ASSESSMENT OF THE IMPACTS OF OPENING THE HARD SHOULDER TO TRAFFIC ON TRAVEL TIME RELIABILITY^{*}

By Babak MEHRAN^{***} and Hideki NAKAMURA^{****}

1. Introduction

Travel time reliability represents mobility levels and road users' satisfaction simultaneously. Thus, it is a suitable measure for assessing the efficiency of congestion relief schemes on expressway segments. Currently, applications of travel time reliability are limited to before-after studies and road users' information provision. However, road authorities are more interested in evaluation of the impacts of alternative improvement schemes on travel time reliability, prior to implementation. One barrier to this application is the limitations of travel time reliability estimation methods, as most of them mainly rely on empirical data. Hence, regarding the unavailability of such data in present time (before implementing the improvement scheme), verification of the potential improvements in travel time reliability is not possible.

This study aims to demonstrate the potential application of travel time reliability for planning purposes. For a segment of an intercity expressway, reliability measures are first evaluated through empirical data. Then a model will be developed which is capable of assessing the impacts of congestion relief schemes on travel time reliability. After validating the model, it is finally applied to evaluate the impacts of opening the hard shoulder to traffic, on travel time reliability.

2. Background and literature review

Travel time reliability is defined as how much travel times vary over the time. Such variations are the result of interactions between demand, capacity, weather conditions, accidents and traffic composition on expressways. Such interactions were investigated by a number of studies. Tu, *et al.* $(2007)^{1/2}$ evaluated the impacts of inflow and adverse weather on travel time variations on Dutch motorways. They quantified threshold inflows above which travel time variability increases sharply while adverse weather was found to lower the threshold values. The significance of capacity and bottleneck operations with respect to travel time reliability was also highlighted by several studies^{3) 4)}. As breakdown of traffic flow and consequently the capacity of a roadway are proven to be random events³, probability of breakdown should necessarily be included in travel time reliability models. Yet, only few studies attempted to clarify the nature of such a relationship⁴).

Previously, Mehran and Nakamura (2008)⁵⁾ developed a methodology to estimate travel time reliability as a function of probability of breakdown, demand variations, accidents and weather conditions. In this paper, by using the same approach, a simulation model is developed and calibrated for the test bed of this study and the model will further be used to assess the impacts of opening the hard shoulder to traffic on travel time reliability.

3. Test bed definitions and characteristics

A two lane segment of Tomei expressway between Okazaki Interchange and Toyota Junction (Nagoya bound, 9.9 km) is used as the test bed for this study and analysis period is the years 2003 and 2006. Toyota Junction was opened to traffic in 2005, preceding the inauguration of the EXPO 2005 in Nagoya. Consequently, directional AADT (Average Annual Daily Traffic Volume) of the test bed increased from 38,630 (veh/day) in 2003 to 48,200 (veh/day) in 2006, resulting in extended congested hours and unreliable travel conditions. There are 5 double loop detectors installed on this segment (almost every 2 km) reporting spot speeds and traffic counts every 5 minutes for each lane. Detector data were available from 2002 to 2004 and 2006, and were used to estimate travel times, reliability measures, demand variations and speed-flow relationships over analysis period. However, weather data and accident records were only available for 2003.

4. Travel time reliability and congestion measures

Travel times were estimated for each 5-minute interval during analysis period from spot speeds collected by double loop detectors by using "*Piecewise Linear Speed Based*" model⁶⁾. In this study, travel time index (TTI) is used as a measure of congestion levels while planning time index (PTI) and buffer time index (BTI) are estimated as measures of travel time reliability. These measures are derived for each 5-minute interval:

$$TTI_{i} = \overline{TT}_{i} / FT \tag{1}$$

$$PTI_i = 95^{th} TT/FT$$
(2)

$$BTI_{i} = (95^{th} TT_{i} - \overline{TT}_{i})/\overline{TT}_{i} \times 100$$
(3)

Where, \overline{TT}_i and 95th TT_i are the average and the 95th percentile travel time at time interval *i*, (*i*= 1,2...288) respectively, and *FT* is the free-flow travel time. Free-flow speed on the test bed was estimated to be 93km/h by averaging the spot speeds of the vehicles while traffic flow was low. **Figure 1** represents the BTI at each 5-minute interval in 2003 and 2006. Average values of travel time (TT), BTI, TTI and PTI during the peak period (3pm to 11pm) are also represented in **Figure 1**. The AADT of the test bed has increased by almost 25% in 2006 compared with 2003. As shown in **Figure 1**, the extents of congested hours and unreliable travel conditions have drastically increased in 2006. However, the highest values of BTI have apparently reduced which is basically due to disproportionate increase in

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^{**}Student member, M.Sc., Dept. of Civil Eng., Nagoya Univ. (Furo-cho, Chikusa-ku, Nagoya 464-8603, Tel. 052-789-5175, FAX: 052-789-3837, Email: babak@genv.nagoya-u.ac.jp)

^{***} Member, Professor, Dr. Eng., Dept. of Civil Eng., Nagoya Univ.



TTI and PTI during the peak period and could not be interpreted as improved travel conditions. This implies the significance of such supplementary measures as TTI and PTI while explicating reliability trends over the time.

Some congestion relief schemes may improve the reliability trends shown in **Figure 1**. However the extents, to which travel time reliability will improve, cannot be evaluated using the same empirical method due to unavailability of required data before implementation. The following section describes a model that is capable of assessing the impact of congestion relief schemes on reliability.

5. Modeling methodology

Figure 2 represents the general framework of the proposed model. i) For an expressway segment, patterns of demand and capacity are generated for each 5-minute interval (365×24×12=105,120 intervals) by applying Monte-Carlo simulation technique. ii) Weather condition and its impacts on capacity and demand variations are simulated according to available meteorological data during the analysis period. iii) Accidents are generated randomly based on a model that links accident rate to traffic density. However, the relationship between adverse weather and accident likelihood is not considered yet. iv) The whole year analysis is performed by comparing demand and available capacity for each scenario, and queue length is estimated for each time interval through shockwave analysis. v) Travel times are estimated using speed-flow relationships developed for expressways. vi) Finally, BTI is estimated as a measure of travel time reliability. A simulation model is developed by using the procedure above and model calibration is done according to the



Figure 2: Framework of the proposed model

characteristics of the test bed in 2003, which will be described in the proceeding section.

(1) Model development and calibrations

Model development and calibrations are done following the methodology described in Mehran and Nakamura (2008)⁵⁾, which will be reviewed in brief.

In this study, demand represents arriving traffic flow during uncongested conditions. Demand patterns were estimated by analyzing the detector data from 2002 to 2004, using a methodology proposed by Nakamura, *et al.* $(2007)^{7}$. Capacity was treated as a random variable with Weibull distribution. Impacts of heavy vehicles and precipitations on capacity were considered by applying appropriate adjustment factors.

Traffic conditions were defined by comparing demand and capacity at each 5-minute interval and shockwave analysis was used to estimate resulting queues when demand exceeds capacity. To estimate the speed of the traffic flow during uncongested conditions, speed-flow relationships calibrated by Hong and Oguchi (2008)⁸⁾ were first used to estimate the 85th percentile speeds. Afterwards, 85th percentile speeds were adjusted to reproduce average speeds. Adjustments were defined according to traffic volume by comparing average speeds obtained from detector data with estimated 85th percentile speeds derived from Hong and Oguchi (2008)⁸⁾ models. For congested conditions, a speed-flow relationship was developed through investigation of 5minute average speeds and traffic volumes of the congested flow in 2003.

Accidents were generated randomly according to traffic density by using the models developed by Hikosaka and Nakamura (2001)⁹⁾. Finally travel times were calculated at each 5-minute interval and BTI was estimated as a measure of travel time reliability.

(2) Model outputs and validation

The simulation model was run 5 times and the BTI and predicted number of accidents were estimated in 2003 and compared with observed values from empirical data.

As shown in **Figure 3**, the model correctly predicts the beginning and the end of the daily congested periods. Simulation results show the same tendency as the observations made through empirical data for the extents of travel time reliability throughout a whole year. Model predicts BTI with little over- or underestimations during the peak periods. However the root mean square error (RMSE) is lower than 7% in all trials of the simulation.



Figure 4: Speed-flow relationship of the test bed in three-lane conditions

According to available accident records, 16 accidents occurred on the test bed in 2003 which is almost equal to the number of predicted accidents from the model.

The low values of the estimation errors would imply the applicability of the proposed methodology to estimate the impact of congestion relief schemes on travel time reliability and safety for planning applications, at least on the test bed of this study.

6. Model application

An overview of congestion and reliability measures in **Figure 1** reveals that congestion levels extended and travel time reliability deteriorated in 2006 due to the significant increase in AADT. An alternative solution to renovate the overall travel conditions could be opening the hard shoulder to traffic during the peak period of some or all days. Hereafter, the proposed methodology is used to assess the impact of such an action on travel time reliability and safety.

(1) Base model

Since the daily demand patterns of the test bed have changed after 2005, the calibrated model of 2003 may not be used for further investigations. Accordingly, a base model was developed and calibrated using the estimated demand patterns in 2006 (latest available data). The weather condition was assumed to be the same as the year 2003. Since the accident records in 2006 were not available, it is not possible to judge how accurate the model predicts the number of accidents. However, several trials of simulation estimated 23 accidents in 2006 that is reasonable considering the increase in AADT and extended hours of congestion. (2) Model adjustments for three-lane conditions When the hard shoulder is opened to traffic, the test

when the hard shoulder is opened to traffic, the test bed should be treated as a three-lane segment. As a result, capacity and speed-flow relationships should be modified when the hard shoulder is open to traffic.

a) Capacity adjustment

The capacity of a three-lane segment might be slightly higher than 1.5 times than that of a two-lane segment due to the ease of lane changing maneuvers. But, since the hard shoulder could not be utilized perfectly as an ordinary lane, for the purpose of this study, estimated capacities were modified for three-lane conditions by using the adjustment factor of 1.4.

b) Speed-flow relationship

Uncongested conditions: As shown in **Figure 4a**), Hong and Oguchi (2008) models were used to estimate 85th percentile speeds and then estimated values were adjusted to reproduce average speeds in three-lane conditions. Adjustments were done according to traffic volume likewise the two-lane conditions.

Congested Conditions: The previously developed model for two-lane conditions was modified to estimate the speed-flow relationship of three-lane conditions. The main hypothesis is that when traffic condition is congested, all the lanes are almost fully utilized at the same speed. So, for the same speed, traffic volume in three-lane condition is 1.5 times of that of a two-lane condition. Such a substitution yields a modified speed-flow relationship that is represented in **Figure 4b**).

(3) Dynamic lane operation schemes

To define the most appropriate schemes to open the hard shoulder to traffic, distribution of travel times during the peak period of all categories of days were



Figure 5: Impact of opening the hard shoulder to traffic on travel time reliability

analyzed. On weekdays/non-holidays, the average travel time on Tuesdays and Fridays were found to be slightly higher due to higher demand, while for weekends/holidays, Saturdays and special days (during Obon and Golden Week) had the highest average travel times. Consequently, two different schemes were defined for opening the hard shoulder to traffic: i) Scheme A: Opening the hard shoulder to traffic on Tuesdays, Fridays, Saturdays and special days from 3pm to 8pm, ii) Scheme B: Opening the hard shoulder to traffic on all days from 3pm to 8pm. Although implementation of Scheme A may not be very realistic in practice, it is considered as an option to demonstrate the applicability of the proposed methodology.

(4) Impact assessment

Simulation model was run 5 times for each scheme and the average of estimated BTI and numbers of predicted accidents are represented in **Figure 5**. Supplementary congestion and reliability measures were also estimated during the peak periods and compared with corresponding values in 2006.

Implementing *Scheme A*, the period of unreliable travel conditions is shortened almost by 2 hours on a daily basis. However, the average BTI during the peak period may not significantly change due to disproportionate drop in TTI and PTI. Reduced TTI implies that the congestion levels drop significantly. As for safety impacts, the total number of accidents is estimated to be reduced by 13%.

Deploying *Scheme B*, results in significant improvements in travel time reliability, mobility and safety on the test bed. BTI drops into lower than 5% and TTI approaches 1.0, which is comparable to free-flow traffic conditions. Moreover, the total numbers of accidents are reduced by 26%. Therefore it is obvious that opening the hard shoulder to traffic during the peak periods results in significant improvements in travel time reliability and safety.

7. Conclusions and future work

In this study, a possibility of applying travel time reliability for planning applications was demonstrated. For this purpose, a methodology was proposed and applied to estimate the impacts of opening the hard shoulder to traffic on travel time reliability.

So far, evaluation of the efficiency of congestion relief schemes on expressways has generally been based on total travel time analysis. However, proposed methodology reckons demand and capacity dynamically and makes it possible to estimate travel time variations over the time. Hence, travel time reliability can be estimated and used for assessing the efficiency of congestion relief schemes prior to their implementation.

There are still some issues that need to be figured out before the methodology can universally be used. The proposed simulation model is site-specific and needs to be calibrated according to the characteristics of the expressway segment. To develop a comprehensive methodology, more generalized forms of speed-flow relationships are required. It should also be noted that the results of this study are valid based on the analysis of the limited number of intercity expressway segments. Yet, development of a more authentic methodology calls for extra investigations on various expressway segments.

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