_{i=1}^{n}a_i!}\prod_{i=1}^{n}\alpha_{ij}^{a_i}\cdot E\left[\prod_{i=1}^{n}V_i^{a_i}\right] \tag{5}$$

Then, we can decompose the right side of (5) by: $E\left[\prod_{i=1}^{n}V_i^{a_i}\right] = E\left[\prod_{i=1}^{n}[(V_i-\mu_i)+\mu_i]^{a_i}\right]$ (6)

By Binomial expansion, we have: $[(V_i-\mu_i)+\mu_i]^{a_i} = \sum_{k_i=0}^{a_i}\binom{a_i}{k_i}\mu_i^{a_i-k_i}(V_i-\mu_i)^{k_i}$, where $\binom{a_i}{k_i} = \frac{a_i!}{k_i!(a_i-k_i)!}$

Then, we can write (6) into a new form:

$$E\left[\prod_{i=1}^{n}[(V_i-\mu_i)+\mu_i]^{a_i}\right] = E\left[\prod_{i=1}^{n}\left(\sum_{k_i=0}^{a_i}\binom{a_i}{k_i}\mu_i^{a_i-k_i}(V_i-\mu_i)^{k_i}\right)\right]$$

$$= E\left[\sum_{k_1=0}^{a_1}\cdots\sum_{k_n=0}^{a_n}\left\{\prod_{i=1}^{n}\binom{a_i}{k_i}\mu_i^{a_i-k_i}\cdot\prod_{i=1}^{n}(V_i-\mu_i)^{k_i}\right\}\right]$$

Finally, we get: $E\left[\prod_{i=1}^{n}[(V_i-\mu_i)+\mu_i]^{a_i}\right] = \sum_{k_1=0}^{a_1}\cdots\sum_{k_n=0}^{a_n}\left\{\prod_{i=1}^{n}\left(\binom{a_i}{k_i}\mu_i^{a_i-k_i}\right)\cdot E\left[\prod_{i=1}^{n}(V_i-\mu_i)^{k_i}\right]\right\}$ (7)

Substituting (7) into (6), then (5) takes the form:

$$S_j = \beta_j!\sum_{\substack{a_i\in A(n,\beta_j)\\(i=1,2,\cdots,n)}}\sum_{k_1=0}^{a_1}\cdots\sum_{k_n=0}^{a_n}\frac{\prod_{i=1}^{n}\left(\alpha_{ij}^{a_i}\mu_i^{a_i-k_i}a_i!\right)}{\prod_{i=1}^{n}\left(a_i!\,k_i!\,(a_i-k_i)!\right)}E\left[\prod_{i=1}^{n}(V_i-\mu_i)^{k_i}\right] \tag{8}$$

Similarly, S'_j can be evaluated in the same way as S_j by simply substituting β_j by $2\beta_j$. The detailed calculation of $E\left[\prod_{i=1}^{n}(V_i - \mu_i)^{k_i}\right]$ can be referred to Clark and Watling[2], which requires link flow V_i to be Normal random variable. Here, it can be seen how the approximation of variation of link flow to multivariate Normal distribution is useful in this approach. It is worth to note also that the above expectation term is calculated in function of mean, variance, and covariance of modal link flow given by (1), (2), and (3) implying that the moments of link travel time are obtained with the consideration of modal interaction. Clearly, the first and second order moments of link travel time of mode j can be deduced analytically once S_j and S'_j are estimated by the above formulations.

(3) Evaluation of travel time reliability

Now that mean and variance of network travel time distribution can be measured in an analytical way, travel time reliability can be evaluated accordingly to assess how reliable the network travel time is by incorporating mixed traffic condition. It is widely known that there are two types of travel time reliability: path travel time reliability and OD travel time reliability. While the former is defined as the probability that the travel time of a given path is within an acceptable threshold, the latter is the probability that the weighted average travel time of a given OD pair is within a threshold where weights are the corresponding mean route flows. In this study, the OD travel time reliability which is an aggregate measure for the level of service between O and D is focused since this measure is an important proxy to evaluate the performance of an OD pair. It is reasonable to postulate that travel time on a path consisting of many links follows Normal distribution regardless of link travel time distribution[1] whose mean and standard deviation (SD) can be written as $\mu_{C_{rj}^{od}} = \sum_a \delta_{ar}^{od} \mu_{T_a}$ and $\sigma_{C_{rj}^{od}} = \sqrt{\sum_a \delta_{ar}^{od} \sigma_{T_a}^2}$. This approximation is more likely to be true and realistic in real network problem since the number of links in one route is, in most cases, significantly large. Thence, OD travel time which is the weighted average of path travel time also follows the Normal distribution. Therefore, the OD travel time reliability can be expressed mathematically as $\Pr(T_{i,od} \le t) = \Phi((t - \mu_{i,od})/\sigma_{i,od})$, where t is a given threshold and $\Phi(.)$ is the cumulative standard Normal distribution. Here, it is clear that the travel time reliability estimated in this study takes into account the modal interaction in mixed traffic network, which was not incorporated in other reliability studies.

4. Numerical Example

In this section the travel time reliability in mixed traffic network is investigated numerically by adopting a five-link network with one OD pair given in Figure 1 and Table 1. It is assumed that the network is operated by only two modes: car (c) and motorbike (m). The updating mechanism of travel time of equipped drivers is assumed to follow the function known as exponentially weighted moving average whose form is given by: *Updated TT* = $(1-\varphi)$ * *Updated past TT* + φ * *TT supplied by ATIS*; $(0 \le \varphi \le 1)$. Mode c is assumed to be the only mode that is equipped with ATIS with φ=0.8. Moreover, all drivers are assumed to remember travel time of the past 10 days with equal weights imposed on each day. The reference period is split into 10 intervals, and that only the last interval is subject to study. The flow converting factor is set to α_{cm}=2.0 and α_{mc}=0.3. Distribution of OD demand is $Q_{od} \sim N(q_{od}, \omega . q_{od})$ with ω=0.2. Mode choice probabilities are 0.60 and 0.40 for mode c and mode m respectively; and the vehicle occupancy of both modes are 1. The Probit-based traffic assignment is used with link perception error $\xi_a \sim N(0, \tau . t_a)$, where τ is equal to 0.2 for mode c and 0.3 for mode m.

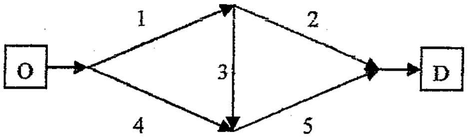

Figure 1: Test network, q_{od} = 100 pers. trip/hr (Route 1: 1→2, Route 2: 1→3→5, and Route 3: 4→5)

Table 1: Network characteristics

Link No.	t_{0a} (min)		C_a (veh/hr)		β_a		γ_a	
	C	m	c	m	c	m	c	M
1	4.00	6.00	40.00	60.00	4	2	0.40	0.50
2	5.00	5.00	40.00	60.00	4	2	0.40	0.50
3	2.00	1.00	60.00	80.00	4	2	0.40	0.50
4	6.00	8.00	40.00	60.00	4	2	0.40	0.50
5	3.00	3.00	40.00	60.00	4	2	0.40	0.50

Before proceeding, it is important to check the accuracy of the proposed analytical method of estimating moments of travel time. One way for checking accuracy of the model is to compare the results of the analytical method with that of the Monte Carlo simulation method given that simulation can well imitate real world phenomena, which can most probably give exact values of travel time moments. In this case, Monte Carlo simulation is undertaken whereby each pseudo-random draw of Normally distributed Q_{od} is assigned onto network probabilistically using base route choice fraction. In simulation approach, mean and variance of travel time are estimated from the collection of travel time statistics resulting from the traffic assignment of pseudo-random draw of Q_{od}. A sensible method for verifying results of the proposed model versus simulation model is the percentual Root Mean Square Error (RMSE%) such that the smaller the RMSE%, the better the model. RMSE% can be given by the following expression:

$$RMSE\% = \sqrt{1/n\left(\sum_{i=1}^{n}(\hat{a}_i - a_i)^2\right)}\Big/\bar{a} \qquad \text{with } \bar{a} = 1/n\sum_{i=1}^{n}\hat{a}_i ,$$

where $\hat{a}_i$ is the exact value obtained from Monte Carlo simulation approach and a_i is the value resulting from proposed analytical model.

By using results ranging from the case of no market penetration to full market penetration of ATIS, it is found that RMSE% of mean travel time is 0.020 and RMSE% of SD of travel time is 0.022. Clearly, RMSE% is very small for both mean and SD of travel time which underscores the accuracy of the proposed analytical model vis-à-vis simulation approach even though network size is small. So, it is plausible that the method can be used in the subsequent analyses.

In the analysis below, the effect of ATIS on travel time reliability under stochastic OD demand is investigated. So, to compare this effect across equipped and non-equipped drivers, the base travel time which is the travel time of the case without information provision is used as the threshold value for calculating the reliability. This consideration is very useful in arguing whether the provision of ATIS is beneficial or not compared with the base condition. Moreover, the so-called threshold multiplier is introduced to represent the threshold travel time relative to the base travel time. In this regard, while threshold multiplier 1.0 corresponds to the base travel time, the multiplier 1.2 is equivalent to the threshold travel time which is 20% higher than base travel time.

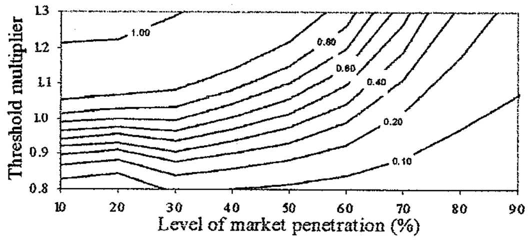

Figure 2: Reliability contour for equipped drivers

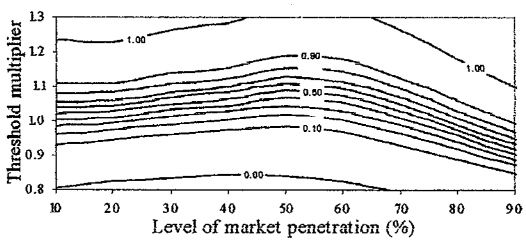

Figure 3: Reliability contour for all non-equipped drivers

Figure 2 and 3 show respectively iso-reliability contour curves of travel time of equipped and non-equipped drivers in respect of proportion of drivers equipped with ATIS. The increasing pattern of the contour curves indicates that as the number of ATIS users increases, travel time threshold needs to be also increased to maintain the same travel time reliability. The increase in value of threshold, in this case, implies that travel time reliability decreases. It is vice versa for decreasing pattern of contour curve.

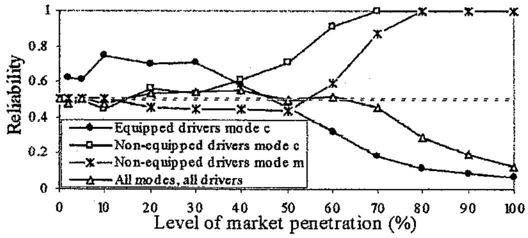

Figure 4: Level of market penetration v/s reliability

According to Figure 2, it is observable that travel time reliability of equipped drivers tends to decrease when number of ATIS users increases, and the decreasing rate of travel time reliability seems to become much faster at high level of market penetration. However, Figure 3 shows two different patterns of evolution of travel time reliability of non-equipped drivers. First, their travel time reliability is worse off in similar way to the reliability of equipped drivers as number of ATIS users augments, then travel time reliability of non-equipped drivers becomes better off after level of market penetration of ATIS reaches certain level and in this example when number of ATIS is higher than 50%. The fact that traveling without ATIS is likely more reliable than traveling with ATIS might disappoint the ATIS users who expect to get better travel time reliability by purchasing this information technology. In this case, it is possible to postulate that the adverse impact may be caused by overreaction and concentration among equipped drivers, such that too many drivers switch from congested route to uncongested one or their perception is concentrated around the true value.

The comparative scheme of travel time reliability is also depicted in Figure 4 where evolution of travel time reliability of all types of drivers and modes with respect to level of market penetration of ATIS is observed. It is observable that at the level of market penetration of less than 30%, travel time reliability of equipped drivers is much higher than that of non-equipped drivers who have a rather stable reliability. However, when the fraction of ATIS users reaches 40%, the equipped drivers start to be worse off while non-equipped drivers of mode *c* tend to be better off; and at the same time the travel time reliability of drivers of mode *m* remains nearly unaffected. It is seen that the travel time reliability of mode *m*'s drivers increases remarkably after the proportion of informed drivers reaches 50%, and they even outperform the equipped drivers of mode *c*. In addition to separate observation on equipped and non-equipped drivers, it is also useful to monitor the total travel time reliability of all drivers. It is clear that total travel time reliability remains stable up to 60% of level of market penetration of ATIS, and it starts to decrease after this level. This tendency is a very important indicator for planners in carefully deciding the number of ATIS to be distributed in order to maintain network performance at an acceptable level. It should be mindful that the results discussed in this numerical example are strongly dependent on the setting of variables of the model.

5. Conclusion

In this paper, the analysis of travel time reliability under stochastic day-to-day variation of OD travel demand considering mixed traffic condition is explicitly given with main components mean and variance of travel time readily available based on an analytical approach. The link flow moments which are the inputs of the analytical model are also given based on theoretical ground. It has been also shown that the proposed analytical method is able to compute travel time moments which are highly comparable to the ones obtained from Monte Carlo simulation. This can clearly confirm the accuracy of the proposed model for the analytical estimation of travel time moments.

Based on these results the effects of ATIS on travel time reliability can be observed by using numerical example of a five-link network with two modes operating on it. In this example, impacts study of ATIS on travel time reliability is analyzed by clearly taking into consideration not only the interaction of equipped and non-equipped vehicles but also the two vehicle types operating on the transportation network. It has been proved in the example that with low market penetration of ATIS, i.e. low portion of ATIS users, the informed drivers can well improve their travel time reliability, whereas at higher market penetration their reliability tends to decrease; and the benefits seem to be transferred to non-equipped drivers who pay nothing for the system. It can be argued that the adverse impacts of ATIS on its users in transportation network when there are many ATIS users are attributed to overreaction and concentration behavior of drivers whereby too many drivers change traveling route from congested route to less congested one or they have the same perception of travel time which create new congestion on the uncongested route. What is more, this adverse effect can even exacerbate the whole network performance. This problem highlights the importance of policy to provide ATIS to drivers in terms of market penetration such that the number of ATIS provided should be carefully designed in order to maintain the reliability of transportation system users as a whole.

It should be noted that the inclusion of mixed traffic condition in the analysis of travel time reliability may be much appropriate for traffic condition in developing countries where transportation network exhibits high mixture of vehicle types. In this context, another challenge is to apply the proposed analytical approach to realized network with more than two modes so that interaction among different vehicle types and characteristics can be rigorously modeled. Yet, the inclusion of multiple modes in the practical application requires much more effort to compute the analytical model.

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Travel Time Reliability Analysis in Mixed Traffic Network under Provision of Advanced Traveler Information System *

By Phyrum KOV**, Yasuhiro HIROBATA***, and Yasuyuki NAKAHIRA****

In mixed traffic network, interaction among different vehicle types usually takes place making travel time of any one mode dependent on other modes. Under day-to-day variation of travel demand, travel time in mixed traffic network is not stable as it varies from one day to another. The purpose of this paper, therefore, is to quantify analytically the travel time reliability of mixed traffic network under stochastic travel demand; and to analyze the effects of ATIS on travel time reliability of mixed traffic network. This study will give an insight into how provision of ATIS in mixed traffic network under stochastic travel demand can positively and negatively impact on travel time reliability.

所要時間情報提供下での混合交通ネットワークにおける旅行時間信頼性の解析*

コブ ピーロン**・廣畠康裕***・中平恭之****

混合交通ネットワークにおいては，ある交通手段の旅行時間が他の交通手段の影響を受けるという車種間の相互作用が生じる．交通需要の日間変動の下では混合交通ネットワークにおける旅行時間は日々変動するため不安定である．そこで，本論文では確率的交通需要変動下での混合交通ネットワークの旅行時間信頼性について解析的に定量化するとともに，所要時間情報提供システムが混合交通ネットワークの旅行時間信頼性に与える影響を分析する．それによって，確率的交通需要変動下での混合交通ネットワークにおける所要時間情報の提供がどのように旅行時間信頼性に対して正負の影響を及ぼすのかについての知見を得ることを目指す．