Travel-Time Reliability in Dynamic Transportation Networks
under User Equilibrium

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Abstract: - Travel time reliability of a transportation network is usually examined from the system’s perspective. However, an average driver, during conditions of uncertainties, tends to navigate through available routes between his/her origin-destination (O-D) pair to minimize his/her aggregate travel time. In this paper, we analyze travel time reliability of a transportation network under user equilibrium. We show the relationship between the traffic information and the travel time reliability of the network. We demonstrate the effectiveness of our approach by performing a numerical analysis for a typical rush hour commuter in the Baltimore-Washington area. This analysis is important because it provides drivers with accurate route guidance information and also generates the shortest path (or less congested alternate paths) connecting specified origins and destinations. It is expected that this analysis will be useful in the planning, design and management of transportation facilities and networks in the future.

Key-Words: - travel-time reliability, user equilibrium, dynamic transportation networks

1 Introduction

Experience has shown that there is usually considerable uncertainty about how long it will take to travel from a given origin to its destination. This uncertainty could be associated with the probability of delay occurring along the traffic flow network. This delay may be in the form of accidents, changes in weather conditions, fluctuations in traffic density, variations in speed, traffic control devices, and work zones. Non-recurring delays typically account for unreliability in travel time. Travel-time reliability is concerned with the consistency or dependability in travel time measured from day to day or across different times of the day for given origin-destination pairs. For a typical driver, travel time reliability information provides him/her the most reliable path that connects the origin to destination. This path minimizes the total travel time.

In this paper, we focus on improving the travel time estimate of an average driver in a transportation network (Figure 1) under user equilibrium. Typically, user equilibrium models are used to predict traffic pattern of the network under congestion. Drivers will tend to choose the route that minimizes the aggregate travel time between the origin and the destination. In other words, the total travel time in all routes actually used should be equal and less than those which could have been experienced by a single vehicle on any unused route. In other to accomplish this, we assume each route to consist of links that collectively represent the commuting path of the driver. We formulate a network design problem that incorporates a travel time reliability factor and minimizes the total travel time. The aim of this paper is to develop an efficient methodology for improving travel time estimate. It is expected that policy makers in the transportation industry will find this approach useful in monitoring the performance of transportation facilities. We perform a numerical analysis to examine the effectiveness of this approach.

2 Literature Review

Several travel-time reliability related studies were found in the literature. A shockwave-based methodology for reliability estimation was proposed by Jha and Okonkwo [10]. Samanta and Jha [14] performed a reliability study of facility locations for retail Services of a food item. According to April 2009 newsletter of University Transportation Centers (UTC) programs, Researchers at Perdue University, in conjunction with Indiana
Department of Transportation and Nextrans are applying cutting edge technology to develop a model that will accurately measure travel time reliability. This model relies on signals picked up by consumer electronics such as cell phones and GPS devices in passing cars to obtain travel time data and then integrated with traffic and weather data obtained from the loop detector to measure travel time reliability. The model will provide a new basis to monitor the performance and benefits of any activity implemented on any roadway network. According to the Strategic Highway Research Program 2 (SHRP 2), the current SHRP2 emphasis is on reducing non-recurrent congestion and improving travel time reliability through incident reduction, management, response and mitigation.

Figure 1. A Transportation Network under user equilibrium

The American Transportation Research Institute has identified congestion as one of the trucking industry’s critical transportation issues, and within congestion, reliability has been cited to be continually declining in urban areas (http://www.atrionline.org/2007_top_industry_issues.pdf). According to the 2007 Mobility Report prepared by the Texas Transportation Institute (http://tti.tamu.edu/) the peak hour traveler in America already spends an extra 38 hours in traffic due to congestion, but a more reliable system would at least allow improved trip planning. Heydecker et al. [9] proposed the travel demand satisfaction ratio (DSI) for assessing the road network performance. The DSI is the ratio of the equilibrium travel demand and latent travel demand. Further, the authors introduced the travel demand satisfaction reliability (DSR) defined as the probability of the DSI being greater than a specified value. The DSR is proposed to analyse how a network satisfies existing demand and to distinguish the latent travel demand. Heydecker et al. [9] also explained that the DSR can be equivalent to the travel time reliabilities under certain conditions. Chen et al (2007) proposed a multiobjective reliable network design problem model that considered travel time reliability and capacity reliability to determine the optimal link capacity enhancement under demand uncertainty. All of these models are derived by a systematic approach and based on the conventional user’s equilibrium principle. Haitham and Emam (2006) introduced a methodology for estimating travel time reliability and capacity reliability under the effect of travel demand variation and link capacity degradation. They defined travel time reliability as the probability that the expected travel time at degraded capacity is less than the link-free-flow travel time plus an acceptable tolerance. Tolerance is related to the level of service that should be maintained despite the capacity degradation.

Liu et al [14] studied the value of travel time (VOT) and value of reliability and uncovered the heterogeneity of the motorist’s route decision. They discovered that VOR is higher than VOT in traveler’s route choices. Chen et al. (2003) examined the effect of incorporating travel time variability and risk-taking behavior into the route choice models to estimate travel time reliability under demand and supply variation. In their study, drivers’ perception of risk and their preference in making route choice decisions under an uncertain environment was examined using Monte Carlo simulation. Chen et al (2002) distinguished between unreliability due to normal variation in daily demand and that due to capacity variations arising from network degradation. On the latter they considered for each O-D movement the ratio of travel time in a degraded state to the travel time in a non degraded state. Travel time reliability was then defined as the probability that this ratio will be less than some pre-defined acceptable level. Chen and Recker [6] considered risk taking behavior in estimating travel-time reliability. They accomplished this by examining different route choice models to determine how travelers make trade-off decisions between longer routes with reliable travel-times and shorter routes with unreliable travel time. These models were further integrated with simulation to account for demand and supply variations and to estimate travel-time reliability. Bell et al [4] proposed a sensitivity analysis procedure to estimate the variance of travel time arising from daily demand fluctuations. Asakura [3] further extended the travel time reliability to consider capacity degradation due to deteriorated roads. He defined travel time reliability as a function of the ratio of travel times under degraded and non degraded states.
Abdel-Aty et al. [1] indicated that travel time reliability is either the most or the second most important reason for choosing their daily commuting routes. Asakura and Kashiwadani (1991) introduced the concept of travel time reliability and defined it as the probability that a trip between a given origin and destination pair can be made successfully within a given time interval and a specified level of service, and the main performance indicators examined are specified travel time and specified network service. Based on this concept, various mathematical models have been developed to measure the travel time reliability of transportation systems.

3 Travel-time Reliability Measures

Several travel time reliability measures have been reported in the literature. They include

- Mean difference between the expected arrival time and the scheduled arrival time
- The standard deviations of arrival times
- The probability of early departure time
- Probability that a vehicle arrives x minutes late
- The probability density functions of the travel times.

However, the user equilibrium approach has not been undertaken in estimating travel-time reliability. We discuss this approach applicable to dynamic transportation networks in the next section.

4 Solution Approach

We assume each route to be 100% reliable if the travel time is less than or equal to the free flow travel time. We also assume that failure in any link of any route will result in failure in that route (based on the configuration of the segment). Let

- $q_{OD}$ = the trip rate between the origin and the destination during the period of analysis
- $f_{k}^{OD}$ = the flow on path $k$ connecting the origin $O$ and the destination $D$
- $C_{k}^{OD}$ = the travel time on path $k$ connecting origin $O$ and the destination $D$
- $x_{a}$ = the flow on link $a$
- $t_{a}$ = the travel time on link $a$
- $r_{a}$ = the reliability of link $a$

The travel time on a particular path is the sum of the travel time on the links comprising that path. The relationship can be expressed mathematically as

$$C_{k}^{OD} = \sum_{a} f_{a}^{OD} \delta_{a,k}$$  \hspace{1cm} (1)

where

$$\delta_{a,k} = \begin{cases} 1 & \text{if link } a \text{ is a part of } k \text{ connecting } O-D \\ 0 & \text{otherwise} \end{cases}$$

Under free flow condition, the link flow can be expressed as a function of the path flow, that is

$$x_{a} = \sum_{O} \sum_{D} \sum_{k} f_{k}^{OD} \delta_{ak}^{OD}$$  \hspace{1cm} (2)

This equation means that flow on each route is the sum of the flow in all links going through that route.

Let $t_{a} = t_{a}(x_{a})^* r_{a}$, where $t_{a}(x_{a})$ represents the relationship between flow and travel time for link $a$. In other words, $t_{a}(x_{a})$ is the link performance function

The network design problem can be formulated as

$$\text{Min. } \sum_{a} \int_{0}^{x_{a}} t_{a}(w) dw$$  \hspace{1cm} (3)

s.t.

$$\sum_{a} f_{k}^{OD} = \{O, D\} \quad \forall O, D$$  \hspace{1cm} (4)

$$f_{k}^{OD} \geq 0 \quad \forall k, O, D$$  \hspace{1cm} (5)

$$x_{a} = \sum_{O} \sum_{D} f_{k}^{OD} \delta_{ak}^{OD}$$  \hspace{1cm} (6)

$r_{a}$ can be estimated using existing reliability measure as listed above or in literature or rather through the use of reliability soft wares such as Weibull ++.

The objective function is the sum of the integral of the link reliability function. This function does not have any intuitive economic
or behavioral interpretation. It is a mathematical construct that is utilized to solve equilibrium problem.

5 Numerical Example

In this example, we calculate reliability, $r_a$ of the O-D path a for a typical transportation network, similar to Fig.1 that has to be in user equilibrium, and show that travel time reliability improves the total/aggregate travel time of a typical urban commuter. We collect the travel-time data (Table 1) for three alternate routes for an average urban commuter between the Rosedale area and the Morgan State University (MSU) in Baltimore, Maryland. The commuter driver can navigate through the three routes as follows: (1) Old Philadelphia road, then onto the freeway and finally to school (route 1); (2) Pulaski Highway, then onto the arterials and finally to MSU (route 2); (3) Golden Ring Road, then onto the freeway and finally to MSU (route 3). We find that the travel time data fits well to a Weibull distribution.

<table>
<thead>
<tr>
<th>Time/Link</th>
<th>Route 1</th>
<th>Route 2</th>
<th>Route 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>4:00-4:15</td>
<td>12</td>
<td>15</td>
<td>20</td>
</tr>
<tr>
<td>4:15-4:30</td>
<td>10</td>
<td>15</td>
<td>20</td>
</tr>
<tr>
<td>4:30-4:45</td>
<td>8</td>
<td>15</td>
<td>20</td>
</tr>
<tr>
<td>4:45-5:00</td>
<td>6</td>
<td>15</td>
<td>20</td>
</tr>
<tr>
<td>5:00-5:15</td>
<td>4</td>
<td>15</td>
<td>20</td>
</tr>
<tr>
<td>5:15-5:30</td>
<td>2</td>
<td>15</td>
<td>20</td>
</tr>
<tr>
<td>5:30-5:45</td>
<td>1</td>
<td>15</td>
<td>20</td>
</tr>
</tbody>
</table>

Table 1. Travel time data of the numerical problem

Reliability software WEIBULL++ was used to estimate the probability density functions of the travel times for each link in each route. For route 1, it is observed that for link I,

$$F (T) = 0.125 \text{ hence } R(T) = 0.875 = 87.5$$

(7)

For link II,

$$F (T) = 0.0585 \text{ hence } R(T) = 0.9994 = 99.94\%$$

(8)

For link III,

$$F (T) = 0.0475 \text{ hence } R(T) = 0.7825 = 78.25\%$$

(9)

Therefore the reliability of route 1 will be computed as

$$0.875 \times 0.9994 \times 0.7825 = 0.6842$$

(10)

Similarly for route 2, link I,

$$F (T) = 0.135 \text{ hence } R(T) = 0.865 = 86.5\%$$

(11)

For link II,

$$F (T) = 0.078 \text{ hence } R(T) = 0.922 = 92.20\%$$

(12)

For link III

$$F (T) = 0.175 \text{ hence } R(T) = 0.825 = 82.50\%$$

(13)

Therefore the reliability of route 2 will be computed as

$$0.865 \times 0.922 \times 0.825 = 0.6579$$

(14)

Finally, for route 3, link I,

$$F (T) = 0.0855 \text{ hence } R(T) = 0.9145 = 91.45\%$$

(15)

For Link II,

$$F (T) = 0.057 \text{ hence } R(T) = 0.943 = 94.3\%$$

(16)

For Link III

$$F (T) = 0.115 \text{ hence } R(T) = 0.885 = 88.50\%$$

(17)

Therefore, the reliability of route 3 will be computed as

$$0.9145 \times 0.943 \times 0.885$$

At user equilibrium the flow volume across all three routes connecting the origin to destination will be the same.

The improved total travel time for route I becomes

\[ t_a(x_a)r_a = 0.6842 \times 221 = 151.2 \text{ mins} \]  \hspace{1cm} (19)

The improved total travel time for route 2 becomes

\[ t_a(x_a)r_a = 0.6579 \times 201 = 132.2 \text{ mins} \]  \hspace{1cm} (20)

The improved total travel time for route becomes

\[ t_a(x_a)r_a = 0.7632 \times 201 = 132.2 \text{ mins} \]  \hspace{1cm} (21)

From the above computation, it is observed that route 2 offers the most reliable path that connects the origin to the destination, i.e., the least total travel time.

6. Conclusion

A method has been developed for improving the travel-time reliability of a transportation network under user equilibrium. It opens up new possibilities for evaluating the effectiveness of highway improvements, incident response systems and new vehicle highway technology. It can also be applied in dynamic route guidance system to generate shortest path or alternative path for given origin destination pairs. In Future works, we compare current and future trends in travel time reliability through simulation. The result obtained could be beneficial to policy makers in setting funding priorities.

7. Acknowledgements

This work was completed at the Center for Advanced Transportation and Infrastructure Engineering Research (CATIER) at the Morgan State University and is part of the doctoral research of the second co-author.

References

Civil Engineering in the New Millennium: Opportunities and Challenges (CENeM-2007), 11-14 January, 2007, Bengal Engineering and Science University, Shibpur, Howrah, India.