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Empirical Analysis of Travel Time Reliability Measures in Hanshin Expressway Network

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Travel time reliability is a key indicator of system performance and has become increasingly important in today’s world as businesses as well as households require on-time transportation for their activities. In order to analyze travel time reliability, an enormous amount of traffic flow data is needed. Recently, the development of advanced traffic flow data collection systems has enabled us to handle that. This article aims to examine the fundamental characteristics of travel time reliability measures using the traffic flow data from the Hanshin Expressway network. Differences and similarities in characteristics (average travel time, 95th percentile travel time, standard deviation, coefficient of variation, buffer time, and buffer time index) are investigated on one radial route (Route 11: Ikeda Line). The result shows that buffer time and buffer time index profiles have a similar tendency as those of the standard deviation and coefficient of variation, respectively. Differences in characteristics among five radial routes in the network are also investigated in order to explore each route’s characteristics of time-of-day variation of traffic flow. Additionally, the effect of traffic incidents on travel time reliability measures is analyzed on one radial route (Route 14: Matsubara Line). The results show that traffic incidents are the dominant factor for travel times in off-peak hours on the Hanshin Expressway network.

Keywords Travel Time; Travel Time Reliability; Traffic Incidents; Ultrasonic Vehicle Detector; Urban Expressway Network

The Hanshin Expressway is an urban toll expressway network of 233.4 km (as of 2007) that stretches from Osaka to Kobe area, which make up the Hanshin Area, in Japan. The Hanshin Expressway accommodates massive traffic flow and major freight transportation demand in the Hanshin Area, one of the three major metropolitan areas in Japan that include Tokyo and Nagoya. The Hanshin Expressway started its operation in 1964, and that year around 5,000 vehicles used the expressway per day. Traffic volumes have steadily increased as the expressway network extended, and in 2004, a total of 350 million vehicles or 900,000 vehicles per day travelled on the expressway. This rapidly increased expressway users resulted in traffic congestions on the network. “Congestion” on the Hanshin Expressway network is defined as a condition in which vehicles are either driving slower than 30 km per hour or stopping for 1 km or a longer section for at least 30 minutes.

Particularly, in 2004, the occurrence of traffic congestions on the expressway totalled 12,051 in a year or 34.2 occurrences per day on average. The main contributor of traffic congestions on the expressway for the year was excess traffic demand for certain times of day, which accounted for 78% of the total events. The remaining contributors are accidents (12%), road work (4%), and others (6%). These remaining contributors are referred to as “incidents” in this article.

The Hanshin Expressway introduced a traffic control system in 1969 and has continuously improved the system to date. The aim for implementing a traffic control system is to keep smooth traffic flow all the time, optimizing the functions of the
Travel time reliability is one of the indicators to measure the performance of road network reliability. Initially, Iida and Wakabayashi (1989) introduced connectivity reliability, defined as the probability that network nodes are connected or disconnected. The binary limitation of this reliability indicator led to the development of various reliability indicators (Recker et al., 2005), such as travel time reliability (Asakura and Kashiwadani, 1991), travel demand reduction (Nicholson and Du, 1997), capacity reliability (Chen et al., 1999), travel demand satisfaction reliability (Lam and Zhang, 2000), and more. Out of these various network reliability indicators, travel time reliability is considered to be one of the most useful for network users as well as planners.

Since the initial introduction of the concept of travel time reliability, the literature on ways to measure travel time reliability has increased. Travel time reliability measurements can be classified into heuristic measurements and statistical measurements. Primarily, 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. Chen and colleagues (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. Recently, 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. Heydecker and colleagues (2007) 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, they 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 and colleagues (2007) also explained that the DSR can be equivalent to the travel time reliabilities under certain conditions. Chen and colleagues (2007) proposed a multiobjective reliable network design problem model that considered travel time reliability and capacity reliability to determine the optimal link capacity enhancements under demand uncertainty. All of these models are derived by a systematic approach, and based on the conventional user equilibrium (UE) principle.

In the category of statistical measurements, Florida’s Department of Transportation (FLDOT) defined travel time reliability as expected travel time plus a certain acceptable additional time (FLDOT, 2000). This method uses the median of travel time plus some percentage of median travel time during the period of interest. Recently, the U.S. Federal Highway Administration (FHWA) has defined travel time reliability as the consistency...
or dependability in travel time, as measured from day-to-day and/or across different times of the day (FHWA, 2006; Margiotta, 2002). The 95th percentile travel time, Buffer Index (BI), and Planning Time Index (PTI) were introduced as performance indicators. This approach is simple and easy to understand for the nontechnical community, and the travel time distribution was used as a basis for the development of all these indices. Statistical measurements are mainly derived from the travel time distribution. All these measurements are useful to both transport system planners as well as users (FHWA, 2006; Lomax, et al., 2003; Margiotta, 2002). Case examples of using the above-mentioned three performance indicators are briefly explained in the following paragraphs (FHWA, 2006; Lyman and Bertini, 2008).

95th Percentile Travel Time: Minnesota Department of Transportation (MN/DOT) studied the effects of a ramp meter shutdown on Minneapolis—St. Paul freeways in the United States. Also Washington State Department of Transportation (WSDOT) used this indicator as travel time reliability information to commuters in the Puget Sound area.

Planning Time Index (PTI): FHWA conducts a national traffic monitoring program and tracks PTI and BTI for more than 30 cities in the United States. The results are presented in its monthly dashboard reports.

Buffer Time Index (BTI): FHWA launched a program for measuring the travel time reliability in freight-significant corridors (five different corridors of different lengths ranging from 285 to 2,460 miles). Portland State University proposed travel time reliability measures to improve regional transportation planning and operation for Portland freeway system in Oregon.

Note that these indices are calculated from the distribution of travel times. The 95th percentile travel time and buffer time are considered to be easier for nontechnical communities to understand than the buffer time index and planning time index. All of these indices are discussed briefly in a later section of the travel time reliability indices.

TRAVEL TIME ESTIMATION OF THE HANSHIN EXPRESSWAY

Ultrasonic vehicle detectors are installed at approximately every 500 meters along the expressway, and the traffic volume and time occupancy are observed at 5-minute intervals. The spot speed of traffic flow is estimated as follows: 

\[ v = \frac{Q}{k} = \frac{Q}{(Oc/100l)} = 100 \frac{Q}{l} / Oc, \]  

where \( v \): spot speed, \( Q \): traffic volume, \( k \):density, \( O \):time occupancy, \( l \): estimated average vehicle length. As the ultrasonic vehicle detector identifies the height of passing vehicles, the average length of vehicles is estimated as the weighted average of the small and large vehicles. This is expressed as

\[ T = \frac{l_s Q_s + l_l Q_l}{Q_s + Q_l}, \]  

where \( l_s, l_l \): average lengths of small and large vehicles, respectively, and \( Q_s, Q_l \): traffic volumes of small and large vehicles, respectively. The travel time of a section is calculated as the length of the section (about 500 meters) divided by the spot speed. One-year record of the travel times for each section of the entire expressway network was obtained from the DWH for this study.

Conventionally the travel time of an entire route is calculated simply by accumulating the travel times of each section at a given time. It is expressed as

\[ T(s) = \sum_{i=1}^{N} t_i(s), \]  

where \( t_i(s) \) denotes the travel time of section \( i \) at a given time \( s \). Sections in a route are numbered sequentially toward downstream direction. This method generates an instantaneous travel time based on the assumption that vehicles instantaneously traverse the route. When traffic condition is stable and travel speed is constant, the travel time can be calculated correctly through this method; however, the estimated travel time may not be correct when traffic flows are not stable. The alternative method of calculating the route travel time is the Time Slice Method, with which the travel times of each section are accumulated successively with the delay of the section travel time. The route travel time is represented as

\[ T(s) = \sum_{i=1}^{N} t_i(s + \tau_i(s)), \]  

where \( \tau_i(s) \) denotes the travel time from section 1 to section \( i - 1 \) and written as

\[ \tau_i(s) = \sum_{j=1}^{i-1} t_j(s + t_j(s)). \]  

As shown in Figure 1, when ultrasonic vehicle detectors are located densely enough, the time slice method can generate more accurate travel time than the instantaneous method.

Yoshimura and Suga (2004) compared two sets of travel times estimated by the instantaneous method and the time slice method using Automatic Vehicle Identification (AVI) data as “true values.” They found that the instantaneous method could cause larger errors during the periods when traffic congestion increases and decreases, and that the time slice method could follow the actual travel time fluctuations without delay. Through the correlation analysis of travel time data obtained with the AVI system and those estimated by the time slice method, R-square value obtained was 0.976 and RMS error was 40 seconds where the range of travel time was 300 to 1,800 seconds.

Based on those findings, the time slice method was employed for the calculation of travel times in our study. By calculating the travel time of a route at a given time of day in a year, the standard deviation (SD) and the coefficient of variation (CV), which are the fundamental statistics for the fluctuating route travel times, can be calculated. As a result, not only a day-to-day fluctuation of the travel time of the route can be estimated, but also the probability density function can be obtained, which can also be used as the data for estimating travel time reliability indices.

TRAVEL TIME RELIABILITY INDICES

Travel time reliability is defined as the probability that a trip between a given origin and destination pair can be made successfully within a given time interval. This probability is represented as

\[ \Phi(T) = \int_{0}^{T} \phi_T(t) dt, \]  

where \( T \): given period, and \( \phi_T(t) \): probability distribution function of travel time at departure times.
inverse function of the travel time reliability $\Phi^{-1}_t(p)$ implies the travel time with a given travel time reliability $p$.

The SD and CV of travel times and the above-mentioned travel time reliability index expressed with a probability function are effective to explain the statistical characteristics of travel times. They may not, however, easily understandable for such nontechnical community as transport policymakers or general road-users. The US-DOT, therefore, has proposed four different travel time reliability measures that could be intuitively understood. They are the planning time, planning time index, buffer time, and buffer time index, and were used in this empirical study.

The planning time represents the total travel time expected or “planned” before trip starts with a given probability, and is presented as $T_{\text{plan}} = \Phi^{-1}_t(p)$, where the percentage of 95 is used as a given probability $p$. The 95% probability indicates the worst travel time that commuters may experience once per month, namely one of 20 business days. The planning time is not comparable between routes with different route length.

The planning time index is the ratio of the planning time to the free-flow travel time. This index indicates the severity of traffic congestion as it represents the worst level of congestion at a given time of day in comparison with the free flow traffic condition.

The buffer time is defined as planning time minus average travel time, and expressed as $T_{\text{buffer}} = \Phi^{-1}_t(p) - E[t] = \Phi^{-1}_t(p) - \int_{0}^{\infty} t \varphi_s(t) dt$. The buffer time represents the extra time to ensure on-time arrival to the destination. This extra time accounts for any unexpected delay. In other words, the buffer time may be almost proportional to the variance of travel time. The buffer time itself is not comparable between different routes.

The buffer time index is defined as the ratio of buffer time to the average travel time. When the buffer time is assumed to correspond to the variance of travel time, the buffer time index may coincide with the CV.

It is necessary to calculate these reliability indices at different times of day, and to investigate the time-of-day dynamics of these indices because these reliability indices may vary dynamically depending on the time of day. These measurements are useful to find reliable time periods of a day for travelling (Asakura, 2006a). And the comparison of these indices among several routes in the network enables us to find the severity and variance of traffic congestions of those routes. The findings of this research will be effective to understand fluctuating traffic congestions of different routes in the expressway network.
FUNDAMENTAL CHARACTERISTICS OF RELIABILITY INDICES

The Hanshin Expressway has five radial routes, which stretch from a loop route located in downtown Osaka City to different suburban areas. Among them, Route 11: Ikeda Line was chosen to examine the fundamental characteristics of the travel time reliability indices. The route of a total length of 12.0 km runs north to south to connect to the loop route in central Osaka. One full year’s data of the southbound traffic from April 1, 2005 to March 31, 2006 were used for the analysis. Statistics parameters such as the maximum, minimum, average, 95th percentile travel time (the planning time), SD, and CV are shown in the following figures. The reliability parameters such as the 95th percentile travel time (the planning time), planning time index, buffer time, and buffer time index are calculated and discussed further in the following paragraphs (Asakura, 2006b).

Figure 3a shows the travel time profiles including the maximum, minimum, and average travel time for each hour of day. The figure clearly shows the morning and evening peaks. The maximum travel time is almost twice the average travel time in peak hours, but the ratio of the maximum travel time to the average travel time is much higher in off-peak hours.

Figure 3b, which displays the time-of-day dynamics of the planning time, shows that the planning time in the evening peak, which is around 50 minutes, is longer than that of the morning peak of around 40 minutes. Free flow travel time is shown to be about 10 minutes. And the planning time index (the planning time/free flow time) is about 4.0 in the morning peak and 5.0 in the evening peak.

Figures 4a to 4d describe time-of-day fluctuations of the SD, CV, buffer time, and buffer time index, respectively. The figures reveal that the time-of-day fluctuation patterns of the SD and buffer time are similar, and so are those of the CV and buffer time index. This indicates that among the travel time profiles, the SD and buffer time, and the CV and buffer time index, can be interchangeably used. But buffer time and buffer time index are more self-explanatory parameters in terms of measuring the reliability of travel times. The time-of-day variation of the SD seems similar to that of the planning time; however, a careful examination reveals that the morning peaks of the SD and buffer time come at the late morning hour of around 10:00 a.m., about two hours later than the peak hours of the planning time and the average travel time. This indicates that the traffic congestion in the morning peak is relatively stable while it becomes unstable during the shoulder hours after the morning peak. This tendency is more clearly observed in the figures of the CV and buffer time index (Figures 4a and 4b). The value of the buffer time index in the morning peak is about 0.4, and it continuously increases in later morning hours. The maximum value of the buffer time index is about 1.0 at noon. The buffer time index gradually declines in the afternoon and then it rises sharply after the evening peak. These findings are most likely due to the instability of the length of congestion hours.

COMPARISON AMONG DIFFERENT ROUTES

Figure 5 shows the Hanshin Expressway network. In addition to Route 11: Ikeda Line, four other radial routes are examined. They are Route 12: Moriguchi Line (total length of 10.8 km), Route 13: Higashiosaka Line (11.1 km), Route 14: Matsubara Line (12.1 km), and Route 15: Sakai Line (11.7 km). They are all connected to the downtown loop route in Osaka City, and the travel times are measured on their downtown-bound lanes. These five routes with similar length were selected to make the free flow travel times for each route approximately the same. Note that each route may have different tendency originated from the differences in time-of-day stability patterns of traffic flows.

Figures 6a and 6b depict the time-of-day patterns of the average travel time and planning time (95th percentile travel time) for the five routes, respectively. The average travel time of Route 11 is longer than the other four routes, while that of the Route 15 is shorter than the average almost all the time. Except Route 11, four other routes have longer average travel times during the
Figure 4 (a) Standard Deviation (SD). (b) Coefficient of Variation (CV). (c) Buffer Time. Figure 4d. Buffer Time Index.

Figure 5 Hanshin Expressway Network.
morning peak hour than the evening peak hour. The morning peak hour of Route 12 shifted one hour later in comparison with other routes. This is explained by the characteristics of its road use, which is for freight transportation and business trips more than for commuting. Although the peak hours of planning time are different for those five routes, Routes 12 and 13 have higher peaks during the morning peak hour than Route 11, which is considered to be the busiest route in terms of the average travel time. The planning time index in morning hours is within a range of 3.5 to 4.0 for all of the five routes.

Figures 7a and 7b represent the buffer times and buffer time index for the five routes, respectively. The values of buffer time in daytime are about 10 to 14 minutes. Although no significant differences exist among those routes, Routes 12, 13, and 14 have slightly higher values than the other two routes. In comparison with Route 11, the buffer time graphs of the other four routes have steeper rise in the morning and have earlier peaks than that of Route 11 in the evening (Figure 7a). The buffer time index of Route 14 is the highest in the morning and keeps higher values during daytime, while Route 13 has overall higher buffer time
INFLUENCE OF TRAFFIC INCIDENTS ON TRAVEL TIME OF ROUTE 14: MATSUBARA LINE

Route 14: Matsubara Line was further examined for analyzing the influence of traffic incidents on travel time reliability. In this section, the discussion is limited only to the traffic congestion caused by traffic incidents. Traffic incidents are defined in this article as random events that affect or impede the normal traffic flow, and that include road works, traffic accidents, vehicle breakdown, fallen loads, and more. This 12.1-km route is connected to three other expressways operated by a different express company; therefore, travel time information on Route 14 has a great significance especially for those driving on any expressway. Traffic incidents of Route 14 are categorized into accidents (69.1%), vehicle breakdown (9.9%), inattentive driving (3.8%), fallen loads (2.3%), fire (0.4%), and others. Traffic accidents account for a majority of the traffic incidents that occurred on Route 14.

Figures 8a, 8b, and 8c depict the weekday travel time ranking during the off-peak hour (12:00–1:00 p.m.), and 5:00–6:00 p.m. time periods on weekdays in FY 2006, respectively. The three figures have a common feature that travel times in higher ranks are outstanding. The off-peak hour (12:00–1:00 p.m.) shows the travel times from the top to about 60th forms a very steep declining curve (Figure 8b), while the morning peak hour (7:00–8:00 a.m.) displays a rather gentle decline for the same range (Figure 8a). And the evening peak hour (5:00–6:00 p.m.) displays the level intermediate between the other two time periods (Figure 8c). Another finding is travel times become longer when traffic incidents occurred on this route. A comparison of Figures 8a, 8b, and 8c reveals the frequency of traffic incidents is lower in peak hours (7:00–8:00 a.m.) and 5:00–6:00 p.m.) than the off-peak hour (12:00–1:00 p.m.), and that the frequency of traffic incidents is about 10% in each hour.

Figure 9 depicts the causes of traffic congestion for the top 5% of all travel times for each time period. This figure shows the frequency of traffic incidents is higher in peak hours (7:00–8:00 a.m. and 5:00–6:00 p.m.) than the off-peak hour (12:00–1:00 p.m.), and the frequency of traffic incidents is over 50% in all the three time periods.

Table 1 shows the frequency of traffic incidents is about 10% in each hour.

Table 1  The variance of reliability indices with and without traffic incidents.

<table>
<thead>
<tr>
<th>Reliability Indices</th>
<th>Average Travel Time (min.)</th>
<th>Planning Time (min.)</th>
<th>Buffer Time (min.)</th>
<th>Buffer Time Index</th>
<th>Coefficient of Variation</th>
</tr>
</thead>
<tbody>
<tr>
<td>With Incidents</td>
<td>23.6</td>
<td>32.1</td>
<td>8.6</td>
<td>0.36</td>
<td>0.25</td>
</tr>
<tr>
<td>Without Incidents</td>
<td>22.9</td>
<td>30.5</td>
<td>7.6</td>
<td>0.33</td>
<td>0.21</td>
</tr>
<tr>
<td>7–8 a.m. (Morning peak hour)</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Reliability Indices</td>
<td>Average Travel Time (min.)</td>
<td>Planning Time (min.)</td>
<td>Buffer Time (min.)</td>
<td>Buffer Time Index</td>
<td>Coefficient of Variation</td>
</tr>
<tr>
<td>With Incidents</td>
<td>10.9</td>
<td>23.2</td>
<td>12.3</td>
<td>1.13</td>
<td>0.47</td>
</tr>
<tr>
<td>Without Incidents</td>
<td>10.0</td>
<td>17.3</td>
<td>7.4</td>
<td>0.74</td>
<td>0.36</td>
</tr>
<tr>
<td>12–1 p.m. (Off-peak hour)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reliability Indices</td>
<td>Average Travel Time (min.)</td>
<td>Planning Time (min.)</td>
<td>Buffer Time (min.)</td>
<td>Buffer Time Index</td>
<td>Coefficient of Variation</td>
</tr>
<tr>
<td>With Incidents</td>
<td>15.9</td>
<td>30.2</td>
<td>14.2</td>
<td>0.90</td>
<td>0.47</td>
</tr>
<tr>
<td>Without Incidents</td>
<td>14.9</td>
<td>27.6</td>
<td>12.6</td>
<td>0.85</td>
<td>0.44</td>
</tr>
<tr>
<td>5–6 p.m. (Evening-peak hour)</td>
<td></td>
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</tbody>
</table>
Figure 8  (a) Annual Ranking of Travel Time: 7:00–8:00 a.m. Weekdays, FY 2006 (Morning Peak Hour). (b) Annual Ranking of Travel Time: 12:00–1:00 p.m., Weekdays, FY 2006 (Off-peak Hour). (c) Annual Ranking of Travel Time: 5:00–6:00 p.m., Weekdays, FY 2006 (Evening peak hour).
Travel time data are very useful for evaluating the level of service (LOS) of routes or on-off ramp pairs. As the travel time fluctuates due to several reasons, it is necessary to employ appropriate evaluation indices that could reflect the uncertainty of travel time. Travel time reliability would be a useful measure to examine the fluctuations of LOS. Although the travel time measures widely discussed in this article were originally proposed by US-DOT, the characteristics of those indices have not yet fully investigated by using “reliable” travel time data from actual road networks. In this article, empirical analysis for measuring travel time reliability of the Hanshin Expressway network was performed.

The main findings of this study are summarized as follows. (1) Reliability indices could capture the various characteristics of travel time fluctuations. Although the range of variation of travel times changes with time of day, it may not be always proportional to the average travel time. Average travel time shows two prominent peaks in a day, but buffer time and buffer time index may not always have two similarly prominent peaks. (2) From the statistical definitions, buffer time and buffer time index profiles have a similar tendency with travel time reliability indices. This clearly indicates that the capacity decline caused by traffic incidents interrupts the stability of travel times. And also this indicates that minimizing the occurrence of traffic incidents by using advanced traffic control system such as ITS technologies could improve travel time reliability.

CONCLUSION AND FUTURE PROSPECTS

Travel time data are very useful for evaluating the level of service (LOS) of routes or on-off ramp pairs. As the travel time fluctuates due to several reasons, it is necessary to employ appropriate evaluation indices that could reflect the uncertainty of travel time. Travel time reliability would be a useful measure to examine the fluctuations of LOS. Although the travel time measures widely discussed in this article were originally proposed by US-DOT, the characteristics of those indices have not yet fully investigated by using “reliable” travel time data from actual road networks. In this article, empirical analysis for measuring travel time reliability of the Hanshin Expressway network was performed.

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The Hanshin Expressway is providing only average travel time information based on the accumulated traffic data in the DWH to users through the website named “Hanshin Expressway Drive Navigation System” (http://www.hanko-navi.jp/, in Japanese). It is recommended that the information on travel time reliability should be provided to expressway users as a part of traffic control measures in the near future. In order to achieve this objective, further research is necessary to reveal how well the indices relate to road users’ perceptions. Behavioral studies are needed, such as what type of travel time reliability indices are more useful to road users, how these indices should be informed to the users, how to make users aware of the importance of travel time reliability, and how the media should present the information. Presently, Hanshin Expressway Corporation is conducting a questionnaire survey to analyze the attitude of customers towards the travel time reliability measures. The results will be presented on another occasion.

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