A MACROSCOPIC APPROACH TO EVALUATE THE EFFECT OF INCIDENT ON TRAVEL TIME RELIABILITY OF A HIGHWAY

William H.K. LAM  
Professor  
Department of Civil and Structural Engineering  
The Hong Kong Polytechnic University  
Hung Hom, Kowloon  
Hong Kong  
Fax: +852-2334-6389  
E-mail: cehklam@polyu.edu.hk

G.C.K. WONG  
Research Assistant  
Department of Civil and Structural Engineering  
The Hong Kong Polytechnic University  
Hung Hom, Kowloon  
Hong Kong  
Fax: +852-2334-6389  
E-mail: a9014439@graduate.hku.hk

Abstract: In order to evaluate the effect of incident on road users, this paper uses a macroscopic traffic flow model, the Multi-Class Lighthill-Whitham-Richards (MCLWR) model, developed by Wong and Wong (2002) to determine the travel time reliability of a highway with the occurrence of traffic incidents. A Monte Carlo simulation approach, which incorporates the MCLWR model and a distribution of traffic demand due to daily fluctuation, is proposed to estimate the travel time reliability of a highway with different types of incident. These incidents are assumed to block all traffic lanes with different extends on blockage time. The application of the proposed approach is illustrated by a numerical example in Hong Kong. Travel times are determined from the solution of the MCLWR model and the travel time reliability is then calculated for different types of incident and plotted for discussions.

Key Words: macroscopic approach, travel time reliability, multi-class

1.  INTRODUCTION

Unlike the delay due to daily traffic demand variation, the delay caused by incident on highways is unanticipated and increases the economic cost of travel to road users. Empirical evidence confirms that a major cause of day-to-day variability in trip times is the occurrence of traffic incidents, including major incidents that block traffic lanes for extended periods and many minor incidents such as vehicle breakdowns (see Giuliano, 1989). Such variability usually result in either the road user arrives late or the road user makes an earlier departure than desired, with the possibility on any given day of arriving earlier than necessary. Either way, time is lost or at least used in a less than optimal fashion and the highway (as part of a transport system) is therefore less than reliable.

Nowadays, as the value of time has increased, the stability of road networks has become an important issue since an unexpected delay can results in great loss to road users. Smooth traffic flow in a road network can be affected by external factors such as natural disasters and traffic incidents. In such degraded conditions, the level of network flow and the level of service will decrease and affect the performance of the network. There are two types of measure for evaluating the performance of road networks, connectivity reliability and travel time reliability (Bell and Iida, 1997). Connectivity reliability is concerned with the probability that there exists at least one path without disruption or heavy delay to a given destination within a given time period. Travel time reliability, on the other hand, is defined as the probability that a trip between a given Origin-Destination pair can be made within a given
time period. It is a useful measure to evaluate network performance under daily flow fluctuations due to demand variations (Bell et al., 1999) or capacity degradation as a result of deteriorated roads (Asakura, 1998).

In road network reliability analysis, each road link is treated like a ‘black box’ and the link flow, link travel time etc are calculated without knowing what happened along each link. Such approach therefore requires a calibrated formula to model the effect of incident to a road network. This formula is difficult to obtain especially when the duration, or the location of an incident within a road link varies. In view of this, we attempt to use a macroscopic traffic flow model to describe the traffic and by solving the model, estimate the travel time reliability of a highway subjected to incident. This approach allows more flexible incident conditions to be set for analysis and that the variation of traffic along each road link can be examined in detail if needed.

2. TRAVEL TIME RELIABILITY

Travel time reliability is defined as the probability that a trip will arrive at its destination within a given period. For example, if the travel time reliability to arrive at a destination in 10 minutes is 0.8, this means that drivers will arrive at the destination within 10 minutes 8 times out of 10. It is a measure of the stability of travel time, and therefore is affected by variations in traffic flow as a result of fluctuations in demand, weather condition, and occurrence of incidents etc. The link travel time has to be calculated in order to determine the travel time reliability of a link/path affected by incident. For network reliability analysis, the link travel times are usually calculated from the BPR (Bureau of Public Roads) type formula (Lam and Xu, 1999)

\[ t_a = t_a(0) + k \left( \frac{v_a}{s_a} \right)^p \]  

(1)

where \( s_a \) and \( v_a \) are the capacity and link flow of link \( a \), \( t_a(0) \) is the free flow travel time (in minutes) and \( p \) and \( k \) are parameters of link \( a \). However, it is difficult, if not impossible, to calibrate the parameters for the BPR type formula for use in incident analysis. This is due to the difficulty of getting recurrent incidents needed for calibration. Therefore in this paper, we attempt to determine the link travel time directly by solving a macroscopic continuum model. This has the advantage that there is no need to calibrate for parameters that include an incident. The information the MCLWR model needs is the range of free-flow speeds and their distribution. The range of free-flow speeds can be obtained from field observations and then the upper and lower bounds, as well as the mean free-flow speed can be determined. It is assumed that the distribution of free-flow speeds is normal and the required travel time with or without incident can be obtained for any given demand by solving the MCLWR model. In fact for the case of no incident, we can obtain a BPR type formula by solving the macroscopic model with different demand level (Figure 1). Once a BPR type formula is obtained, the travel time of a link can be easily calculated using the formula instead of solving the macroscopic model.
3. MACROSCOPIC APPROACH OF ESTIMATING RELIABILITY

In this section, a newly developed macroscopic continuum model of traffic flow, the MCLWR model by Wong and Wong (2002) is used to estimate the travel time reliability of a road. Unlike microscopic simulation (Cameron and Duncan, 1996; Fellendorf, 1996; Owen et al., 2000) the macroscopic approach represents the aggregated behavior of a stochastic process for a large population and is therefore applicable, mainly to large-scale problems for strategic evaluation of alternative traffic scenarios. One of the advantages of modeling traffic macroscopically is that it avoids setting detail rules for vehicles and only use the concept of conservation of vehicles and a speed-density relationship to govern their motions. In microscopic simulation, on the other hand, one has to set rules like how a vehicle will change lane, how it will accelerate or decelerate, in order to simulate its motion. Such rules are in general hypothetical and are difficult to verify. The MCLWR, extended from the Single-class Lighthill-Whitham-Richards (SCLWR) model (Lighthill and Whitham, 1955; Richards, 1956), takes into account of different classes of road users with different speed choice behaviors in response to the same density when traveling on a highway section. It means that for a given total density, there exists a distribution of speeds by different user classes. It is expected that the variation around the mean speed (averaged over all user classes) increases when density decreases due to lesser interactions between road users, and vice versa due to tighter interactions. Let $q_m(x,t)$, $\rho_m(x,t)$ and $u_m(x,t)$ be, respectively, the flow, density and speed of user class $m$ in the space-time domain. The MCLWR model consisted of a set of partial differential equations

$$\frac{\partial \rho_m(x,t)}{\partial t} + \sum_{n=1}^{M} c_{mn}(x,t) \frac{\partial q_m(x,t)}{\partial x} = 0, \quad \forall m = 1,2,\ldots,M$$

where

$$t_a = 13.388 + 7.986 \left( \frac{v_a}{s_a} \right)^{2.30}$$
\begin{equation}
    c_{mn} = U_m \delta_{mn} + \rho_m \frac{\partial U_m}{\partial \rho_n}, \quad \forall m = 1, 2, \ldots, M,
\end{equation}

is the kinematic wave speed of user class \( m \) in response to the presence of class \( n \) users, and \( \delta_{mn} = 1 \) if \( m = n \); and \( \delta_{mn} = 0 \) if \( m \neq n \). Here \( U_m \) represents a speed-density relationship assumed for each class. Note that the problem stipulated in equation (3) reduces to the original LWR model when \( M = 1 \) (i.e. homogeneous users). The problem becomes one of solving the set of differential equations (2), subject to certain initial spatial and time boundary conditions. Although the problem formulation is straightforward, it was found that the model is capable of producing the desired properties of a macroscopic traffic flow model and it explains many puzzling phenomena, such as the two-capacity or reverse-lambda state, hysteresis, and platoon dispersion, but it would not be subject to other deficiencies such as wrong-way travel (Daganzo, 1995).

3.1 Monte Carlo Simulation Procedure

Although the MCLWR model takes into account of a distribution of road users, it is still a deterministic model. In order to simulate the stochastic nature of real traffic flow, the Monte Carlo simulation method is used. With the advancement of computer technology, there has been increased interest in using the Monte Carlo simulation to estimate the reliability measures by simulating the random behavior of the system (Billinton and Li, 1994). One of the advantages of using Monte Carlo simulation is that it can calculate the reliability measures in the form of expected values from the random variables, and in additional, the distributions of these measures, which in general cannot be achieved using analytical methods.

To estimate the distribution of average travel time of a highway with or without incident, we develop a procedure using the Monte Carlo simulation method and an assumed distribution of demand for the highway. The procedure can be described as follows:

Step 0: Initialize the MCLWR model with the distribution of road users
Step 1: Set sample number \( k := 1 \).
Step 2: Generate the demand for the highway.
Step 3: Solve the MCLWR model with the generated demand.
Step 4: Collect statistics to construct the travel time reliability distribution function.
Step 5: If sample number \( k \) is less than the required sample size \( k_{\text{max}} \), then increment sample number \( k := k+1 \) and go to Step 2. Otherwise, go to Step 6.

The Weighted Essentially Non-Oscillatory (WENO) scheme (Jiang and Shu, 1996; Zhang et al., 2002) is used to solve the MCLWR model. The average travel time is determined for one time step of vehicles from the difference between the times of arrival at the upstream end and the downstream end of the highway. In this manner, a First-In-First-Out behavior is implied in order to calculate the required travel time for each class of road users. To simulate incident effect, we randomly generate a period of blockage 500m from downstream end. It is assumed that the incident actually blocks all traffic lanes on the highway during the blockage. The duration of the blockage is depended on the type of incidents involved, which are discussed in the numerical simulation section. In the present study, it is assumed for simplicity that there is an equal chance of occurrence of an incident during the simulation period regardless
of the flow rate. In realistic situations, the chance of occurrence of incident may need to be simulated to account for its dependency among the occupancy of the highway.

4. NUMERICAL SIMULATIONS

In order to illustrate the macroscopic approach proposed for reliability analysis, the North Lantau Expressway (Figure 2) is used as the example highway for simulation.

The North Lantau Expressway connects the Hong Kong International Airport to Tsing Yi Island. The highway is approximately 20 km in length and it is a 3-lane dual carriageway. Since it is the only highway to the airport, its reliability is therefore of great concern to road users to determine their travel time to the airport. We will analyze the effect of incident on the travel time reliability of this highway using the MCLWR model and the Monte Carlo simulation approach discussed.

In this analysis, we use the modified Drake’s speed-density relationship

\[ u_m = U_m(\rho_1, \rho_2, \ldots, \rho_M) = u_{fm} \exp\left(-\frac{(\rho/\rho_0)^2}{2}\right) \]  

(4)

with \( \rho_0 = 40 \text{ veh/km} \) and assumed the same user-class distribution (Figure 3) as in Wong and Wong (2002) for all simulations. Throughout this study, the demand (in terms of density value) for the highway is assumed to increase from zero to a peak value for the first hour and then drop back from this peak value to zero for the next one hour. The simulation period is set to be three hours, and the daily variation for peak value of demand is assumed to be normally distributed with mean, \( \mu = 35 \text{ veh/km} \) (corresponding to a demand of approximately 2400 veh/h) and standard deviation, \( \sigma = 2.5 \) (The Annual Traffic Census, 2001).
The first simulation is carried out (excluding incident effect) to show the difference when modeling using the SCLWR model and the MCLWR model. Figure 4 depicts the computed average travel time reliability curves. The LWR case is modeled using the MCLWR model with the free-flow speed of each class of road users equals to 90 km/h, i.e. the mean free-flow speed of the multi-class case. Although the mean free-flow speeds of the road users are the same for the SCLWR model and the MCLWR model, the resulting behavior is not the same. From the figure, it is notice that for the range of travel time reliability values from 0.0 to 0.7 approximately, the average travel time given by the multi-class model is less than that given by the single-class model. For the range of reliability values from 0.7 to 1.0, however, the multi-class model gives higher travel time. This is because the MCLWR takes into account a distribution of user class that has different free-flow speed, the travel times are therefore expected to spread around that calculated using the single-class LWR model. Thus those user classes with free-flow speed higher than the single-class’s free-flow speed will have shorter travel times, and those with lower free-flow speed will have longer travel times. Note that there is a slight spread of average travel time for the single-class LWR model which is due to daily fluctuation of demand but not due to the modeling result of LWR model.

The second simulation is carried out to evaluate the effect of incident on the travel time reliability of the highway. In this study, we classified incidents into three categories: light, serious and fatal. The blocking time for each type of incident is set to be 3 min., 15 min., and 30 min respectively. For this simulation, the incident is assumed to occur at a fixed location (500m from the downstream end) and the time at which incident happen is not fixed. The resultant travel time reliability functions obtained from this simulation with light, serious and fatal incidents are plotted in Figure 5. The reliability curve for light incident is similar to that for no incident. For serious and fatal incidents, the reliability curves obviously bend to the right of that without incident because of long blockage time due to incident. The reliability curves are bended but not shifted to the right because of the assumption that incident can occur at any time regardless of the occupancy status. Therefore the same blocking duration
may result in different number of vehicles being trapped and thus vary the effect on travel time. Individuals come before the incident or after the clearance of the incident can enjoy a less-interrupted journey whereas those come during the blockage period will expect longer travel time.

![Figure 4. Travel Time Reliability (without incident) Computed Using MCLWR and SCLWR Models](image)

From the figure, the travel time reliability value for travel time of 30 minutes is 1.0 for both without incident and with light incident. The reliability value has drops to approximately 0.95 and 0.65 with serious and fatal incident for travel time of 30 minutes. This means that 95% users can arrive at the airport via the North Lantau Expressway within 30 minutes with serious incident. But only 65% users can arrive at the airport within 30 minutes with fatal incident.
incident. We can also look at the travel time reliability curves by choosing a fix reliability value and see how average travel time change with different types of incident. For example if we fixed the travel time reliability value to be 0.9 then the average travel time when there is no incident occur is 19.8 minutes. That means 90% users can arrive at the airport within 19.8 minutes when there is no incident. For the case when there is a fatal incident occurred, the average travel time is 43.4 minutes for a reliability value of 0.9. Hence 90% users can finish the trip to the airport within 43.4 minutes which has increased significant from the case without incident.

Table 1 gives a summary of two useful figures that can be extracted from the travel time reliability curves. The first one is the travel time value when the travel time reliability is 0.5. For example, the travel time reliability to travel through the North Lantau Expressway in 16.83 minutes is 0.5 for the case with serious incident, this mean that the drivers will arrive at the airport within 16.38 minutes 1 time out of 2. The results show that, even with fatal incident of which the highway will be blocked by 30 minutes, the travel time for a reliability value of 0.5 is only affected by a few minutes as compare to the case without the occurrence of incident. Another useful figure is the maximum travel time that an individual may experience. This is the value of travel time corresponding to a travel time reliability value of 1. From the table, it can be seen that if incident does occur, the maximum travel time is the sum of the maximum travel time when no incident occurred and the total blockage time (due to incident). This maximum travel time is in fact the travel time experienced by an individual who arrived right after the incident took place. In addition to these figures, the mean travel time for each case has been given. This figure cannot be read from the reliability curve but is calculated from the result of the Monte Carlo simulation. It is interesting to note that the mean travel time without incident is not equal to the travel time estimated when the reliability value is 0.5. This suggests that the distribution of travel time is no longer a normal distribution even though the input demand and user class are assumed to be normally distributed. Thus the MCLWR model is not just taking the average behavior of a distribution of road users but is modeling the interaction between difference classes.

<table>
<thead>
<tr>
<th>Travel time (min)</th>
<th>Travel time (min) at reliability value of 0.5</th>
<th>Maximum travel time (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean Standard Deviation</td>
<td>Mean Standard Deviation</td>
<td>Mean Standard Deviation</td>
</tr>
<tr>
<td>No Incident 15.79 1.40</td>
<td>15.07</td>
<td>18.00</td>
</tr>
<tr>
<td>Light Incident 15.87 3.12</td>
<td>15.27</td>
<td>27.00</td>
</tr>
<tr>
<td>Serious Incident 18.85 3.16</td>
<td>16.83</td>
<td>30.00</td>
</tr>
<tr>
<td>Fatal Incident 25.59 6.17</td>
<td>19.77</td>
<td>42.00</td>
</tr>
</tbody>
</table>

5. CONCLUSIONS

A macroscopic traffic flow model, the MCLWR model, has been used to evaluate effect of incident on travel time reliability of a highway. Unlike the usual manner where the average link travel time is determined by the BPR (Bureau of Public Roads) type formula with calibrated parameters, the present approach obtained the travel time by solving the traffic flow model. The macroscopic approach allows more flexible control on the duration as well as the location (not shown in this paper) of incident to be simulated. Such macroscopic approach has the advantages of avoiding detail understanding on individual vehicular
movement as in the rules set for microscopic simulation and of direct evaluation of the traffic flow variation instead of using calibrated formulas to determine link travel time. In addition, the MCLWR model provides a more realistic modeling approach by taking into account a distribution of road users that are characterized by their choice of free-flow speeds. This is important because different compositions of road users in a traffic stream will affect the acceleration-deceleration characteristic of a traffic stream before and after an incident. The results of numerical simulations are promising and that the macroscopic approach can be used to evaluate the travel time reliability of a highway under recurrent and non-recurrent blockage. Further research will be needed, however, to investigate the treatment of a partial blockage (rather than a complete blockage) of a highway due to incident.

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