ASSESSING IMPACTS OF HARD SHOULDER UTILIZATION ON TRAVEL TIME RELIABILITY AND SAFETY*

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1. Introduction

Quality of service on intercity expressways is affected by congested segments on the network. Strategies such as hard shoulder utilization during peak periods may reduce congestion and improve overall traffic operations. Efficiency of such congestion relief schemes is generally evaluated based on their impact on average travel times. However, road users are much more concerned about reliability and safety of their trips. Thus it is very significant to evaluate impacts of improvement schemes on travel time reliability and safety prior to their implementation in real conditions. Such an evaluation is not practical because existing methods for estimating travel time reliability mainly rely on empirical data.

Recently Mehran and Nakamura[1)] established a framework to estimate travel time reliability on expressway segments as a function of demand, capacity and weather conditions while accidents are modeled according to traffic conditions. This paper applies their methodology to evaluate impacts of hard shoulder utilization on travel time reliability and safety.

For a segment of an intercity expressway, reliability and congestion measures are first evaluated through empirical data. Then after a brief review of modeling methodology, a model is developed and calibrated according to characteristics of the test bed. After model validation, the model is adjusted for the conditions when the hard shoulder is in operation and finally impact assessment is accomplished.

2. Background and literature review

Travel time variations on expressways are the result of interactions between demand, capacity, weather conditions, accidents, work zones and traffic composition. Such interactions were investigated by a number of studies. Tu *et al.*[2)3)] evaluated the impact 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. Elefteriadou and Cui[4)] developed separate models to estimate travel time reliability for different scenarios of traffic conditions and non-recurring events on freeways. However, their models could only be used for predefined scenarios. The significance of capacity and bottleneck operations with respect to travel time reliability was also highlighted by several studies[5)6)]. As breakdown of traffic flow and consequently the capacity of a roadway are proven to be random events, probability of breakdown should necessarily be included in travel time reliability models. Tu *et al.*[6)] proposed a methodology that incorporates breakdown probability into travel time reliability. But their methodology cannot produce common reliability measures which are based on travel time distributions. Mehran and Nakamura[1)] proposed a methodology to estimate travel time variations as a function of demand, capacity and weather conditions which will be discussed in more details in this paper. In their methodology capacity is treated as a random variable while demand is modeled considering its regular and short term random variations. The next section describes the characteristics of an intercity expressway segment which is the test bed of this study.

3. Test bed characteristics

A two-lane segment of Tomei expressway between Okazaki Interchange and Toyota Junction is considered as the test bed for this study (Nagoya bound, 9.9 km). There are no on/off ramps midway and analysis period is the years 2003 and 2006. Toyota Junction that connects Tomei and Isewangan Expressways 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. Accident records were available for 2003 and 2006 and were used for model validation. However, weather data were only available for 2003 that were used to adjust demand, capacity and speed-flow relationships.

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"* model[7)]. 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:

$$TTI_i = \overline{TT}_i / FT \quad (1)$$

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

$$BTI_i = (95^{th}\ TT_i - \overline{TT}_i) / \overline{TT}_i \times 100 \quad (3)$$

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. **Figure 1** represents the BTI at each 5-minute interval in 2003

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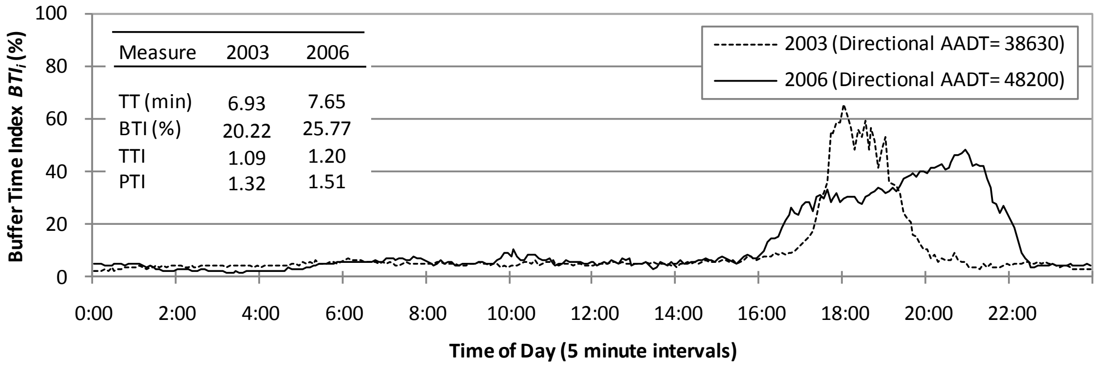

Figure 1: Congestion and reliability trends in 2003 and 2006

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 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 culminate in less variable travel times and improve reliability trends shown in **Figure 1**. The following section describes the methodology proposed by Mehran and Nakamura[1)] which is capable of assessing impacts of congestion relief schemes on travel time reliability and safety prior to their implementation.

5. Modeling methodology and calibration procedure

Figure 2 represents the general modeling framework. *i)* For an expressway segment, traffic conditions are modeled over a year by estimating hourly traffic demands and capacities. 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 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. In the following, model development and calibrations are reviewed briefly.

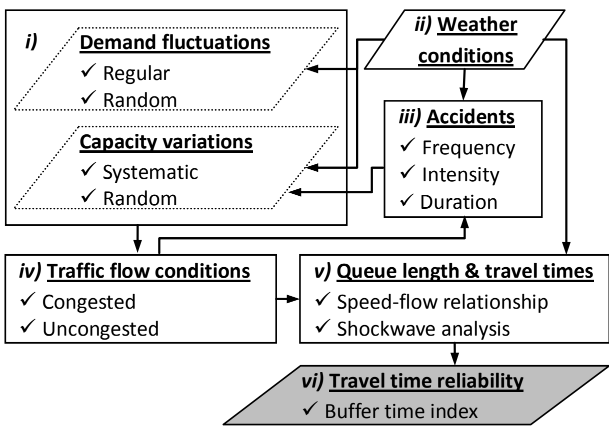

Figure 2: Framework of the proposed model

(1) Description of model components

In this study, demand represents arriving traffic flow during uncongested conditions. Regular patterns of demand were modeled by analyzing historical traffic volume data according to month of the year, day of the week, hour of the day and weather conditions (Nakamura, *et al.*[8)]). Short term random variations of demand were considered by applying a normal distributed random term.

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.

Demand and capacity were compared at each 5-minute interval and if demand exceeds capacity, the interval was defined as congested. Consequently, speed-flow relationships and shockwave analysis were used to estimate temporal and spatial extents of the resulting queue. To estimate the speed of the traffic flow during uncongested conditions, speed-flow relationships calibrated by Hong and Oguchi[9)] 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[9)] models. For congested conditions, a speed-flow relationship was developed through investigation of 5-minute average speeds and traffic volumes of the congested flow in 2003.

After initial assessment of traffic conditions at each time interval, accidents were generated randomly according to traffic density by using the models developed by Hikosaka and Nakamura[10)]. Since available capacity and traffic conditions may have changed at intervals with accident, demand and available capacity were compared again at each time interval over analysis period and traffic conditions were defined by using speed-flow relationships and shockwave analysis.

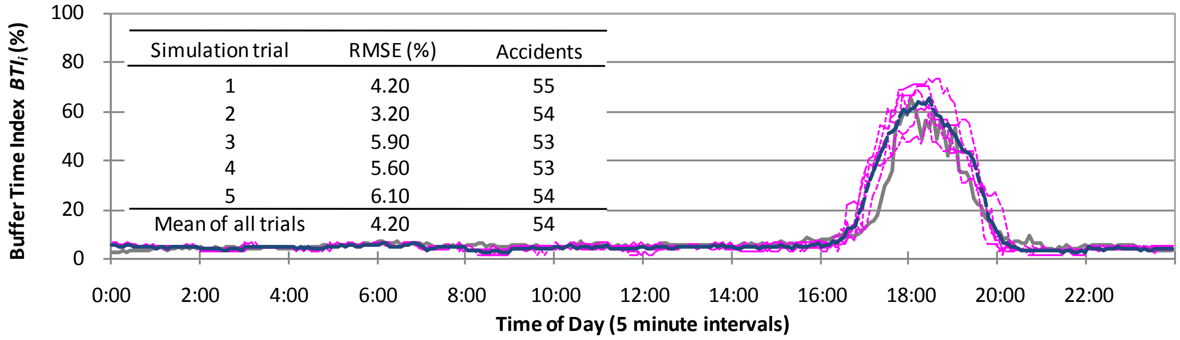

Figure 3: Model outputs compared with measured values (2003)

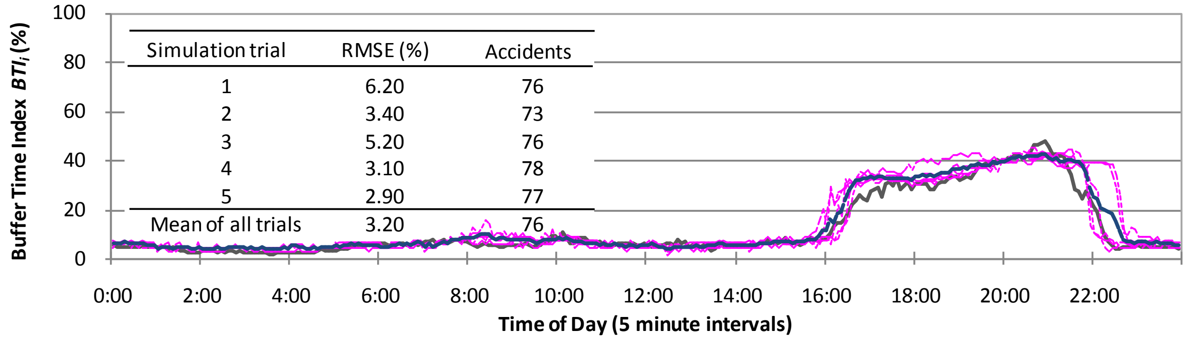

Figure 4: Base model outputs compared with measured values (2006)

Travel time at each 5-minute interval was estimated regarding traffic conditions. For uncongested intervals, travel time was estimated given the average speed of traffic flow and segment length. For congested intervals, travel time was estimated considering the bottleneck location and different operating speeds for upstream, queuing vehicles and downstream. Finally, BTI was estimated regarding the distribution of travel times at each 5-minute interval.

A simulation model was developed by using the above-mentioned procedures and model calibration was done according to characteristics of the test bed in 2003.

(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 previously observed values from empirical data. To make an intuitive evaluation, the mean BTI from all trials of simulation was also estimated and presented in **Figure 3**.

The model predicts BTI with little over- or underestimations during the peak periods. However the RMSE is lower than 7.0% in all cases. Estimation errors might be caused by either any of various models applied in the methodology or transient traffic conditions that were not considered in this study.

According to available accident records, 53 accidents occurred on the test bed in 2003. As shown in **Figure 3**, predicted number of accidents is reasonably close to the real number of occurred accidents.

The low values of the estimation errors would imply the applicability of the proposed methodology to estimate impacts 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

Hereafter, the proposed methodology is used to assess impacts of hard shoulder utilization during the peak period (3pm to 8pm) on travel time reliability and safety.

(1) Base model

Since the daily demand patterns on 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). Since weather data was not available for the year 2006, it is assumed that the weather condition is the same as the year 2003. Estimated BTI, RMSE and predicted numbers of accidents are represented in **Figure 4**. The BTI estimation error is lower than 7.0%. According to the accident data in 2006, there were 77 accidents occurred on the test bed. Several trials of simulation model estimate 76 accidents for the test bed in 2006 which is almost the same as the real number of occurred accidents.

(2) Model adjustments for three-lane conditions

When 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 hard shoulder is in use.

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. However, since the hard shoulder might not be utilized perfectly as an ordinary lane, for the purpose of this study, the proportion is assumed to be 1.4.

b) Speed-flow relationship

Uncongested conditions: Likewise the two-lane conditions, Hong and Oguchi[9)] models were used to estimate 85^{th} percentile speeds and then estimated values

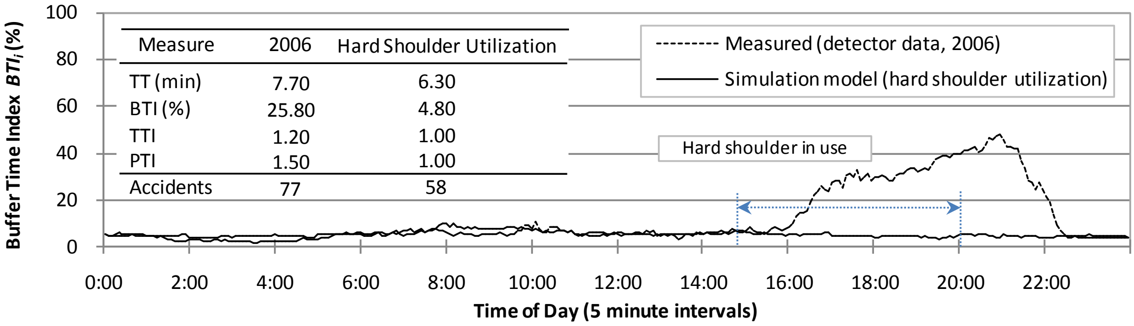

Figure 5: Impact of hard shoulder utilization on travel time and safety

were adjusted to reproduce average speeds in three-lane conditions.

Congested Conditions: For congested conditions, it is assumed that all the lanes are almost fully utilized at the same speed. As a result, for the same speed, traffic volume in three-lane condition is 1.5 times of that of a two-lane condition. Such a substitution in the previously developed speed-flow relationship for two-lane condition yields a modified speed-flow relationship for three-lane condition.

(3) Impact assessment

Simulation model was run 5 times for each scheme and the average of estimated BTI and numbers of 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. Hard shoulder utilization during peak periods results in conspicuous improvements in travel conditions. The average peak period travel time is reduced from 7.7 minutes to 6.3 minutes and average BTI is dropped from 25.8% to 4.8% which is comparable with off-peak traffic conditions. Distribution of travel times during the peak period is flattened as TTI and PTI values approach each other. Improved travel conditions after opening the hard shoulder to traffic during the peak periods results in significant improvements in traffic safety. The total number of accidents is expected to be reduced from 77 in 2006 to 58 after hard shoulder utilization, which shows 25% reduction.

Safety appears to be improved after hard shoulder utilization during peak periods. However it should be noted that accidents are modeled solely based on traffic density, and other influencing factors are not considered.

7. Conclusions and future work

A novel methodology was applied to evaluate impacts of congestion relief schemes, on travel time reliability and safety. So far, evaluation of the efficiency of congestion relief schemes on expressways has generally been based on average 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. Moreover, since the relationship between traffic conditions and accident likelihood is considered, the methodology is capable of evaluating impacts of congestion relief schemes on safety.

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. To develop a comprehensive methodology, more generalized forms of speed-flow relationships are required. Development of general forms for capacity distribution function, demand patterns and speed-flow relationships makes it possible to apply the methodology for designing new expressway segments based on travel time reliability and safety criteria. In this study, impact of induced demand from neighboring routes as a result of improved traffic conditions after implementing an improvement scheme is not considered. 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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