Estimating the Effects of Operational Strategies on Travel-Time Reliability for Smart Mobility

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***Abstract*— Smart mobility is an essential element in building smart cities. To realize connected and automated smart mobility as a service, the capability to efficiently estimate the travel-time reliability measures responding to various operating conditions is of critical importance. This paper presents a travel-time reliability estimation system, which is applied to determine the effects of the operational changes on the travel-time reliability. The application results to the metro freeway network in Minnesota indicate the substantial improvements in travel-time reliability after the changes were introduced, indicating the possibility of modeling the causal relationship between reliability and specific operational strategies.**

Keywords—Travel-time, reliability, and transportation

I. Introduction

Smart mobility is one of the eight essential aspects that define a Smart City. Developing a reliable roadway network that can provide consistent travel times under various operating conditions is of critical importance in providing efficient, safe and environmentally friendly mobility services [1]. An essential element in developing such smart mobility service systems is the capability to monitor and assess the travel-time reliability of given traffic systems responding to various operating conditions and management strategies. While the importance of travel-time reliability in measuring the performance of the transportation systems has been well recognized by the transportation professionals [2], the current state-of-the-practice in traffic management has not reached the point where various types of reliability measures are automatically generated and incorporated into the daily operations of a given network. To be sure, some studies have estimated the reliability measures affected by external operating conditions, such as work-zones and incidents [3], [4], very few research efforts to identify the causal relationships between reliability measures and specific operational strategies have been found in the literature. The primary difficulty lies with the fact that estimating the travel-time reliability measures requires an extensive process for gathering and managing a significant amount of data from multiple sources, such as traffic, weather, incident, special events and construction databases. Such a complicated process in estimating reliability measures and the lack of the precise knowledge regarding the effects of specific management strategies on the travel-time reliability makes it difficult for practicing engineers to develop and prioritize the reliability-oriented operational methods for a given network.

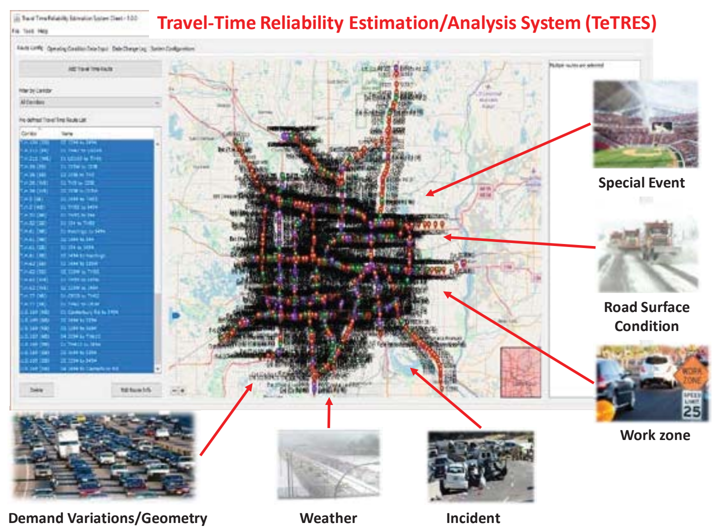

Figure 1. Travel-Time Reliability Estimation System (TeTRES)

This paper presents a Travel-Time Reliability Estimation System (TeTRES) and an assessment of the travel-time reliability variations resulting from the recent operational changes in the metro freeway network in Twin Cities, Minnesota. First, as illustrated in Figure 1, a comprehensive data collection and analysis system was developed for efficient estimation of a list of the travel-time reliability indices by integrating various types of data, including traffic flow, weather, incidents, work zones and special events [5]. The resulting TeTRES is then applied to estimate the travel-time reliability measures in the metro freeway corridors before and after two operational changes were implemented, i.e., an adaptive ramp metering [6] and the short-term aggressive incident management during the 2018 Super-Bowl event in Minneapolis, Minnesota [7].

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The rest of this paper describes the main features of TeTRES and the field assessment results of the operational changes in the travel-time reliability.

II. BACKGROUND

Travel-time reliability is formally defined by the US Department of Transportation as the consistency or dependability in travel times, as measured from day-to-day and/or across different times of the day [1]. While the quantification of the reliability of traffic systems have been studied by several researchers [8], [9], [10], the most comprehensive effort to date has been made by the Strategic Highway Research Program 2- SHRP2 [11], where a series of the research projects were conducted to organize the existing reliability concepts and develop a set of the practical guidelines in measuring the travel-time reliability for a given network [11], [12], [13]. For example, the SHRP2-L14 project has developed a lexicon summarizing the existing reliability indices and their potential application areas [12]. Further, a process to develop the travel-time reliability monitoring system was developed in SHRP2 L02 [13]. The reliability measures identified from the SHRP2 projects include 90th or 95th percentile travel time, buffer index, planning time index, and frequency that congestion exceeds some expected threshold, travel-time index, semi-variance and misery index. Among them the most commonly used ones are the buffer and planning time indices, whose specific formula are as follows [1], [12], [13]:

$$Buffer\ Index = \frac{\text{(95th \%ile Travel Time} - \text{Average Travel Time)}}{\text{Average Travel Time}}$$

$$Planning\ Time\ Index = \frac{\text{95th \%ile Travel Time}}{\text{Free Flow Travel Time}}$$

As shown in the above formula, the buffer index represents the extra buffer time travelers add to their average travel time to arrive on time 95% of all trips, while the planning time index indicates the total travel time reflecting both typical and unexpected delays for a given roadway [11], [12], [13].

III. TRAVEL-TIME RELIABILITY ESTIMATION SYSTEM (TETRES) ARCHITECTURE

In this section, we present the architecture of TeTRES and estimation of travel-time reliability measures with infrastructure-based sensors.

A. Estimation of Travel-Time Reliability Measures with Infrastructure-based Sensors

Figure 2 shows the structure of the Travel-Time Reliability Estimation System (TeTRES) developed at the University of Minnesota Duluth to estimate the travel-time reliability measures, identified in SHRP2, of the freeway corridors in the Twin Cities' metro area in Minnesota. As indicated in Figure 2, TeTRES adopts the server-client structure, where all the computational engines, including travel-time calculation/categorization and reliability estimation modules, reside in the server, while the user-clients handle the processes for configuring travel-time routes, specifying the operating conditions to estimate reliability and generating outputs. In particular, most of the data needed for reliability calculation, such as traffic and weather data, can be automatically downloaded following predefined-time schedules. While the current version of TeTRES is designed to work with the existing infrastructure-based sensors, such as loop or radar detectors, in calculating travel times, other types of sensors can be easily accommodated in the current structure. The detailed architecture of TeTRES can be found elsewhere [5].

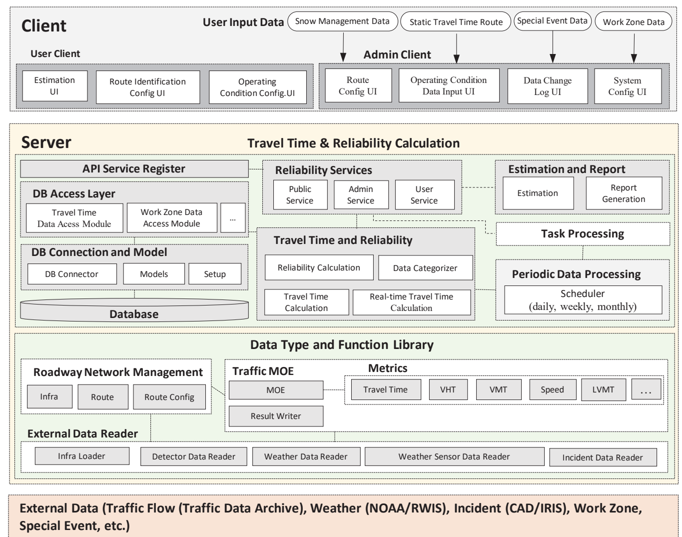

Figure 2. Structure of Travel-Time Reliability Estimation System

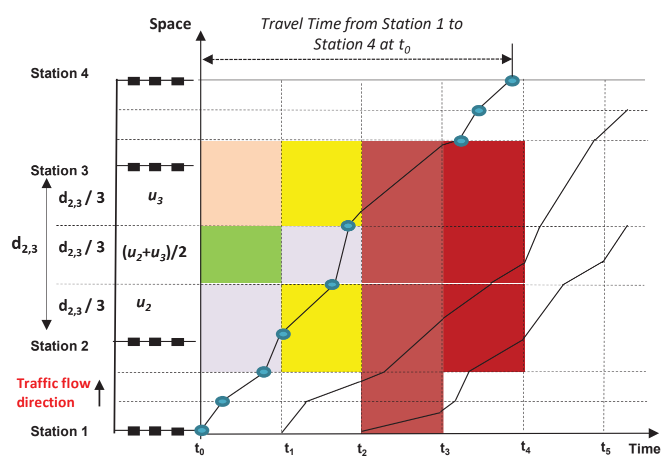

Figure 3. Vehicle Trajectory Identification with the Speed Data from Loop Detectors

Figure 3 illustrates the travel-time calculation process using the traffic-speed data collected from the loop-detector stations in a freeway corridor. As shown in Figure 3, the travel-time estimation procedure first divides a section between two detector stations on a given route into three equal-length subsections and determines the speed of each subsection using the measured speed data, u_i, from station i for each time interval. The speed values of each subsection for each time interval are then applied to determine the travel-trajectory of a vehicle leaving the first station at the beginning of each time interval until it reaches the last station of a given route. The travel-time is then calculated as the difference between the departure time at the first station and the arrival time at the last station of a given route. In the current TeTRES, the travel time of each user-defined route is calculated every 5 min on a daily basis. The details of the above process and the field test results can be found elsewhere [6]. The travel times of given routes are then categorized by the user-specified operating conditions.

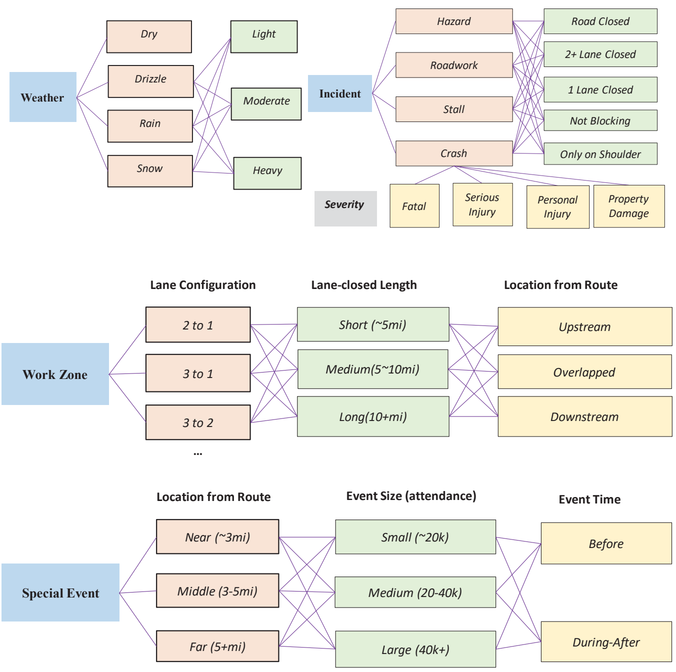

Figure 4. Combinations of External Operating Conditions affecting Reliability

Figure 4 includes the various types of operating-condition combinations that can be defined in the current version of TeTRES, whose reliability-estimation module calculates the reliability indices for given routes and time periods using only the travel-time data collected under specific operating conditions defined by user. A screen-shot of the user-client for entering specific conditions to estimate reliability measures for the selected routes is illustrated in Figure 5.

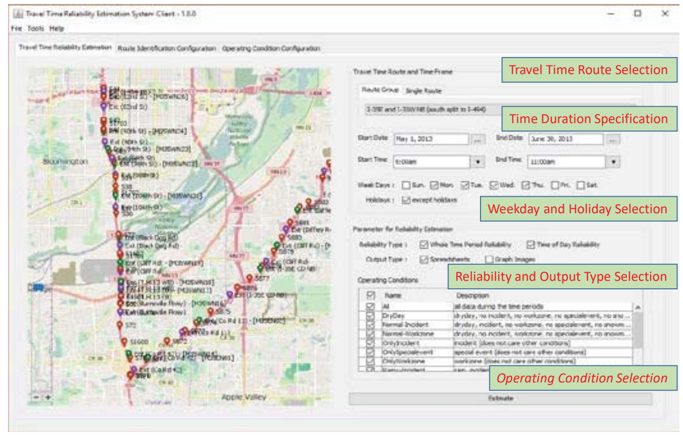

Figure 5. Travel-Time Reliability Estimation Client Panel

IV. Case Studies

A. *Effects of Adaptive Ramp Metering on Reliability in Freeway Corridors*

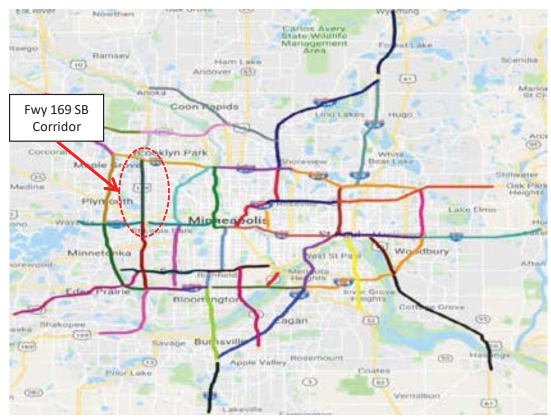

Figure 6. Metro Freeway Network in Twin Cities, Minnesota

Figure 6 shows the location of the 169 southbound corridor in metro freeway network in Twin Cities, Minnesota, where TeTRES has been applied to estimate the effects of the adaptive ramp metering strategy, which was developed at the University of Minnesota Duluth and implemented by the Minnesota Department of Transportation on April 18, 2013 on this corridor. The adaptive metering scheme first identifies the bottlenecks in a given corridor by examining the acceleration/deceleration rates of the traffic flow between two consecutive detector stations using the speed values collected every 30 seconds from each station. Next, for each bottleneck station, a metering zone is defined and the minimum/maximum rates of each entrance ramp within a given zone are determined with the consideration of the operational restrictions, such as the maximum wait time and the on-ramp queue size. Finally, the metering rate of each entrance ramp is calculated with the dynamic control rule, which is based on the density of the mainline segment and also adjusted through time by reflecting the minimum/maximum rates of each ramp. The details of the adaptive metering strategy and its test results can be found elsewhere [6].

For this assessment, the daily values of the planning-time index (PTI-95th %ile) of the 169 southbound corridor during the morning peak period, i.e., 6:00 a.m. to 10:00 a.m., were estimated with TeTRES for each weekday before and after the new metering scheme was activated. Further, to address the effects of traffic demand on the reliability, the daily values of the total vehicle-miles-traveled (VMT) are calculated for the same corridor and time periods. In this analysis, the VMT and PTI values of the normal weekdays under dry weather condition were selected, so that only the effects of the metering changes can be reflected in the resulting reliability estimates. Figure 7 shows the relationships between the daily VMT and planning-time index in the test corridor during the before and after periods in 2013. It can be noted that the after period ends on June 10, 2013, when a new construction started in this corridor. As indicated in Figure 7, the high values of the planning-time index after the new metering strategy was implemented are consistently lower than those in the before period at compatible VMT values. Further, the range of the 'after' PTI values is substantially narrower than that of the 'before' period, indicating both the severity of congestion and the variability of the travel time were significantly reduced during the morning peak-period in this corridor with the new adaptive metering strategy.

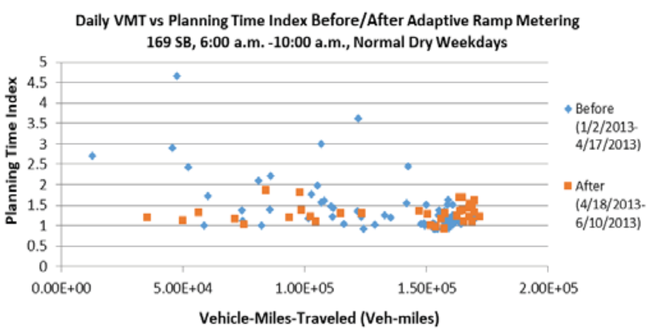

Figure 7. Daily VMT vs Planning Time Index (169 SB)

B. Effects of Short-term Aggressive Incident Management during 2018 Super-Bowl Event on Reliability

This section analyzes the effects of the aggressive incident management strategy, conducted during the 2018 Super-Bowl week, i.e., from January 26, 2018 until February 4, 2018, in Minneapolis, Minnesota, on the travel-time reliability in the metro freeway corridors. According to the Regional Traffic Management Center, Minnesota Department of Transportation, the State Patrol leadership instructed their troopers to expedite the clearance of incidents on metro area freeways during the week of the Super Bowl. Troopers were encouraged to only activate rear facing emergency lights so as to not cause gawker slowdowns in the opposing direction. They were also encouraged to relocate non-injury minor crashes as soon as possible to side streets, frontage roads, or parking lots. The above measures were intended to reduce the clearance time of the minor property-damage only incidents and to mitigate the negative impacts on the opposing flows [7].

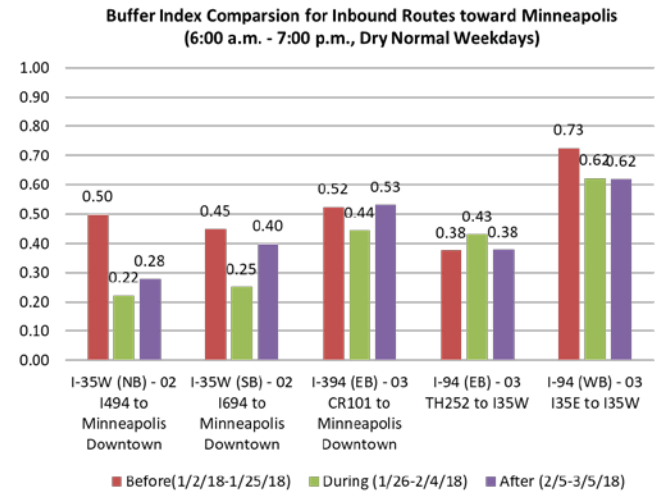

Figure 8. Comparison of Buffer Indices

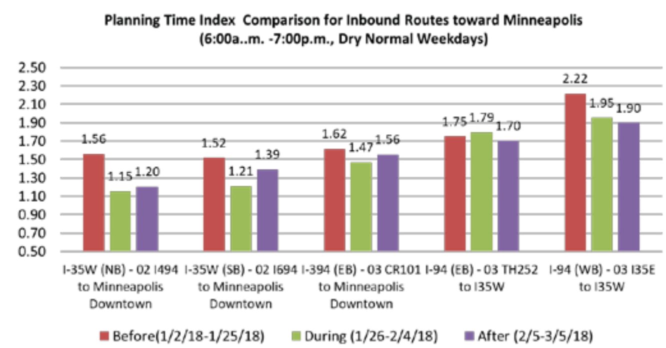

Figure 9. Comparison of Planning Time Indices

The effects of the above incident-management strategy on the travel-time reliability were examined by estimating the reliability indices of the major corridors towards the Minneapolis downtown, where the Super-Bowl venue was located. Specifically, the 95th percentile buffer and planning-time indices of the normal weekdays during the 6:00 a.m.-7:00 p.m. period before, during and after the Super-Bowl week were estimated for the normal weekdays under dry weather condition. Figures 8 and 9 show the values of the buffer and planning-time indices of the five major routes coming towards the Minneapolis downtown on the normal weekdays. As indicated in these figures, both buffer and planning-time indices of the four routes show consistently reduced values during the Super-Bowl period compared to those during the before and after periods, while no significant differences were observed in one route.

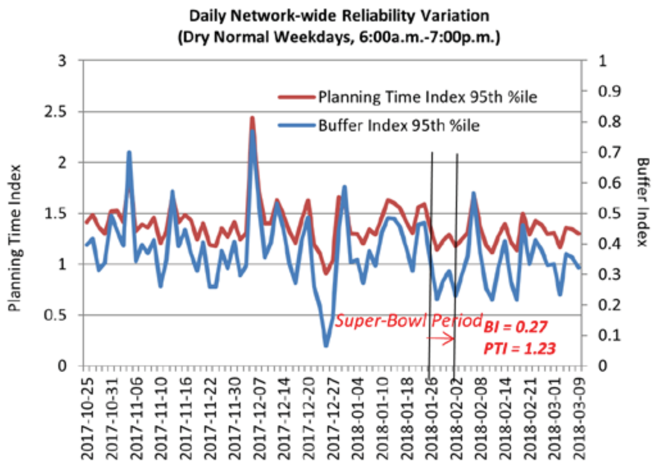

Figure 10. Comparison of Planning Time Indices

Figure 10 shows the daily variations of the network-wide buffer and planning-time indices during the same time periods. The network-wide indices are the weighted averages of the buffer and planning-time indices of all the individual routes in the metro network. The VMT of each route was used as the weight. As indicated in Figure 10, the network-wide indices during the Super-Bowl event clearly show reduced values compared to those during before and after periods. The above results appear to indicate the short-term aggressive incident management scheme made a positive impact on the travel-time reliability in the metro freeway network.

V. CONCLUSION

A key element in building smart cities is a reliable traffic network, where efficient mobility services can be provided with consistent travel times in a time-variant environment. Developing such a network requires an efficient estimation of the travel-time reliability measures responding to various operating conditions and strategies, so that the causal relationship between the reliability measures and the operational strategies can be identified for a given network. This paper presented a travel-time reliability estimation system, which integrates multiple datasets and determines the various types of the travel-time reliability measures under different operating conditions for a given network. The system was applied to evaluate the effects of two operational changes in the metro freeway network in Minnesota on the travel-time reliability. The comparison of the reliability measures before and after each operational change clearly shows the substantial improvements in terms of the travel-time variability and the congestion severity in a given network. Future work includes the modeling the causal relationship between the travel-time reliability and specific operational strategies for a given traffic system.

VI. ACKNOWLEDGEMENT

This research was financially supported by the Minnesota Department of Transportation.

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