1. INTRODUCTION

Intercity expressway networks in Japan provide service to trucks, expressway buses and private users that are mostly relying on “scheduled travel times.” However, various sections of intercity expressways experience extended periods of congestion, especially near large metropolitan areas. Once congestion starts to build up on a segment of a route, road accidents may also increase and escalate congestion beyond road users’ expectations. As a result, travel conditions on the whole route becomes unreliable. Considering extra costs incurred by road users due to unreliable travel conditions, road authorities are always seeking effective congestion relief schemes in order to mitigate congestion and improve travel conditions on critical expressway segments which maintain reliable travel conditions on the whole route as well.

Travel time reliability is a preferable measure to evaluate the level of service of expressway segments as it reflects mobility and road user satisfaction at the same time. Evaluation of the efficiency of congestion relief schemes on expressways has generally been based on average travel time analysis. However, road authorities are much more interested in knowing the possible impacts of improvement schemes on safety and travel time reliability prior to implementing them in real conditions. A methodology is presented to estimate travel time reliability based on modeling travel time variations as a function of demand, capacity and weather conditions. For a subject expressway segment, patterns of demand and capacity were generated for each 5-minute interval over a year by using the Monte-Carlo simulation technique, and accidents were generated randomly according to traffic conditions. A whole year analysis was performed by comparing demand and available capacity for each scenario and shockwave analysis was used to estimate the queue length at each time interval. Travel times were estimated from refined speed-flow relationships and buffer time index was estimated as a measure of travel time reliability. It was shown that the estimated reliability measures and predicted number of accidents are very close to observed values through empirical data. After validation, the methodology was applied to assess the impact of two alternative congestion relief schemes on a subject expressway segment. One alternative was to open the hard shoulder to traffic during the peak period, while the other was to reduce the peak period demand by 15%. The extent of improvements in travel conditions and safety, likewise the reduction in road users’ costs after implementing each improvement scheme were estimated. It was shown that both strategies can result in up to 23% reduction in the number of occurred accidents and significant improvements in travel time reliability. Finally, the advantages and challenging issues of selecting each improvement scheme were discussed.

Key Words: Travel time reliability, Buffer time index, Safety, Congestion relief schemes
variations as the function of demand, capacity, weather conditions and road accidents. Accidents are modeled as a function of traffic conditions. Hence the methodology is capable of evaluating impacts of congestion relief schemes on travel time reliability and safety, prior to implementing them in real conditions. For a segment of an intercity expressway, reliability and congestion measures are first measured through empirical data. Afterwards, the proposed methodology is applied to develop a simulation model to estimate travel time reliability as well as the number of accidents on the test bed. After validating the model, it is finally applied to evaluate impacts of opening the hard shoulder to traffic, as well as reducing demand during the peak periods, on travel time reliability and safety.

2. BACKGROUND AND LITERATURE REVIEW

Unlike delays, travel time reliability refers to variability of travel times from time to time because of unpredictable underlying conditions over the time. Travel time variations on expressways are the result of interactions between demand, capacity, weather conditions, accidents, work zones and traffic composition. All these components have some stochastic characteristics. Such interactions were investigated by a number of studies. Impacts of inflow and adverse weather conditions on travel time reliability were investigated by Tu et al. on Dutch motorways. Travel time variations were found to be increased under adverse weather conditions. They could also quantify critical inflows above which travel time variability increase steeply. Their findings imply that critical inflows are much smaller in adverse weather conditions.

Several models have been previously developed to estimate travel time variations on expressway segments. Emam and Al-Deek examined several distribution functions in order to model travel time variations on a specific link and found that lognormal distribution is the best fit model for this purpose. Lint and Zuylen proposed new reliability metrics based on the width and skew of day-to-day travel time distributions. They developed a stochastic artificial neural network (ANN) model to predict long-term day-to-day travel time variations. Most of these models are based primarily on field data and cannot be applied in case of an accident or when the basic characteristics of the subject road segment are supposed to change.

Few studies attempted to develop models to estimate travel time reliability according to traffic conditions and combinations of non-recurring events. Eleftheriadou and Cui analyzed travel time data of an 8.72 mile portion of US 202 located in Philadelphia over a four month period. They developed separate models to estimate travel time variations for different scenarios of recurring and non-recurring congestion. However, developed models are deterministic and include a limited number of predefined scenarios.

The relationship between accidents and travel time reliability is another important issue which has not been investigated adequately. Most of the existing research is limited to evaluation of delay due to accidents. Moreover, traffic condition is ranked on the top in the list of influencing factors on accident rate, by several studies. Zhou and Sisiopiku found that the correlation between volume-to-capacity (v/c) ratio and accident rate follows a general U-shape pattern on the freeways of the United States. Later, Chang et al. as well as Hikosaka and Nakamura observed the same patterns on Korean freeways and Japanese expressways respectively. These findings emphasize that congested traffic conditions and especially stop-and-go conditions increase the risk of certain types of accidents (e.g. rear-end). As a result, since road accidents could easily affect the stability of travel times, the relationship between traffic conditions and accident likelihood should be considered in travel time reliability estimation models.

The significance of capacity and bottleneck operations with respect to travel time reliability was highlighted by a number of investigations. Brilon et al. proposed a methodology to assess traffic flow performance of German motorway segments over a whole year that includes the stochastic nature of both capacity and traffic demand. The assessment of traffic flow quality within their model is based on a simple deterministic queuing model that estimates total delay and resulting queues on a subject motorway segment over a year. Although their methodology provides a valuable insight towards the reliability of motorway operations but it cannot be used to produce travel time variations and travel time reliability measures on expressway segments. As breakdown of traffic flow and consequently the capacity (capacity reliability) of a roadway are proven to be random events, probability of breakdown should necessarily be included in travel time reliability models. Yet, only few studies attempted to clarify the nature of such a relationship.

Given the insufficiency of the existing research, this study aims to build up such a model that estimates travel time reliability as a function of probability of breakdown, demand variations, accidents, weather conditions and traffic composition as the root sources of travel time (un)reliability.
The next section will describe the characteristics of an intercity expressway segment which is used as the test bed of this study.

3. TEST BED CHARACTERISTICS

As shown in Figure 1, a segment of the Tomei Expressway that runs from Tokyo to Nagoya is considered as the test bed for this study. This is a two-lane segment, between Okazaki Interchange and Toyota Junction (Nagoya bound, 9.9 km) with no on/off ramps midway and the 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. Accidents occur frequently on this segment due to the prevalent congested periods. 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. However, provided weather data by AMeDAS (Automated Metrological Data Acquisition System) were available for 2003 only.

![Fig. 1 Test bed location and position of detectors](image)

4. TRAVEL TIME RELIABILITY AND CONGESTION MEASURES

Travel times were estimated for each 5-minute interval during the analysis period from spot speeds collected by double loop detectors by using a “Piecewise Linear Speed Based” (PLSB) model. Buffer measures were previously applied to evaluate the performance of expressway segments in Japan and were found to be suitable indicators of congestion levels and reliability. In this study, travel time index (TTI) is used as a measure of congestion levels (Equation (1)) while planning time index (PTI) (Equation (2)) and buffer time index (BTI) (Equation (3)) are estimated as measures of travel time reliability. These measures are derived for each 5-minute interval during the analysis period for three categories of days: i) All days (365 days); ii) Weekdays/non-holidays (235 days) and iii) Weekends/holidays (130 days).

\[
TTI_i = \frac{\bar{TT}_{ij}}{FT} \\
PTI_i = \frac{95^{th} TT_{ij}}{FT} \\
BTI_i = \frac{95^{th} TT_{ij} - \bar{TT}_{ij}}{\bar{TT}_{ij}} \times 100
\]

where, \(\bar{TT}_{ij}\) and \(95^{th} TT_{ij}\) are the average and the 95th percentile travel time at interval \(i\) of the day category \(j\) respectively, \((i=1, 2\ldots 288; j=1)\) for weekends/holidays; \(j=2\) for weekdays/non-holidays; \(j=3\) for all days) 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 2 represents the BTI at each 5-minute interval for three categories of days in 2003 and 2006. Average values of travel time (TT), BTI, TTI and PTI during the busiest times (3pm to 11pm) are also represented in Figure 2.

The AADT of the test bed had increased by almost 25% in 2006 compared with 2003. As shown in Figure 2, the extent of congested hours and unreliable travel conditions have drastically increased in 2006. However, the highest values of BTI in the case of weekdays/non-holidays and all days 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. The most serious impact of increased AADT is evident on weekends/holidays of 2006, where BTI rises up to 60%. Such unreliable travel times are the result of increased demand for travel on some weekends/holidays and special vacations in Japan such as Obon (mid August) and Golden Week (end of April and beginning of May). Some congestion relief schemes may culminate in less variable travel times and improve the reliability trends shown in Figure 2 and probably reduce the number of accidents. However the extent to which travel time reliability or safety 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 impact of congestion relief schemes on reliability and safety.

5. MODELING METHODOLOGY

Figure 3 represents the general framework of the proposed model. 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 impact 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. 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.

![Fig. 2 Congestion and travel time reliability trends in 2003 and 2006](image-url)
Regular patterns of demand are modeled by analyzing historical traffic volume data according to month of the year, day of the week, hour of the day and weather conditions. Short-term random variations of demand are considered by applying a Normal distributed random term. Capacity is modeled as a random variable with Weibull distribution. Demand and capacity are compared at each 5-minute interval and if demand exceeds capacity, the interval is defined as congested. Consequently, speed-flow relationships and shockwave analysis are used to estimate travel time at each 5-minute interval given the average speed of traffic flow during uncongested periods which has both regular and stochastic characteristics. Daily and hourly demand values were estimated based on a methodology first proposed by Brilon [16] and further extended by Nakamura et al. [17] on Japan’s expressways. The main hypothesis is that the regular patterns of demand can be modeled as a function of day of the year and weather conditions. Daily traffic demand ratio \(DD_{dh}\) is defined as the ratio of daily traffic demand to directional AADT. Considering the time of the day, the hourly traffic demand \(HD_{dh}\) on a day category of \(d\) is estimated from Equation (4):

\[
HD_{dh} = DD_{dh} \times HDC_{dh} \times AADT
\]  (4)

where, \(HDC_{dh}\) represents the ratio of hourly traffic demand to daily traffic demand. \(HDC_{dh}\) is estimated by dividing hourly traffic volumes by daily traffic demand during uncongested hours. Estimated values are then categorized for each hour based on the day category and the median is selected as \(HDC_{dh}\) for each hour of a specific day category. Equation (5) is used to estimate daily traffic demand ratios according to the categories of day, month and weather conditions:

\[
DD_{d} = \alpha_{m} + \beta_{d} + \gamma_{r} + \mu + \epsilon \quad \text{(5)}
\]

where, \(\alpha_{m}\) is a dummy month with 12 categories (January to December); \(\beta_{d}\) is a dummy of day with 9 categories (Monday to Saturday, Sunday/holidays, consecutive holidays and special days); \(\gamma_{r}\) is a dummy precipitation with 4 categories (no rain, 1-30mm/day, 30-90mm/day and above 90mm/day); \(\mu\) is a constant value and finally \(\epsilon\) is the random error term with normal distribution and mean of zero. Model parameters in Equation (5) were estimated by analyzing 5-minute aggregated traffic counts from the year 2002 to 2004.

Finally, the short-term stochastic variation of demand was considered to generate demand values for each 5-minute time interval \(D_{1min}\) from estimated hourly demands:

\[
D_{3\text{min}} = \varphi \times \frac{HD_{dh}}{12} \quad \text{(6)}
\]

Here, \(\varphi\) is a random term with an expected value of 1. The relationship between 5-minute traffic counts and hourly traffic volumes during uncongested hours was analyzed in 2003 and for the test bed, \(\varphi\) was found to be Normal distributed with standard deviation of 0.13.
6.2 Capacity

Capacity is treated as a random variable in this study. Empirical capacity distribution function for a roadway under specific prevailing conditions can be estimated by using mathematical methods for lifetime data analysis. Empirical studies revealed that freeway capacity is Weibull distributed\(^{10}\):

\[
F_c(q) = 1 - e^{-\frac{q}{\beta}}
\]

where \(\alpha\) and \(\beta\) represent the shape and scale parameters of the distribution function, respectively, and \(F_c(q)\) is the capacity distribution function. Inano et al.\(^{18}\) investigated the breakdown phenomena on several segments of intercity expressways in Japan and estimated shape and scale parameters of the capacity distribution function of several bottleneck sections. Since breakdown of traffic flow may occur in different locations of a road segment, considering the independency of different breakdown events\(^{10}\), the probability of breakdown on a segment with \(n\) bottlenecks can be estimated from Equation (8):

\[
F_c(q) = 1 - \prod_{k=1}^{n} (1 - F_{c,k}(q_k))
\]

where, \(F_{c,k}(q_k)\) and \(F_c(q)\) represent the capacity distribution function of the bottleneck \(k\) and a segment with \(n\) bottlenecks respectively. For the test bed of this study, estimations from Equation (8) delivered a Weibull distribution with shape and scale parameters of 12.2 and 356 veh/5-minute-2lane. Thus capacity of the segment is generated using the inverse of the Weibull distribution:

\[
C = \beta [-\ln(u)]^{\frac{1}{\alpha}}
\]

where \(C\) represents the segment capacity and \(u\) is a uniform distributed random term between 0 and 1.

6.2.1 Adjustments due to rain and heavy vehicles

Chung et al.\(^{19}\) investigated impacts of rain on the capacity of several highly congested segments of the Tokyo Metropolitan Expressway. Results of their study are implemented to adjust simulated capacities according to weather conditions. Adjustment factors of 0.94 and 0.91 are applied for the hourly precipitation of 1 to 3 mm and 3 to 10 mm respectively. For heavier rainfalls, an adjustment factor of 0.89 is applied. In addition, capacity values need to be adjusted relative to the proportion of heavy vehicles in the traffic flow. Assuming the passenger car equivalent factor of 1.7, the Japan Road Association\(^{20}\) approach is adopted to estimate adjustment factors (similar to HCM 2000\(^{21}\) methodology).

6.2.2 Capacity drop and Queue Discharge Flow (QDF)

Existence of different capacity values under flowing and congested traffic conditions has been proven by a number of studies. Using the distribution of breakdown flow rates (measured immediately prior to breakdown) and the distribution of queue discharge flow, an average drop of 3\% to 24\% is observed by several investigations\(^9\). However, an average capacity drop of 10\% is adopted for the purpose of this research that is consistent with Inano et al.\(^{18}\).

6.3 Speed-flow relationship

Traffic density is a key parameter of the shockwave analysis. Since traffic volume is known, density can be estimated if speed is known. Hence, it is necessary to estimate the average speed at congested and uncongested time intervals.

6.3.1 Uncongested conditions

Given the traffic volume, speed-flow relationships calibrated by Hong and Oguchi\(^{22}\) are used to estimate the 85\% percentile speeds during uncongested conditions. Using their models, first, distribution of the vehicles through different lanes is defined regarding the pavement surface conditions (dry/wet) and number of lanes. Then the 85\% percentile speed for each lane is estimated by using the calibrated speed-flow relationships.

Since the proposed methodology requires average speeds rather than 85\% percentiles, estimated speeds from the Hong and Oguchi model needs to be adjusted to calculate the average speeds. To define the required adjustments, for different traffic volumes, average speeds \((v_d)\) were obtained from detector data and compared with the estimated 85\% percentile speeds \((v_m)\) derived from the Hong and Oguchi model. To assure uncongested conditions, only samples with average speeds of above 80 km/h were analyzed. Finally, appropriate second order polynomial functions were fitted to both data sets. As shown in Figure 4a), the difference between observed average speeds and the estimated 85\% percentile speeds increases as traffic flow approaches capacity. The difference \((\Delta v)\) is represented by Equation (10), which is applied to modify the estimated 85\% percentile speeds \((v_m)\) and convert them into average values \((v_d)\) according to traffic volume:

\[
\Delta v = v_d - v_m = 66.82 \times 10^{-5} q^2 - 35954.53 \times 10^{-6} q - 4.3
\]

6.3.2 Congested conditions

Speed of the congested flow is mostly governed by QDF at the bottleneck. To estimate the average speed of the congested flow, a speed-flow relationship is devel-
6.4 Accidents

After initial assessment of traffic conditions at each time interval, the relationship between accident rate and traffic condition is considered in the proposed model. Accidents are generated based on a model that relates accident rate to traffic density. Hikosaka and Nakamura\(^9\) investigated the relationship between accident rate and traffic flow conditions on various segments of the Tomei Expressway and developed separate models to estimate accident rate relative to traffic density in congested and uncongested conditions. These models are used to generate accidents randomly according to traffic conditions. Since density is known at each time interval, congested and uncongested time intervals are separately categorized based on their density level. For each category, accident rate is estimated according to traffic conditions and density level by using Equations (11) and (12). The number of expected accidents for each category is estimated considering the segment length (\(l\)) and traffic throughput (\(q_n\)) at each density category \(n\) from Equation (13):

\[
\text{Congested : } AR_n = 0.0488k^3_n - 2.983k_n + 60.456 \tag{11} \\
\text{Uncongested : } AR_n = 0.0416k^3_n - 3.1716k_n + 97.142 \tag{12} \\
AN_n = \frac{AR_n \times l \times \sum q_n}{10^3} \tag{13}
\]

where \(AR_n (AN_n \times 10^6/\text{veh-km})\) is accident rate, \(k_n\) is average traffic density and \(AN_n\) is the number of accidents corresponding to density category \(n\). Predicted numbers of accidents for each category of density and traffic conditions (congested/uncongested) are generated at corresponding time intervals on a random basis. It should be noted that these models were developed by using average values of accident rate and traffic density. Therefore to avoid over- or underestimation, an appropriate adjustment factor was applied to the models.

6.4.1 Clearance time and capacity reduction

Duration of an accident is directly related to accident clearance time, which is defined as the time period between the occurrence and removal of an accident. Clearance time data of 268 accidents occurred on the Tomei Expressway in 2003 were analyzed and their distribution was investigated. For the modeling purpose, several functional forms were considered and finally a Weibull function with shape parameter of 1.13 and scale parameter of 66 (minute) was found to best describe the distribution of the clearance time. Depending on the lane on which the accident occurs the remaining available capacity might be different. To estimate the available capacity after accidents, considering the number of lanes, adjustment factors of 0.81 and 0.35 are adopted from HCM 2000\(^{21}\) for the accidents occurring on the shoulder or main lanes respectively.
6.5 Measurement of queuing vehicles

Figure 5 represents traffic conditions on the test bed during the congested conditions. As demand exceeds capacity, a queue starts to build up. The number of queuing vehicles can be estimated through shockwave analysis. For congested intervals, speed of the shockwave \((w)\) is estimated from Equation (14) and queue propagation rate \((Q_{\text{min}} \text{ (veh/5-minute)})\) is estimated from Equation (15):

\[
w = \frac{Q_1 - QDF}{k_1 - k_2} \quad (14)
\]

\[
Q_{5\text{min}} = (Q_1 - QDF) - k_1 \cdot w \quad (15)
\]

6.6 Travel time and reliability estimation

To estimate BTI as a measure of travel time reliability, travel times should be estimated at each 5-minute interval during the analysis period. For uncongested conditions, the traffic condition is assumed to be uniform along the test bed; therefore travel times could simply be estimated through dividing the segment length by the average speed of traffic flow. As shown in Figure 5, for congested conditions the following areas are defined with different operating speeds: i) upstream from queuing vehicles; ii) queuing vehicles and iii) downstream from queuing vehicles. Different speeds on these areas should be considered to estimate travel times during congested conditions. Regarding Figure 5, Equation (16) is proposed to estimate travel time \((TT)\) during congested conditions:

\[
TT = \frac{\delta \times l - Q / k_2}{v_1} + \frac{Q / k_2}{v_2} + \frac{l - \delta \times l}{v_3} \quad (16)
\]

Given \(Q\) as the number of queuing vehicles and \(k_2\) as the density of congested flow, \(Q/k_2\) yields queue length in kilometers. \(l\) defines the location of the bottleneck and \(\delta\) is an adjustment factor (\(0 < \delta \leq 1\)) that is multiplied to the section length \((l)\) to define the location of the bottleneck.

To estimate travel times from Equation (16), the unknown parameter is \(\delta\) only. Since the ultimate goal of the model is to estimate BTI, \(\delta\) can be defined through an iterative procedure by minimizing the Root Mean Square Error (RMSE) of estimated BTI from the model and measured values from empirical data. The following steps describe the procedure to define \(\delta:\)

1. Set \(\delta = 0.1\);
2. Run the simulation model 5 times and estimate travel times and BTI at each 5-minute interval for the whole analysis period;
3. Compare estimated BTIs with measured values from empirical data and calculate RMSE for each trial of simulation;
4. Set \(\delta = \delta + 0.1\); if \(\delta > 1\) then go to Step 5, or else go to Step 2;
5. Plot \(\delta\) versus RMSE and select the \(\delta\) value corresponding to the minimum RMSE. Following the steps above, \(\delta\) for weekdays/non-holidays and weekends/holidays were estimated equal to 1.0 and 0.7 respectively.

7. MODEL OUTPUTS AND VALIDATION

A sample output of simulated demand, capacity and resulting queues are presented in Figure 6. Traffic flow is low after midnight and during the morning. The peak period on weekdays starts around 3pm and continues until 8pm where traffic flow gradually starts to drop again. In addition to random variations of capacity, systematic variations are also conspicuous. Capacity during the nighttime is considerably lower than daytime values, due to the high proportion of heavy vehicles in the traffic stream that surges beyond 60% from time to time. Sometimes demand exceeds capacity during peak periods and recurring congestion occurs. However, the magnitude of recurring congestion might be smaller than that of non-recurring congestion, which occurs occasionally due to accidents.

The simulation model was run 5 times and the BTI and predicted number of accidents were estimated for all categories of days 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 for each category of days and presented in Figure 7.

The model correctly predicts the beginning and the end of the daily unreliable congested periods. Simulation results show the same tendency as the observations made.
**Fig. 6** Demand, capacity and resulting queues (Simulated for Okazaki-Toyota section, 17-23 March 2003)

**Fig. 7** Model output compared with measured values (2003)
through empirical data for the extents of travel time reliability throughout a whole year. The model predicts BTI with little over- or underestimations during the peak periods. However the RMSE is lower than 9% in all cases. Estimation errors might be caused by either any of various models applied in the methodology or travel time estimation method used in the simulation.

According to available accident records, 53 accidents occurred on the test bed in 2003, from which 39 accidents took place on weekdays/non-holidays and 14 accidents happened on weekends/holidays. As shown in Figure 7, the predicted number of accidents is close to the real number of actual accidents in all categories of days.

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

### 8. MODEL APPLICATION

As presented in Figure 2 for the test bed of this study, congestion levels extended and travel time reliability deteriorated in 2006 due to the significant increase in AADT. In order to renovate the overall traffic conditions, alternative congestion relief schemes could be put in action. However, road authorities need to know the extent of the improvements in travel conditions and safety before implementing a congestion relief scheme in real conditions. Such knowledge helps them to select the best action in terms of traffic operation improvements and economic efficiency.

To demonstrate some applications of the proposed methodology, two different congestion relief schemes are assumed for the test bed of this study: i) Scheme A: Reducing the peak period demand by 15%. ii) Scheme B: Opening the hard shoulder to traffic during the peak periods. Hereafter, the proposed methodology is used to assess impacts of these strategies on travel time reliability and safety.

#### 8.1 Peak period demand reduction

Reducing peak period demand is an effective way to eliminate congestion levels and improve overall travel conditions and safety. The peak period usage of an expressway segment could be controlled through effective variable-priced toll programs. Higher toll prices during the peak period, provides financial incentives for road users to shift their trips to off-peak periods or less crowded parallel links. Such demand-side strategies were practiced by several transportation agencies around the world. Variable-priced tolls on two county bridges in Lee County, Florida, could increase the use of the bridges in the off-peak times and decrease the usage during the peak periods\(^2\). On the New Jersey Turnpike, up to 15% of peak-period traffic was reduced by variable pricing\(^2\).

As shown in Figure 8, the peak period on weekdays/non-holidays starts from 3pm and continues until 8pm on the test bed of this study. Since the peak period is extended, shifting demand to off-peak hours may not be realistic. It is assumed that 15% of the peak period demand could be reduced (shifted to other links) following an effective variable-priced toll program. The ratio of hourly traffic demand to daily traffic demand on weekdays/non-holidays for Scheme A is presented in Figure 8.

#### 8.2 Dynamic use of the hard shoulder during the peak periods

Using the hard shoulder as a running lane tackles congestion by providing additional capacity during the peak periods. This is an alternative solution for constructing an additional lane, which might be very expensive and time consuming. Hard shoulder use aims to make the best use of the existing road space while maintaining and hopefully improving current safety levels.

The experience of other countries notifies that opening the hard shoulder to traffic on expressways during peak periods results in reduced travel times, accident rate and emission levels. The UK Highways Agency is currently implementing an Active Traffic Management

![Fig. 8 Hourly demand coefficients on weekdays/non-holidays (Scheme A)](image-url)
(ATM) system as a pilot scheme over the 17km stretch of the M42 highway (3 lanes + hard shoulder) that allows the operators to open the hard shoulder to traffic at busy hours of the day. A before-after study\textsuperscript{24} pinpointed significant improvements in peak period travel conditions. In addition to reduced travel times, hard shoulder use resulted in less variable travel times. Analysis showed that the average number of personal injury accidents as well as the accident severity index, which is the ratio of the number of fatal and serious accidents to the total number of accidents, decreased. The overall emission rate also showed reducing trends with a maximum reduction in particulate matters (PM)\textsuperscript{24}.

Opening the hard shoulder to traffic on all days from 3pm to 8pm is considered as an alternative congestion relief scheme for the test bed of this study. Impacts of such an action on travel time reliability and safety will be evaluated by using the proposed methodology.

8.3 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). Since the weather data were not available for the year 2006, it is assumed that the weather condition was the same as the year 2003. Figure 9 represents the estimated BTI, RMSE and predicted numbers of accidents in 2006. According to the accident data in 2006, 77 accidents occurred on the

![Fig. 9 Base model outputs compared with measured values (2006)](image)

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<tr>
<th>Simulation trial</th>
<th>RMSE (%)</th>
<th>Accidents</th>
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<tr>
<td>1</td>
<td>9.00</td>
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<tr>
<td>Mean of all trials</td>
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</tbody>
</table>

a) Weekends/holidays ($j=1,130$ days)

<table>
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<th>Simulation trial</th>
<th>RMSE (%)</th>
<th>Accidents</th>
</tr>
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<tbody>
<tr>
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<td>Mean of all trials</td>
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b) Weekdays/non-holidays ($j=2,235$ days)

<table>
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<th>Simulation trial</th>
<th>RMSE (%)</th>
<th>Accidents</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6.17</td>
<td>76</td>
</tr>
<tr>
<td>2</td>
<td>3.37</td>
<td>73</td>
</tr>
<tr>
<td>3</td>
<td>5.24</td>
<td>76</td>
</tr>
<tr>
<td>4</td>
<td>3.14</td>
<td>78</td>
</tr>
<tr>
<td>5</td>
<td>2.90</td>
<td>77</td>
</tr>
<tr>
<td>Mean of all trials</td>
<td>3.20</td>
<td>76</td>
</tr>
</tbody>
</table>

c) All days ($j=3,365$ days)
test bed from which 54 accidents were on weekdays/non-holidays and 23 accidents were on weekends/holidays. Several trials of the simulation model estimated 51 accidents for weekdays/non-holidays and 23 accidents for weekends/holidays (76 accidents in total) which are reasonably close to the real number of accidents in 2006.

8.4 Model adjustments for three-lane conditions
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 during the intervals when the hard shoulder is open to traffic.

8.4.1 Capacity adjustments
The capacity of a three-lane segment might be slightly higher than 1.5 times that of a two-lane segment due to the easing of lane changing maneuvers. However, since the hard shoulder may not be utilized perfectly as an ordinary lane, for the purposes of this study, the scale parameter of the capacity distribution function in Equation (9) is multiplied by 1.4 to reproduce the test bed’s capacity in three-lane conditions.

8.4.2 Speed flow relationship
For uncongested conditions, likewise the two-lane conditions, the Hong and Oguchi\(^20\) model was used to estimate 85th percentile speeds and then estimated values were adjusted by using Equation (10) to reproduce average speeds in three-lane conditions (Figure 10a)).

For congested conditions, the previously developed model for two-lane conditions (Figure 4b) was modified to estimate the speed-flow relationship of three-lane conditions. The main hypothesis is that when the traffic condition is congested, all the lanes are almost fully utilized at the same speed. Accordingly, for the same speed, traffic volume in three-lane condition is 1.5 times that of a two-lane condition. Such a substitution yields a modified speed-flow relationship that is represented in Figure 10b).

8.5 Impact assessment
The simulation model was run 5 times for each scheme and the average of estimated BTI and numbers of accidents are represented in Figure 11. Supplementary congestion and reliability measures were also estimated during the peak periods and compared with corresponding values in 2006.

As it is shown in the tables in Figure 11, reducing peak period demand by 15% through Scheme A results in considerable improvements in peak period travel conditions. The peak period travel time dropped from 7.65 min. to 6.68 min. on average. Travel time reliability is also improved significantly as the average peak period BTI is reduced from 25.8% to 5.8%. Lower values of TTI and PTI imply that not only average travel times are becoming shorter but also the variability of the travel times becomes smaller. As for safety improvements, the expected number of accidents on weekends/holidays is reduced by 13%, whereas for weekdays/non-holidays the reduction is about 28%. Overall, the total number of accidents is expected to be reduced from 77 in 2006 to 59 after implementing Scheme A that shows 23% reduction.

Opening the hard shoulder to traffic during the peak periods as Scheme B, results in even more conspicuous improvements in travel conditions. The average peak period travel time is reduced from 7.65 min. to 6.32 min. and average BTI is reduced 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 are also accompanied by a significant reduction in the expected number of accidents on weekends/holidays by 22%, whereas for weekdays/non-holidays the reduction is about 21%. Overall, the total number of accidents is expected to be reduced from 77 in 2006 to 49 after implementing Scheme B that shows 33% reduction.

Fig. 10 Speed-flow relationship of the test bed in three-lane conditions
conditions after opening the hard shoulder to traffic during the peak periods also results in significant improvements in traffic safety. The number of accidents on weekends/holidays and weekdays/non-holidays is reduced significantly. The total number of accidents is reduced from 77 in 2006 to 58 after implementing Scheme B.

Interestingly, both Scheme A and Scheme B may reduce the total number of expected accidents by more than 23% that notifies the similar impact of these improvement schemes on safety. However, for their impact on travel time reliability and peak period travel conditions, Scheme B is slightly more advantageous than Scheme A.

Since impacts of both improvement schemes on travel conditions and safety were almost equally significant, road authorities may consider other criteria such as organizational goals and policies, availability of resources and economic issues to select one of the options.

Considerations should be taken into account while interpreting the conclusions regarding safety improvements after implementation of Scheme A or Scheme B. Safety appears to be improved because accidents are solely modeled based on traffic density in the proposed methodology and other influencing factors are not considered here. In other words, conclusions of this study are valid only based on the assumptions made in the methodology.

The next section aims to evaluate the reductions in road user costs after implementing Scheme A or Scheme B that might be used as a part of economic analysis for

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**Fig. 11** Impacts of congestion relief schemes on reliability and safety

<table>
<thead>
<tr>
<th>Measure</th>
<th>2006</th>
<th>Scheme A</th>
<th>Scheme B</th>
</tr>
</thead>
<tbody>
<tr>
<td>TT (min)</td>
<td>7.53</td>
<td>6.54</td>
<td>6.21</td>
</tr>
<tr>
<td>BTI (%)</td>
<td>33.8</td>
<td>5.4</td>
<td>4.4</td>
</tr>
<tr>
<td>TTI</td>
<td>1.18</td>
<td>1.05</td>
<td>1.00</td>
</tr>
<tr>
<td>PTI</td>
<td>1.58</td>
<td>1.08</td>
<td>1.02</td>
</tr>
<tr>
<td>Accidents</td>
<td>23</td>
<td>20</td>
<td>20</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Measure</th>
<th>2006</th>
<th>Scheme A</th>
<th>Scheme B</th>
</tr>
</thead>
<tbody>
<tr>
<td>TT (min)</td>
<td>7.72</td>
<td>6.74</td>
<td>6.38</td>
</tr>
<tr>
<td>BTI (%)</td>
<td>21.1</td>
<td>5.6</td>
<td>4.6</td>
</tr>
<tr>
<td>TTI</td>
<td>1.21</td>
<td>1.05</td>
<td>1.01</td>
</tr>
<tr>
<td>PTI</td>
<td>1.47</td>
<td>1.12</td>
<td>1.04</td>
</tr>
<tr>
<td>Accidents</td>
<td>54</td>
<td>39</td>
<td>38</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Measure</th>
<th>2006</th>
<th>Scheme A</th>
<th>Scheme B</th>
</tr>
</thead>
<tbody>
<tr>
<td>TT (min)</td>
<td>7.65</td>
<td>6.68</td>
<td>6.32</td>
</tr>
<tr>
<td>BTI (%)</td>
<td>25.8</td>
<td>5.8</td>
<td>4.8</td>
</tr>
<tr>
<td>TTI</td>
<td>1.20</td>
<td>1.04</td>
<td>1.00</td>
</tr>
<tr>
<td>PTI</td>
<td>1.51</td>
<td>1.11</td>
<td>1.04</td>
</tr>
<tr>
<td>Accidents</td>
<td>77</td>
<td>59</td>
<td>58</td>
</tr>
</tbody>
</table>
selecting an appropriate improvement scheme.

8.6 Road user cost analysis

As demonstrated earlier, implementing either Scheme A or Scheme B improves travel conditions and consequently results in shorter travel times on the test bed of this study. Considering the monetary value of time for different road users, shorter travel times culminate in lower total cost incurred by road users. Such a reduction could be estimated given the monetary value of time for different road users and traffic composition.

8.6.1 The value of time

As shown in Table 1, the values of time for different vehicle types that are provided by the Ministry of Land, Infrastructure, Transportation and Tourism (MLIT) for the year 2003 (latest available data) were used for this analysis.25

8.6.2 Traffic composition

The values of time shown in Table 1 are different regarding vehicle type. Hence the knowledge of traffic composition is necessary for further analysis. Since the available detector data only provides information about passenger cars and heavy vehicles in general, results of the traffic count survey of the Road Traffic Census done by MLIT in 2005 were adopted to estimate the composition of the heavy vehicles’ traffic.26 As presented in Table 2, the composition of the heavy vehicles’ traffic is different on weekdays/non-holidays and weekends/holidays.

8.6.3 Cost analysis

Given the traffic volume and travel times for each 5-minute interval, the total road user costs were estimated for 2006 by using Table 1 and Table 2. As for Scheme A and Scheme B, the simulation model was run 5 times and the total road user costs were estimated for each trial of the simulation. Table 3 shows the average road user costs estimated from all simulation trials for Scheme A and Scheme B. Estimated values are compared with the road user costs in 2006 and the average reduction in user costs is estimated for each improvement scheme. Considering the stochastic features of the simulation model, the total annual traffic volume that is generated in each simulation trial is slightly different. On the other hand, since Scheme A is targeting the reduction of the peak period demand by 15%, the total annual traffic volume would be lower than that of Scheme B. As a result for the purpose of comparison, also the average reduction in user cost is estimated for each vehicle.

Table 3 shows that the total user cost and average user cost per vehicle will clearly be reduced after implementing either Scheme A or Scheme B. The analysis points out that implementing Scheme A results in 28.3 JPY reduction in user costs for each vehicle, while Scheme B will reduce the road user costs by 39.6 JPY per vehicle.

Opening the hard shoulder to traffic during the peak period was found to significantly improve travel conditions and reduce the number of accidents. In addition, it has more economic advantages for road users compared with reducing the demand by 15% during the peak periods. It should be noted that the findings of this analysis could only be used as a part of the whole cost-benefit analysis and other issues such as initial costs that are associated with implementation of each improvement scheme should also be considered carefully.

In this section, some applications of the proposed methodology were demonstrated. Since demand and capacity are compared at each 5-minute interval, traffic conditions and travel time variations could be estimated at each time interval, which makes it possible to evaluate the impact of different congestion relief schemes on travel time reliability and safety prior to their implementation. In addition, estimated travel times could be converted to monetary values, which enable road authorities to compare the efficiency of alternative improvement schemes on economical basis.

Table 1 Value of time for different vehicle types (2003)

<table>
<thead>
<tr>
<th>Vehicle Type</th>
<th>Value of Time (JPY/min·veh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Passenger Car</td>
<td>62.86</td>
</tr>
<tr>
<td>Bus</td>
<td>519.74</td>
</tr>
<tr>
<td>Semi Truck</td>
<td>56.81</td>
</tr>
<tr>
<td>Ordinary Truck</td>
<td>87.44</td>
</tr>
</tbody>
</table>

Table 2 Heavy vehicles traffic composition (2005)

<table>
<thead>
<tr>
<th>Vehicle Type</th>
<th>Weekends/ Holidays (%)</th>
<th>Weekdays/ Non-holidays (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bus</td>
<td>7.3</td>
<td>2.0</td>
</tr>
<tr>
<td>Semi Truck</td>
<td>25.5</td>
<td>24.8</td>
</tr>
<tr>
<td>Ordinary Truck</td>
<td>67.2</td>
<td>73.2</td>
</tr>
</tbody>
</table>

Table 3 Road user costs before and after implementing congestion relief schemes

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Total Cost (Million JPY)</th>
<th>Annual Traffic Volume (10^3×veh)</th>
<th>Cost/veh (JPY)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2006</td>
<td>9,174</td>
<td>17,590</td>
<td>522</td>
</tr>
<tr>
<td>Scheme A</td>
<td>8,373</td>
<td>16,976</td>
<td>493</td>
</tr>
<tr>
<td>Scheme B</td>
<td>8,541</td>
<td>17,721</td>
<td>482</td>
</tr>
</tbody>
</table>
9. CONCLUSIONS AND FUTURE WORK

In this study, a methodology was presented to pre-evaluate the efficiency of congestion relief schemes by considering their impacts on travel time reliability and safety. Proposed methodology was further applied to estimate impacts of opening the hard shoulder to traffic, and reducing the peak period demand 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, the proposed methodology determines 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. On the other hand, since the relationship between traffic conditions and accident likelihood is considered, the methodology is capable of evaluating impacts of congestion relief schemes on safety.

Most of the models used in the proposed methodology are based on empirical data collected on expressways in Japan. Yet, the methodology is applicable in other locations as well. If required data are available, capacity distribution functions, demand variations, speed-flow relationships and the relationship between accidents and traffic conditions can be modeled for any other expressway segments.

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. 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, the impact of induced demand from neighboring routes as a result of improved traffic conditions after implementing an improvement scheme was 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.

REFERENCES


