Urban, Planning and Transport Research
An Open Access Journal

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/rupt20

Exploring Correlations between Travel Time Based Measures by Year, Day-of-the-week, Time-of-the-day, Week-of-the-Year and the Posted Speed Limit

Srinivas Pulugurtha & Krupanidhi Koilada

To cite this article: Srinivas Pulugurtha & Krupanidhi Koilada (2020): Exploring Correlations between Travel Time Based Measures by Year, Day-of-the-week, Time-of-the-day, Week-of-the-Year and the Posted Speed Limit, Urban, Planning and Transport Research, DOI: 10.1080/21650020.2020.1845230

To link to this article: https://doi.org/10.1080/21650020.2020.1845230

Published online: 06 Dec 2020.

URBAN, PLANNING AND TRANSPORT RESEARCH
https://doi.org/10.1080/21650020.2020.1845230

Routledge
Taylor & Francis Group

ARTICLE

Exploring Correlations between Travel Time Based Measures by Year, Day-of-the-week, Time-of-the-day, Week-of-the-Year and the Posted Speed Limit

Srinivas Pulugurtha[a] and Krupanidhi Koilada[b]

[a]Civil & Environmental Engineering Department, Infrastructure, Design, Environment, and Sustainability (IDEAS) Center, The University of North Carolina at Charlotte, Charlotte, NC, USA; [b]Civil & Environmental Engineering Department, The University of North Carolina at Charlotte, Charlotte, NC, USA

ABSTRACT

This research explores correlations between travel time-based measures, comprehensively, by year, day-of-the-week (DoW), time-of-the-day (ToD), week-of-the-year (WoY), and the posted speed limit using raw one-minute interval travel time data for 3,290 road links in Charlotte, North Carolina. The data were processed, normalized, and categorized into 57 datasets accounting for the year, DoW, ToD, WoY, and the posted speed limit. Pearson correlation coefficient matrices were generated to explore the correlations between travel time measures (minimum, maximum, and average; 10th, 15th, 50th, 85th, 90th, and 95th percentile travel times), travel time reliability measures (buffer time – BT, buffer time index – BTI, planning time index – PTI, and travel time index – TTI), and travel time variability measures (based on 90th, 85th, 15th and 10th percentile travel times). The percentages based on scores associated with the correlations were also examined. Travel time measures and travel time variability measures are moderately or highly correlated with each other. BT is moderately or highly correlated with all other measures, while the correlation between BTI, PTI and TTI and travel time measures is relatively low. There is a positive correlation between BTI and PTI and a negative correlation between BTI and TTI in most instances.

ARTICLE HISTORY
Received 28 August 2020
Accepted 29 October 2020

KEYWORDS
Travel time; reliability; variation; average; BT; BTI; PTI

Introduction

Traffic congestion is a common problem in many urban areas due to the increasing demand for travel along with the population growth. It occurs when demand exceeds capacity on a road link during a time period. Traffic congestion leads to a decrease in the vehicular speed on a road link, which in turn increases the travel time on the road link.

The census data indicate that from the year 2010 to the year 2017, there was a 16% increase in the population of Mecklenburg County, North Carolina. Similarly, the city of Charlotte, North Carolina has seen, approximately, a 2%-2.5% increase in the population every year, since the year 2010. This growth in the population indicates that thousands of

CONTACT Srinivas Pulugurtha sspulugurtha@uncc.edu Civil & Environmental Engineering Department, Infrastructure, Design, Environment, and Sustainability (IDEAS) Center, The University of North Carolina at Charlotte, Charlotte, NC 28223-0001, USA

new vehicles are using the roads in an urban area like Charlotte, North Carolina every year. This increase in the number of vehicles on roads influences the need to construct new roads, expand the existing road network, or identify solutions to better manage the existing road network. These trends and needs are common in many urban areas across the world.

Traffic congestion is not just due to the population growth and associated travel demand. It is not just due to peak hour or weekday commuters. There are many other factors which cause traffic congestion and delay. These factors include traffic incidents, work zone activity, weather, special events, and holiday weekends. The most common traffic incidents include vehicular crashes, the breakdown of vehicles, and debris on the travel lanes. Vehicular crashes are one of the common reasons for traffic congestion. Even a property damage only (PDO) crash on a road link could lead to vehicle delay. It might not bring the traffic to a complete stop but may result in slow-moving traffic. On the other hand, the vehicular delay and complete stoppage of traffic could exceed 90 minutes in the case of a fatal or severe injury crash (Pulugurtha & Mahanthi, 2016). The magnitude of the effect of traffic incidents is space and time dependent.

The traffic incidents which usually take place on travel lanes disrupt the normal flow of traffic by slowing down the speeds of the vehicles. In addition to the incidents on travel lanes, incidents on the shoulder or roadside can cause congestion by distracting the motorist which causes a change in the normal traffic flow (Masinick et al., 2014).

In addition to annual traffic growth as well as motorists and their behaviors by the day-of-the-week (DoW), time-of-the-day (ToD), and week-of-the-year (WoY), other factors such as the posted speed limit of a road link influence travel demand and travel time on the road link. Different roads and road links have different posted speed limits. Even a road link can have different posted speed limits (for example, for passenger vehicles and trucks). Generally, in the United States, the posted speed limit of a road can range anywhere between 10 mph (16.1 kmph) to 75 mph (120.7 kmph). These posted speed limits influence the travel times and travel patterns of the motorists in urban areas. Besides, travel time is easy to comprehend by the motorists and related measures are expected to be widely used by the practitioners. There is a need to explore travel time-based measures to assess their applicability based on the study purpose (rank road links for allocation of resources, before-after evaluation of transportation projects/alternatives, etc.).

The concept of reliability in the field of transportation has been explored since the late eighties. The connectivity reliability proposed by Iida and Wakabayashi (1989), in their analysis, yields travel time reliability (Asakura & Kashiwadani, 1991) as a byproduct. In general, travel time reliability is defined as the consistency or dependability of travel time measured by DoW and ToD for a trip (FHWA, 2006). It is generally measured using heuristic and statistical methods for various travel conditions (Abdel-Aty et al., 1995; Chen et al., 2002; Haitham & Emam, 2006; Zeng-Ping & Nicholson, 1997). Lognormal distributions were also explored to formulate the travel time reliability measure (Pu, 2011).

The minimum travel time (MinTT) is the shortest time taken, while the maximum travel time (MaxTT) is the longest time (could be due to a fatal or severe crash) taken to traverse through a road link. The free-flow travel time is the time taken to traverse a road link under free-flow conditions (for example, the 15th percentile travel time based on all day observations). It is used to compute planning time index (PTI) (FHWA, 2006; Lyman & Bertini, 2008; Sisiopiku et al., 2012) and travel time index (TTI) (Lyman &

Bertini, 2008). The travel time measures were compared to assess variation in travel time in the past. Tu et al. (2007) compared the 90th and 10th percentile travel times while Wakabayashi (2010) compared the 85th and 15th percentile travel times to compute travel time variation.

The average travel time (ATT) is the arithmetic mean of travel times observed along a road link during a time period, often considered as the expected travel time during the time period. It is used to compute reliability measures like buffer time (BT) (Lomax et al., 2004; FHWA, 2006) and buffer time index (BTI) (Lomax et al., 2004; FHWA, 2006; Lyman & Bertini, 2008). The planning time (PT) or 95th percentile travel time is the time to reach a destination on time 95% of the times (FHWA, 2006). It is the sum of the ATT and BT. Basically, BT is the extra time motorists add to the ATT in order to reach their destination on time. The ratio of the BT to the ATT is defined as the BTI (Lomax et al., 2003, 2004; FHWA, 2006; Lyman & Bertini, 2008).

The traffic volume increases every year. Likewise, the traffic volume is not the same on all the days of a week. It varies by capacity conditions, DoW and ToD (Williams et al., 2013). It also depends on the season or WoY and differs during holiday weeks (Puvvala et al., 2015). Roads with different posted speed limits serve different parts of a trip (for example, local and collector roads provide direct access to an origin or destination while high-speed interstates, expressways, and arterials serve for most part of a trip) and magnitudes of traffic volumes. The variations in traffic volume by DoW, ToD (Williams et al., 2013), WoY (Puvvala et al., 2015), and the posted speed limit are expected to influence travel times on road links in urban areas. Therefore, exploring and examining correlations by accounting these factors would help select a set of suitable measures for evaluating transportation projects/alternatives.

The correlations between travel time-based measures were researched to some extent in the past (Pu, 2011; Pulugurtha et al., 2015, 2016; Wakabayashi & Matsumoto, 2012). However, none of the past researchers focused on the correlations between travel time measures, travel time reliability measures, and travel time variability measures, comprehensively, by year, WoY and the posted speed limit in addition to DoW and ToD. Further, percentages based on scores associated with correlations between categorized datasets were not examined in the past. This research focuses to bridge the gap. The findings help to identify and apply a set of suitable travel time-based measures for assessing transportation projects/alternatives.

Methodology

The city of Charlotte, North Carolina, an urban area, was considered for this research. The raw travel time data at one-minute interval collected by a private data source were gathered for 3,290 road links (Figure 1), for the years 2014 and 2015. The 3,290 road links include 742 road links with the posted speed limit ≤35 mph (56.3 kmph), 1,822 road links with the posted speed limit = 40 or 45 mph (64.4 or 72.4 kmph), 357 road links with the posted speed limit = 50 or 55 mph (80.5 or 88.5 kmph), and 370 road links with the posted speed limit = 60 or 65 mph (96.6 or 104.6 kmph).

The raw travel time database has road link identity (traffic message channel), date and time when the travel time data were collected, the estimated space mean speed for the road link, the average mean speed for the road link for that DoW and ToD, the reference speed (an indicator of free-flow speed for the road link), the estimated travel time to

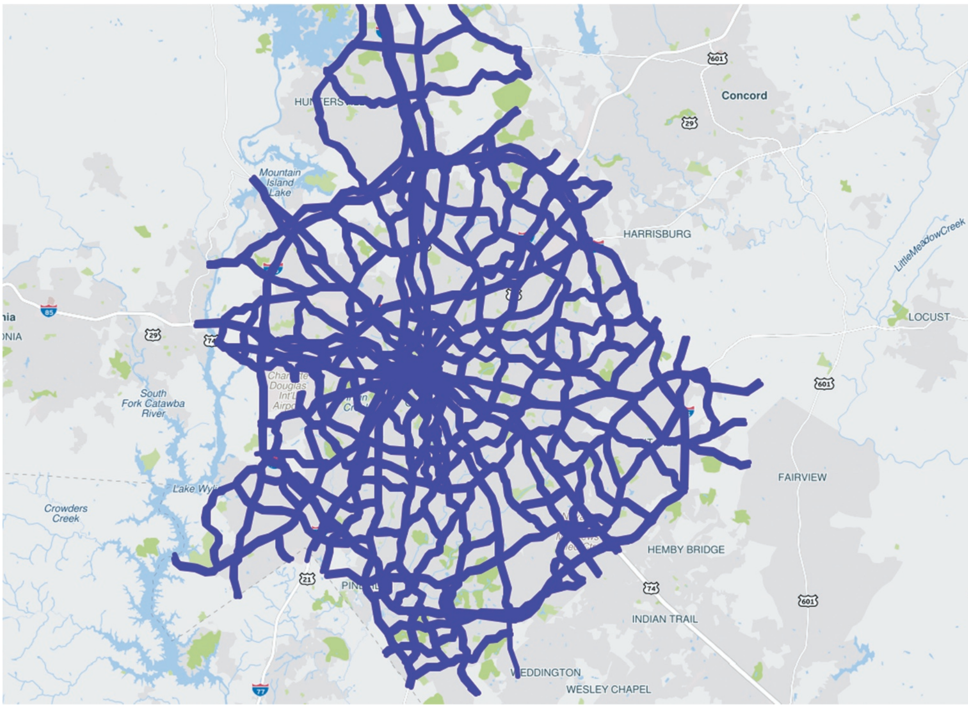

Figure 1. Selected road links.

traverse the road link, and a score (30 indicates real-time data; 20 indicates real-time data across multiple segments; 10 indicates historical data).

The posted speed limit and road link length were added to each road link and travel time record in the database. The travel times were divided by the length of the respective road link to compute travel time per mile (1.6 kilometers). This was done to normalize the travel time and minimize the influence of different road link lengths on travel time during the analysis. Further, to reduce any bias which might arise due to smaller road links (dividing with a very low value), the data for road links with length less than 1/16th mile (0.1 kilometer) were excluded from the analysis in this research.

The raw travel time data were processed using Microsoft SQL Server to compute the minimum (MinTT), maximum (MaxTT), and average (ATT) travel times. Besides, the 10th, 15th, 50th, 85th, 90th, and 95th percentile travel times (TT10, TT15, TT50, TT85, TT90, and TT95) were also computed. These travel time measures were then used to compute travel time reliability measures (BT, BTI, PTI, and TTI) and travel time variability measures based on 90th, 85th, 15th, and 10th percentile travel times (TTV90 and TTV85) using the following equations.

$$\mathrm{BT} = \mathrm{TT95} - \mathrm{ATT}$$

$$\mathrm{BTI} = \frac{\mathrm{BT}}{\mathrm{ATT}} * 100$$

$$\mathrm{PTI} = \frac{\mathrm{TT95}}{\mathrm{TT}_{\mathrm{Free-flow}}}$$

$$\mathrm{TTI} = \frac{\mathrm{ATT}}{\mathrm{TT}_{\mathrm{Free-flow}}}$$

$$\mathrm{TTV90} = \mathrm{TT90} - \mathrm{TT10}$$

$$\mathrm{TTV85} = \mathrm{TT85} - \mathrm{TT15}$$

The 15^{th} percentile travel time was used as the free-flow travel time ($\mathrm{TT}_{\text{Free-flow}}$).

The travel time-based measures were computed separately for each road link and for each year (2014 and 2015). They were also computed for a weekday (Wednesday) and a weekend day (Saturday). For each selected DoW, they also were computed for the following time periods.

- Morning peak hour (8–9 AM)
- Afternoon off-peak hour (12–1 PM)
- Evening peak hour (5–6 PM)
- Nighttime hour (9–10 PM)

Additionally, data were processed and travel time-based measures were computed for five different weeks of a year. They are listed as follows.

- Last week of January – winter
- Last week of April – spring
- Last week of July – summer
- Last week of October – fall
- Thanksgiving week

The complete dataset was also categorized based on the posted speed limit. They are:

- ≤35 mph (56.3 kmph)
- 40 or 45 mph (64.4 or 72.4 kmph)
- 50 or 55 mph (80.5 or 88.5 kmph)
- 60 or 65 mph (96.6 or 104.6 kmph)

The dataset for each speed limit category was processed by DoW as well as by DoW and ToD. Travel time-based measures were also computed using each of these categorized datasets.

Overall, travel time-based measures were computed using 57 different datasets (25 datasets – 2 by year, 2 by DoW, 8 by DoW and ToD, 5 by WoY, and 8 by DoW and posted speed limit; and, 32 datasets by DoW, ToD, and the posted speed limit).

The Pearson correlation coefficient matrices were computed to explore the correlations between the travel time-based measures by year, DoW, ToD, WoY, and the posted speed limit. The computed Pearson correlation coefficients for each dataset were classified as follows and summarized in tables. Moderate and high correlations (both, positive and negative) are typically at a 95% or higher confidence level.

- HP is high positive correlation (>0.7)
- MP is moderate positive correlation (0.3 to 0.7)
- LP is low positive correlation (0 to 0.3)
- LN is low negative correlation (-0.3 to 0)
- MN is moderate negative correlation (-0.7 to -0.3)
- HN is high negative correlation (<-0.7)

A scoring mechanism was then used to combine correlation outputs from the analysis of categorized datasets and further explore correlations. High positive correlation and high negative correlation were given a weight of 3, while moderate positive correlation and moderate negative correlation were given a weight of 2. Low positive correlation and low negative correlation were given a weight of 1, while no correlation (blank cells in the tables) was given a weight of 0.

The minimum possible score for a correlation combination from all the selected datasets is zero. The maximum possible score from the dataset by year is 2 × 3 = 6; by DoW is 2 × 3 = 6; by DoW and ToD is 2 × 4 × 3 = 24; by WoY is 5 × 3 = 15; and, by DoW and the posted speed limit is 2 × 4 × 3 = 24. The sum of scores for each correlation combination from the datasets by year, DoW, DoW and ToD, WoY, and DoW and the posted speed limit was divided by the sum of maximum possible scores (6 + 6 + 24 + 15 + 24 = 75) and converted to percentages. These percentages indicating the strength of correlations between travel time-based measures from the 25 categorized datasets were also examined.

Likewise, scores from the 32 categorized datasets by DoW, ToD, and the posted speed limit were converted to percentages and examined. The maximum possible score in this case is 2 × 4 × 4 × 3 = 96.

Results

The results from the Pearson correlation coefficient matrices and percentages based on scores associated with correlations are discussed in this section.

Correlations by year, day-of-the-week (DoW), time-of-the-day (ToD), week-of-the-year (WoY), and the posted speed limit

The correlations between travel time-based measures are explored for the years 2014 and 2015, by DoW (Wednesday and Saturday), by DoW and ToD (8–9 AM, 12–1 PM, 5–6 PM, and 9–10 PM), by WoY (last week of January – winter, last week of April – spring, last week of July – summer, last week of October – fall, and Thanksgiving week), and by DoW and the posted speed limit (≤35 mph [56.3 kmph], 40 or 45 mph [64.4 or 72.4 kmph], 50 or 55 mph [80.5 or 88.5 kmph], and 60 or 65 mph [96.6 or 104.6 kmph]). Selected results from the analysis using 25 categorized datasets are summarized in Tables 1–5.

The travel time measures are highly correlated with each other compared to the travel time reliability measures (moderately correlated in a few instances). The travel time measures are moderately or highly but positively correlated with BT, TTV90 and TTV85.

Table 1. Correlations by year.

Measure	MinTT	MaxTT	ATT	TT10	TT15	TT50	TT85	TT90	TT95	BT	BTI	PTI	TTI	TTV90
2014														
MaxTT	**HP**													
ATT	**HP**	**HP**												
TT10	**HP**	**HP**	**HP**											
TT15	**HP**	**HP**	**HP**	**HP**										
TT50	**HP**	**HP**	**HP**	**HP**	**HP**									
TT85	**HP**	**HP**	**HP**	**HP**	**HP**	**HP**								
TT90	**HP**	**HP**	**HP**	**HP**	**HP**	**HP**	**HP**							
TT95	**HP**	**HP**	**HP**	**HP**	**HP**	**HP**	**HP**	**HP**						
BT	MP	**HP**	MP	MP	MP	MP	MP	**HP**	**HP**					
BTI	LN	LP	LN	LN	LN	LN	LN	LN	LN	MP				
PTI	LN	LP	LN	LN	LN	LN	LN	LN	LN	LP	**HP**			
TTI	LP	LN	LP	LP	LP	LP	LN	LN	LN	MN	MN			
TTV90	MP	**HP**	MP	MP	MP	MP	**HP**	**HP**	**HP**	**HP**	LP	LP	MN	
TTV85	MP	**HP**	MP	MP	MP	MP	**HP**	**HP**	**HP**	**HP**	LP	LN	MN	**HP**
2015														
MaxTT	MP													
ATT	**HP**	**HP**												
TT10	**HP**	MP	**HP**											
TT15	**HP**	MP	**HP**	**HP**										
TT50	**HP**	MP	**HP**	**HP**	**HP**									
TT85	**HP**	**HP**	**HP**	**HP**	**HP**	**HP**								
TT90	**HP**	**HP**	**HP**	**HP**	**HP**	**HP**	**HP**							
TT95	**HP**	**HP**	**HP**	**HP**	**HP**	**HP**	**HP**	**HP**						
BT	LP	MP	MP	MP	MP	MP	MP	MP	**HP**					
BTI	LN	LP	LN	LN	LN	LN	LN	LN	LP	MP				
PTI	LN	LP	LN	LN	LN	LN	LN	LN	LP	MP	**HP**			
TTI	LP	LN	LP	LP	LP	LP	LP	LP	LN	MN	MN	LN		
TTV90	MP	MP	MP	MP	MP	MP	MP	MP	**HP**	**HP**	MP	LP	MN	
TTV85	MP	MP	MP	MP	MP	MP	MP	MP	MP	**HP**	MP	LP	MN	**HP**

Table 2. Correlations by day-of-the-week (DoW).

Measure	MinTT	MaxTT	ATT	TT10	TT15	TT50	TT85	TT90	TT95	BT	BTI	PTI	TTI	TTV90
Wednesday														
MaxTT	**HP**													
ATT	**HP**	**HP**												
TT10	**HP**	**HP**	**HP**											
TT15	**HP**	**HP**	**HP**	**HP**										
TT50	**HP**	**HP**	**HP**	**HP**	**HP**									
TT85	**HP**	**HP**	**HP**	**HP**	**HP**	**HP**								
TT90	**HP**	**HP**	**HP**	**HP**	**HP**	**HP**	**HP**							
TT95	**HP**	**HP**	**HP**	**HP**	**HP**	**HP**	**HP**	**HP**						
BT	MP	**HP**	MP	MP	MP	MP	MP	**HP**	**HP**					
BTI	LN	LP	LN	LN	LN	LN	LN	LN	LN	MP				
PTI	LN	LP	LN	LN	LN	LN	LN	LN	LN	LP	**HP**			
TTI	LP	LN	LP	LP	LP	LP	LN	LN	LN	MN	MN			
TTV90	MP	**HP**	MP	MP	MP	MP	**HP**	**HP**	**HP**	**HP**	LP	LP	MN	
TTV85	MP	**HP**	MP	MP	MP	MP	**HP**	**HP**	**HP**	**HP**	LP	LN	MN	**HP**
Saturday														
MaxTT	MP													
ATT	**HP**	**HP**												
TT10	**HP**	**HP**	**HP**											
TT15	**HP**	**HP**	**HP**	**HP**										
TT50	**HP**	**HP**	**HP**	**HP**	**HP**									
TT85	**HP**	**HP**	**HP**	**HP**	**HP**	**HP**								
TT90	**HP**	**HP**	**HP**	**HP**	**HP**	**HP**	**HP**							
TT95	**HP**	**HP**	**HP**	**HP**	**HP**	**HP**	**HP**	**HP**						
BT	MP	MP	MP	MP	MP	MP	MP	MP	MP					
BTI	MN		LN	LN	LN	LN	LN	LN	LN	MP				
PTI	LN	LP	LN	LN	LN	LN	LN	LN	LN	MP	**HP**			
TTI	MP		LP	LP	LP	LP	LP	LP	LP	MN	MN	LN		
TTV90	MP	MP	MP	MP	MP	MP	MP	MP	**HP**	**HP**	MP	LP	MN	
TTV85	MP	MP	MP	MP	MP	MP	MP	MP	**HP**	**HP**	LP	LP	MN	**HP**

Table 3. Correlations – wednesday by time-of-the-day (ToD).

Measure	MinTT	MaxTT	ATT	TT10	TT15	TT50	TT85	TT90	TT95	BT	BTI	PTI	TTI	TTV90
Wednesday 8-9 AM														
MaxTT	MP													
ATT	**HP**	**HP**												
TT10	**HP**	MP	**HP**											
TT15	**HP**	MP	**HP**	**HP**										
TT50	**HP**	**HP**	**HP**	**HP**	**HP**									
TT85	**HP**	**HP**	**HP**	**HP**	**HP**	**HP**								
TT90	**HP**	**HP**	**HP**	**HP**	**HP**	**HP**	**HP**							
TT95	**HP**	**HP**	**HP**	**HP**	**HP**	**HP**	**HP**	**HP**						
BT	MP	**HP**	MP	MP	MP	MP	**HP**	**HP**	**HP**					
BTI	LN	LP	LN	LN	LN	LN			LP	MP				
PTI	LN	LP	LN	LN	LN	LN	LN	LN		MP	**HP**			
TTI	LP	LN		LP	LP		LN	LN	LN	MN	HN	MN		
TTV90	MP	**HP**	MP	MP	MP	MP	**HP**	**HP**	**HP**	**HP**	MP	LP	MN	
TTV85	MP	**HP**	MP	MP	MP	MP	**HP**	**HP**	**HP**	**HP**	MP	LP	MN	**HP**
Wednesday 12-1 PM														
MaxTT	MP													
ATT	**HP**	**HP**												
TT10	**HP**	**HP**	**HP**											
TT15	**HP**	**HP**	**HP**	**HP**										
TT50	**HP**	**HP**	**HP**	**HP**	**HP**									
TT85	**HP**	**HP**	**HP**	**HP**	**HP**	**HP**								
TT90	**HP**	**HP**	**HP**	**HP**	**HP**	**HP**	**HP**							
TT95	**HP**	**HP**	**HP**	**HP**	**HP**	**HP**	**HP**	**HP**						
BT	MP	**HP**	MP	MP	MP	MP	MP	MP	**HP**					
BTI	LN	LP	LN	LN	LN	LN	LN	LN		MP				
PTI	LN	LP	LN	LN	LN	LN	LN	LN		MP	**HP**			
TTI	LP		LP	LP	LP	LP				MN	HN	MN		
TTV90	MP	MP	MP	MP	MP	MP	**HP**	**HP**	**HP**	**HP**	MP	LP	MN	
TTV85	MP	MP	MP	MP	MP	MP	**HP**	**HP**	**HP**	**HP**	MP	LP	MN	**HP**
Wednesday 5-6 PM														
MaxTT	MP													
ATT	**HP**	**HP**												
TT10	**HP**	MP	**HP**											
TT15	**HP**	MP	**HP**	**HP**										
TT50	**HP**	**HP**	**HP**	**HP**	**HP**									
TT85	**HP**	**HP**	**HP**	**HP**	**HP**	**HP**								
TT90	**HP**	**HP**	**HP**	**HP**	**HP**	**HP**	**HP**							
TT95	**HP**	**HP**	**HP**	**HP**	**HP**	**HP**	**HP**	**HP**						
BT	MP	**HP**	MP	MP	MP	MP	**HP**	**HP**	**HP**					
BTI	MN	LP	LN	LN	LN	LN	LN		LP	MP				
PTI	LN	LP	LN	LN	LN	LN	LN	LN		LP	**HP**			
TTI	LP	LN	LP	LP	LP	LP	LP	LN	LN	MN	HN	MN		
TTV90	MP	**HP**	MP	MP	MP	MP	**HP**	**HP**	**HP**	**HP**	MP	LP	MN	
TTV85	MP	**HP**	MP	MP	MP	MP	**HP**	**HP**	**HP**	**HP**	MP	LP	MN	**HP**
Wednesday 9-10 PM														
MaxTT	MP													
ATT	**HP**	**HP**												
TT10	**HP**	**HP**	**HP**											
TT15	**HP**	**HP**	**HP**	**HP**										
TT50	**HP**	**HP**	**HP**	**HP**	**HP**									
TT85	**HP**	**HP**	**HP**	**HP**	**HP**	**HP**								
TT90	**HP**	**HP**	**HP**	**HP**	**HP**	**HP**	**HP**							
TT95	**HP**	**HP**	**HP**	**HP**	**HP**	**HP**	**HP**	**HP**						
BT	MP	MP	MP	MP	MP	MP	MP	MP	MP					
BTI	LN		LN	LN	LN	LN	LN	LN	LN	MP				
PTI	LN	LP	LN	LN	LN	LN	LN	LN	LP	MP	**HP**			
TTI	LP	LP	LP	LP	LP	LP	LP			MN	HN	MN		
TTV90	MP	MP	MP	MP	MP	MP	**HP**	**HP**	**HP**	**HP**	MP	LP	MN	
TTV85	MP	MP	MP	MP	MP	MP	**HP**	**HP**	**HP**	**HP**	LP	LP	MN	**HP**

However, their correlation with BTI, PTI and TTI is generally low (moderate correlation in a few instances). BTI and PTI are negatively correlated with travel time measures except in a few instances, mostly when compared with MinTT and MaxTT or analyzed by DoW and the posted speed limit. The correlations between TTI and travel time measures

Table 4. Correlations by week-of-the-year (WoY).

Measure	MinTT	MaxTT	ATT	TT10	TT15	TT50	TT85	TT90	TT95	BT	BTI	PTI	TTI	TTV90
Last Week of January - Winter														
MaxTT	**HP**													
ATT	**HP**	**HP**												
TT10	**HP**	**HP**	**HP**											
TT15	**HP**	**HP**	**HP**	**HP**										
TT50	**HP**	**HP**	**HP**	**HP**	**HP**									
TT85	**HP**	**HP**	**HP**	**HP**	**HP**	**HP**								
TT90	**HP**	**HP**	**HP**	**HP**	**HP**	**HP**	**HP**							
TT95	**HP**	**HP**	**HP**	**HP**	**HP**	**HP**	**HP**	**HP**						
BT	MP	MP	MP	MP	MP	MP	MP	MP	MP					
BTI	LN	LP	LN	LN	LN	LN		LP	LP	MP				
PTI	LN	LP	LN	LN	LN	LN	LP	LP	LP	MP	**HP**			
TTI	LN	LP	LN	LN	LN	LN	LP	LP	LP	MP	HN	**HP**		
TTV90	MP	MP	MP	MP	MP	MP	MP	MP	MP	**HP**	MP	MP	MP	
TTV85	MP	MP	MP	MP	MP	MP	MP	MP	MP	**HP**	MP	MP	MP	**HP**
Last Week of April - Spring														
MaxTT	**HP**													
ATT	**HP**	**HP**												
TT10	**HP**	**HP**	**HP**											
TT15	**HP**	**HP**	**HP**	**HP**										
TT50	**HP**	**HP**	**HP**	**HP**	**HP**									
TT85	**HP**	**HP**	**HP**	**HP**	**HP**	**HP**								
TT90	**HP**	**HP**	**HP**	**HP**	**HP**	**HP**	**HP**							
TT95	**HP**	**HP**	**HP**	**HP**	**HP**	**HP**	**HP**	**HP**						
BT	MP	MP	MP	MP	MP	MP	MP	MP	MP					
BTI	LN	LP	LN	LN	LN	LN		LP	LP	MP				
PTI	LN	LP	LN	LN	LN	LN	LP	LP	LP	MP	**HP**			
TTI	LN	LP	LN	LN	LN	LN	LP	LP	LP	MP	HN	**HP**		
TTV90	MP	MP	MP	MP	MP	MP	MP	MP	MP	**HP**	MP	MP	MP	
TTV85	MP	MP	MP	MP	MP	MP	MP	MP	MP	**HP**	MP	MP	MP	**HP**
Last Week of July - Summer														
MaxTT	**HP**													
ATT	**HP**	**HP**												
TT10	**HP**	**HP**	**HP**											
TT15	**HP**	**HP**	**HP**	**HP**										
TT50	**HP**	**HP**	**HP**	**HP**	**HP**									
TT85	**HP**	**HP**	**HP**	**HP**	**HP**	**HP**								
TT90	**HP**	**HP**	**HP**	**HP**	**HP**	**HP**	**HP**							
TT95	**HP**	**HP**	**HP**	**HP**	**HP**	**HP**	**HP**	**HP**						
BT	MP	MP	MP	MP	MP	MP	MP	MP	MP					
BTI	LN	LP	LN	LN	LN	LN	LN	LP	LP	MP				
PTI	LN	LP	LN	LN	LN	LN	LP	LP	LP	MP	**HP**			
TTI	LN	LP	LN	LN	LN	LN		LP	LP	MP	HN	**HP**		
TTV90	MP	MP	MP	MP	MP	MP	MP	MP	MP	**HP**	MP	MP	MP	
TTV85	MP	MP	MP	MP	MP	MP	MP	MP	MP	**HP**	MP	MP	MP	**HP**
Last Week of October - Fall														
MaxTT	**HP**													
ATT	**HP**	**HP**												
TT10	**HP**	**HP**	**HP**											
TT15	**HP**	**HP**	**HP**	**HP**										
TT50	**HP**	**HP**	**HP**	**HP**	**HP**									
TT85	**HP**	**HP**	**HP**	**HP**	**HP**	**HP**								
TT90	**HP**	**HP**	**HP**	**HP**	**HP**	**HP**	**HP**							
TT95	**HP**	**HP**	**HP**	**HP**	**HP**	**HP**	**HP**	**HP**						
BT	MP	**HP**	MP	MP	MP	MP	MP	MP	MP					
BTI	LN	LP	LN	LN	LN	LN	LP	LP	LP	MP				
PTI	LN	LP	LN	LN	LN	LN	LN		LP	MP	**HP**			
TTI	LN	LP	LN	LN	LN	LN	LN		LP	LP	HN	**HP**		
TTV90	MP	**HP**	MP	MP	MP	MP	MP	**HP**	**HP**	**HP**	MP	LP	LP	
TTV85	MP	MP	MP	MP	MP	MP	MP	MP	MP	**HP**	MP	LP	LP	**HP**
Thanksgiving Week														
MaxTT	**HP**													
ATT	**HP**	**HP**												
TT10	**HP**	**HP**	**HP**											
TT15	**HP**	**HP**	**HP**	**HP**										
TT50	**HP**	**HP**	**HP**	**HP**	**HP**									
TT85	**HP**	**HP**	**HP**	**HP**	**HP**	**HP**								
TT90	**HP**	**HP**	**HP**	**HP**	**HP**	**HP**	**HP**							
TT95	**HP**	**HP**	**HP**	**HP**	**HP**	**HP**	**HP**	**HP**						
BT	MP	MP	MP	MP	MP	MP	MP	MP	MP					
BTI	LN	LP	LN	LN	LN	LN	LP	LP	LP	MP				
PTI	LN	LP	LN	LN	LN	LN	LN	LP	LP	MP	**HP**			
TTI	LN	LP	LN	LN	LN	LN	LP		LP	LP	HN	**HP**		
TTV90	MP	MP	MP	MP	MP	MP	MP	MP	MP	**HP**	MP	LP	LP	
TTV85	MP	MP	MP	MP	MP	MP	MP	MP	MP	**HP**	MP	LP	MP	**HP**

Table 5. Correlations – wednesday by the posted speed limit.

Measure	MinTT	MaxTT	ATT	TT10	TT15	TT50	TT85	TT90	TT95	BT	BTI	PTI	TTI	TTV90
≤35 mph														
MaxTT	MP													
ATT	**HP**	**HP**												
TT10	**HP**	**HP**	**HP**											
TT15	**HP**	**HP**	**HP**	**HP**										
TT50	**HP**	**HP**	**HP**	**HP**	**HP**									
TT85	**HP**	**HP**	**HP**	**HP**	**HP**	**HP**								
TT90	**HP**	**HP**	**HP**	**HP**	**HP**	**HP**	**HP**							
TT95	**HP**	**HP**	**HP**	**HP**	**HP**	**HP**	**HP**	**HP**						
BT	MP	**HP**	MP	MP	MP	MP	**HP**	**HP**	**HP**					
BTI	MN		LN	MN	MN	MN	LN	LN	LN	MP				
PTI	MN		LN	MN	MN	LN	LN	LN	LN	LP	**HP**			
TTI	MP		LP	MP	MP	LP	LP	LP		MN	MN	LN		
TTV90	MP	**HP**	**HP**	MP	MP	MP	**HP**	**HP**	**HP**	**HP**	LP	LP	MN	
TTV85	MP	**HP**	**HP**	MP	MP	MP	**HP**	**HP**	**HP**	**HP**	LP	--	MN	**HP**
40 Or 45 mph														
MaxTT	MP													
ATT	**HP**	**HP**												
TT10	**HP**	MP	**HP**											
TT15	**HP**	MP	**HP**	**HP**										
TT50	**HP**	**HP**	**HP**	**HP**	**HP**									
TT85	**HP**	**HP**	**HP**	**HP**	**HP**	**HP**								
TT90	**HP**	**HP**	**HP**	**HP**	**HP**	**HP**	**HP**							
TT95	**HP**	**HP**	**HP**	**HP**	**HP**	**HP**	**HP**	**HP**						
BT	MP	**HP**	MP	MP	MP	MP	MP	**HP**	**HP**					
BTI	MN		MN	MN	MN	MN	LN	LN	LN	MP				
PTI	MN		MN	MN	MN	MN	LN	LN	LN	LP	**HP**			
TTI	MP	LN	LP	MP	MP	LP	LP	LP	LP	MN	HN	MN		
TTV90	MP	**HP**	MP	MP	MP	MP	**HP**	**HP**	**HP**	**HP**	LP	LP	MN	
TTV85	MP	**HP**	MP	MP	MP	MP	**HP**	**HP**	**HP**	**HP**	LP	LP	MN	**HP**
50 Or 55 mph														
MaxTT	MP													
ATT	**HP**	**HP**												
TT10	**HP**	MP	**HP**											
TT15	**HP**	MP	**HP**	**HP**										
TT50	**HP**	**HP**	**HP**	**HP**	**HP**									
TT85	**HP**	**HP**	**HP**	**HP**	**HP**	**HP**								
TT90	**HP**	**HP**	**HP**	**HP**	**HP**	**HP**	**HP**							
TT95	MP	**HP**	**HP**	**HP**	**HP**	**HP**	**HP**	**HP**						
BT	MP	**HP**	**HP**	MP	MP	MP	**HP**	**HP**	**HP**					
BTI		MP	LP			LP	MP	MP	MP	MP				
PTI		MP	LP				LP	LP	LP	MP	**HP**			
TTI	LN	MN	MN	LN	LN	LN	MN	MN	MN	MN	HN	MN		
TTV90	MP	**HP**	**HP**	MP	MP	**HP**	**HP**	**HP**	**HP**	**HP**	MP	LP	MN	
TTV85	MP	**HP**	**HP**	MP	MP	**HP**	**HP**	**HP**	**HP**	**HP**	MP	LP	MN	**HP**
60 Or 65 mph														
MaxTT	MP													
ATT	**HP**	**HP**												
TT10	**HP**	MP	**HP**											
TT15	**HP**	MP	**HP**	**HP**										
TT50	**HP**	MP	**HP**	**HP**	**HP**									
TT85	MP	**HP**	**HP**	**HP**	**HP**	**HP**								
TT90	MP	**HP**	**HP**	MP	**HP**	**HP**	**HP**							
TT95	MP	**HP**	**HP**	MP	**HP**	**HP**	**HP**	**HP**						
BT	MP	**HP**	**HP**	MP	MP	MP	**HP**	**HP**	**HP**					
BTI		MP	MP	LP	LP	LP	MP	MP	MP	MP				
PTI		MP	LP			LP	LP	LP	MP	MP	**HP**			
TTI		MN	MN	LN	LN	LN	MN	MN	MN	MN	MN	LN		
TTV90	MP	**HP**	**HP**	MP	MP	**HP**	**HP**	**HP**	**HP**	**HP**	MP	LP	MN	
TTV85	LP	**HP**	**HP**	MP	MP	**HP**	**HP**	**HP**	**HP**	**HP**	MP	LP	MN	**HP**

are inconsistent and seem to vary with the considered percentile travel time measure, WoY, DoW, and the posted speed limit.

The two travel time variability measures (TTV90 and TTV85) are highly and positively correlated with each other.

There is moderate positive correlation between BT and BTI. Likewise, there is a low or moderate positive correlation between BT and PTI. However, there is a low or moderate negative correlation between BT and TTI (except when analyzed by WoY). A low or moderate positive correlation between BT and TTI was observed when analyzed by WoY. Most of the trends, except between BT and TTI by WoY, are fairly consistent when analyzed using the 25 categorized datasets.

There is a high positive correlation between BTI and PTI, but a moderate or high negative correlation between BTI and TTI. However, the correlation between PTI and TTI is not very consistent. It is no correlation, low negative correlation, or moderate negative correlation in all instances except when analyzed using Saturday 60 or 65 mph (96.6 or 104.6 kmph) or using WoY datasets. The correlation between PTI and TTI is highly positive when analyzed using WoY datasets.

The correlations involving travel time reliability measures are relatively more sensitive and dependent on the DoW, ToD, and the posted speed limit when compared to travel time measures or travel time variability measures. Therefore, additional analysis was performed using 32 categorized datasets based on the DoW, ToD, and the posted speed limit. As an example, Table 6 summarizes the correlations on a weekday (Wednesday), different times of the day, and the posted speed limit = 60 or 65 mph (96.6 or 104.6 kmph).

The correlations between travel time measures, BT and travel time variability measures are moderately or highly positive when analyzed using the 32 categorized datasets based on the DoW, ToD, and the posted speed limit. They are consistent with the previous 25 datasets. The correlations between travel time measures and BTI and PTI are also consistent with the previous 25 datasets. However, the correlations between travel time measures and TTI are low or moderately positive when analyzed using the categorized datasets based on the DoW, ToD, and low posted speed limits (≤35 mph [56.3 kmph] and 40 or 45 mph [64.4 or 72.4 kmph]). They are low or moderately negative when analyzed using the categorized datasets based on the DoW, ToD, and the posted speed limit = 50 or 55 mph (80.5 or 88.5 kmph). Contrarily, they are negative during the morning and evening peak hours and positive during off-peak hours of a weekday (Wednesday) but do not follow a specific trend on the weekend day (Saturday) when analyzed using DoW, ToD, and the posted speed limit = 60 or 65 mph (96.6 or 104.6 kmph) datasets.

The correlations between BTI, PTI, and PTI are similar when analyzed using the 32 categorized datasets based on the DoW, ToD, and the posted speed limit and compared with the previous 25 datasets, except on weekday (Wednesday) off-peak hours and the posted speed limit = 60 or 65 mph (96.6 or 104.6 kmph).

Percentages based on scores associated with correlations

Figure 2 summarizes the percentages based on scores combined considering year, DoW, DoW and ToD, WoY, and DoW and the posted speed limit. Data bars are also added to visualize the percentages based on scores associated with the correlations from these 25 categorized datasets.

Except for the correlation between MinTT and MaxTT, the percentage scores are greater than 85 between travel time measures. The percentage scores vary from 60 to 91 between travel time measures and BT, TTV90, and TTV85.

Table 6. Correlations – wednesday, different times of the day, posted speed limit = 60 or 65 mph (96.6 or 104.6 kmph).

Measure	MinTT	MaxTT	ATT	TT10	TT15	TT50	TT85	TT90	TT95	BT	BTI	PTI	TTI	TTV90
Wednesday 8-9 AM														
MaxTT	MP													
ATT	**HP**	**HP**												
TT10	**HP**	MP	**HP**											
TT15	**HP**	MP	**HP**	**HP**										
TT50	**HP**	MP	**HP**	**HP**	**HP**									
TT85	MP	**HP**	**HP**	MP	**HP**	**HP**								
TT90	MP	**HP**	**HP**	MP	**HP**	**HP**	**HP**							
TT95	MP	**HP**	**HP**	MP	MP	**HP**	**HP**	**HP**						
BT	MP	**HP**	**HP**	MP	MP	**HP**	**HP**	**HP**	**HP**					
BTI		MP	LP			LP	MP	MP	MP	MP				
PTI		MP	LP				LP	LP	LP	MP	**HP**			
TTI		MN	MN	LN	LN	MN	MN	MN	MN	MN	MN	LN		
TTV90	MP	**HP**	**HP**	MP	MP	**HP**	**HP**	**HP**	**HP**	**HP**	MP	LP	MN	
TTV85	MP	**HP**	**HP**	MP	MP	**HP**	**HP**	**HP**	**HP**	**HP**	MP	LP	MN	**HP**
Wednesday 12-1 PM														
MaxTT	MP													
ATT	**HP**	MP												
TT10	**HP**	MP	**HP**											
TT15	**HP**	MP	**HP**	**HP**										
TT50	**HP**	MP	**HP**	**HP**	**HP**									
TT85	**HP**	MP	**HP**	**HP**	**HP**	**HP**								
TT90	**HP**	MP	**HP**	**HP**	**HP**	**HP**	**HP**							
TT95	**HP**	MP	**HP**	**HP**	**HP**	**HP**	**HP**	**HP**						
BT	LP	MP	MP	LP	LP	LP	LP	MP	**HP**					
BTI		MP	LP	LP	LP		LP	LP	MP	**HP**				
PTI	LP	MP	LP	LP	LP	LP	LP	LP	MP	**HP**	**HP**			
TTI	LP	MP	LP	LP	LP	LP	LP	LP	MP	MP	MP	**HP**		
TTV90	MP	MP	MP	MP	MP	MP	MP	**HP**	**HP**	MP	MP	MP	MP	
TTV85	**HP**	MP	**HP**	**HP**	**HP**	**HP**	**HP**	**HP**	**HP**	MP	LP	LP	LP	**HP**
Wednesday 5-6 PM														
MaxTT	MP													
ATT	**HP**	**HP**												
TT10	**HP**	MP	**HP**											
TT15	**HP**	MP	**HP**	**HP**										
TT50	**HP**	**HP**	**HP**	**HP**	**HP**									
TT85	MP	**HP**	**HP**	**HP**	**HP**	**HP**								
TT90	MP	**HP**	**HP**	**HP**	**HP**	**HP**	**HP**							
TT95	MP	**HP**	**HP**	MP	**HP**	**HP**	**HP**	**HP**						
BT	MP	**HP**	**HP**	MP	MP	**HP**	**HP**	**HP**	**HP**					
BTI		MP	MP		LP	LP	MP	MP	MP	MP				
PTI		MP	LP				LP	LP	MP	MP	**HP**			
TTI		MN	MN	LN	LN	MN	MN	MN	MN	MN	HN	MN		
TTV90	MP	**HP**	**HP**	MP	MP	**HP**	**HP**	**HP**	**HP**	**HP**	MP	LP	MN	
TTV85	MP	**HP**	**HP**	MP	MP	**HP**	**HP**	**HP**	**HP**	**HP**	MP	LP	MN	**HP**
Wednesday 9-10 PM														
MaxTT	MP													
ATT	**HP**	MP												
TT10	**HP**	MP	**HP**											
TT15	**HP**	MP	**HP**	**HP**										
TT50	**HP**	MP	**HP**	**HP**	**HP**									
TT85	**HP**	MP	**HP**	**HP**	**HP**	**HP**								
TT90	**HP**	MP	**HP**	**HP**	**HP**	**HP**	**HP**							
TT95	**HP**	**HP**	**HP**	**HP**	**HP**	**HP**	**HP**	**HP**						
BT	MP	MP	MP	MP	MP	MP	MP	MP	MP					
BTI		LP						LP	LP	**HP**				
PTI		LP						LP	MP	**HP**	**HP**			
TTI	LP	MP	LP	LP	LP	LP	LP	LP	LP	MP	MP	MP		
TTV90	MP	MP	**HP**	MP	MP	MP	**HP**	**HP**	**HP**	**HP**	MP	MP	LP	
TTV85	**HP**	**HP**	**HP**	**HP**	**HP**	**HP**	**HP**	**HP**	**HP**	MP	MP	MP	LP	**HP**

BT, TTV90, and TTV85 are highly correlated with each other (percentage score = 100). However, the percentage scores are less than 41 between travel time measures and BTI, PTI, and TTI. The percentage scores between BT and BTI, BT and PTI, and BT and TTI are 69, 59,

Measure	MinTT	MaxTT	ATT	TT10	TT15	TT50	TT85	TT90	TT95	BT	BTI	PTI	TTI	TTV90
MaxTT	76													
ATT	100	99												
TT10	100	87	100											
TT15	100	87	100	100										
TT50	100	95	100	100	100									
TT85	99	99	100	100	100	100								
TT90	99	100	100	99	100	100	100							
TT95	97	100	100	99	100	100	100	100						
BT	60	81	71	67	67	67	75	79	87					
BTI	41	28	39	37	37	37	33	37	37	69				
PTI	33	31	36	33	33	32	35	33	25	59	100			
TTI	41	28	37	40	39	33	36	31	31	60	88	55		
TTV90	65	83	72	67	67	71	83	87	91	100	60	37	64	
TTV85	64	77	72	67	67	71	84	85	88	100	52	36	67	100

Figure 2. Percentage scores – outputs by year, DoW, ToD, WoY and posted speed limit.

Measure	MinTT	MaxTT	ATT	TT10	TT15	TT50	TT85	TT90	TT95	BT	BTI	PTI	TTI	TTV90
MaxTT	71													
ATT	100	92												
TT10	100	81	100											
TT15	100	83	100	100										
TT50	100	89	100	100	100									
TT85	98	94	100	99	100	100								
TT90	97	96	100	99	100	100	100							
TT95	97	98	100	98	99	100	100	100						
BT	58	81	76	61	64	71	79	84	93					
BTI	36	40	46	40	41	39	45	46	46	72				
PTI	33	40	38	34	34	36	38	40	42	64	99			
TTI	41	38	48	44	43	44	45	42	45	53	79	50		
TTV90	67	85	81	71	71	80	89	94	95	98	51	32	54	
TTV85	69	81	83	73	73	79	92	92	94	96	44	27	61	100

Figure 3. Percentage scores – outputs by DoW, ToD, and posted speed limit.

and 60, respectively. Likewise, the percentage score between BTI and PTI is 100, while it is 88 between BTI and TTI.

Figure 3 summarizes the percentages based on scores combined considering DoW, ToD, and the posted speed limit. Data bars are also added to visualize the percentages based on scores associated with the correlations from the 32 categorized datasets.

Except for the correlation between MinTT and MaxTT, the percentage scores are greater than 81 between travel time measures. The percentage scores vary from 58 to 95 between travel time measures and BT, TTV90, and TTV85.

BT, TTV90, and TTV85 are highly correlated with each other (percentage score ≥96). However, the percentage scores are less than 48 between travel time measures and BTI, PTI, and TTI. The percentage scores between BT and BTI, BT and PTI, and BT and TTI are 72, 64, and 53, respectively. Likewise, the percentage score between BTI and PTI is 99, while it is 79 between BTI and TTI.

Some differences in the percentage scores are observed when Figures 2 and Figure 3 are compared with each other. While these differences are marginal, they indicate some sensitivity of the outputs based on travel time-based measure considered for analysis. The general trends in data bars and correlations are fairly consistent when both the figures are compared.

Discussion & conclusions

Congestion and delay occur regularly on many urban roads during weekdays. Motorists are interested in reliably reaching their destination on time, while practitioners strive to provide a reliable transportation system to the motorists. Literature documents several definitions of travel time measures, travel time reliability measures, and travel time variability measures. Exploring the correlations between these measures to select a set of suitable measures to assess transportation system performance, identifying solutions, and implementing them proactively is vital. Therefore, this research focuses on categorizing data, exploring correlations, and identifying a set of suitable travel time performance measures which help practitioners to incorporate them in travel time-based studies and transportation system assessment.

Pearson correlation coefficient matrices were generated using the categorized datasets and to explore the correlations. The correlations and percentages based on scores associated with these correlations indicate fairly consistent trends irrespective of the categorized dataset considered for analysis. Therefore, it is concluded that the outcomes may be similar in most instances, though, travel time-based measures yield different outputs.

The results indicate that travel time measures are correlated with each other. They are at least moderately correlated with BT, TTV90, and TTV85. However, they are not correlated with BTI, PTI, and TTI. BT is moderately or highly correlated with BTI, PTI, and TTI. BTI is positively correlated with PTI but negatively correlated with TTI. While the correlations between travel time measures are consistent, some differences were observed in the correlations between travel time reliability measures when compared with findings by DoW and ToD from Pulugurtha et al. (2015, 2016). This could be attributed to the larger sample size and relatively recent data used in this research. Further, the lack of consistency in correlations associated with travel time reliability measures could be due to skewness in the data. Pu (2011) opined that the use of BTI is not always appropriate due to such skewness in the data.

The correlation between travel time measures is positive. This indicates that an increase in a travel time measure (for example, the ATT) on a road link would result in an increase in another travel time measure (for example, the 95th percentile travel time or MaxTT) on the same road link.

The ATT is highly correlated with all the travel time measures. It can be used to assess the performance of a road link or in before-after evaluations (for example, compare the performance on a road link before and after constructing a project). It can also be used by the motorists as the expected travel time. However, unless it is converted to ATT per unit distance, it cannot be used to compare between road links for allocation of resources. Furthermore, its correlation with BTI, PTI, and TTI is generally low.

Both, TTV90 and TTV85 are moderately or highly correlated with each other and travel time measures. BT was observed to be moderately or highly correlated with travel time measures, travel time reliability measures, and travel time variability measures. Like TTV90 and TTV85, BT (95th percentile travel time minus ATT) can also be considered as a travel time variability measure. While TTV90 and TTV85 capture variability between high and low travel time observations, BT captures variability between high and average travel time observations. BT can be used along with the ATT by DoW and ToD to plan and reach the destination on-time for most of the trips. Practitioners could also plan and implement solutions (transportation projects/alternatives) to minimize the BT on a road link. However, it does not account for the proportional increase in the 95th percentile travel time with an increase in the ATT based on the posted speed limit, ToD, and DoW. BTI, the ratio of BT to ATT, helps address this limitation and can be used to identify unreliable road links or compare road links for allocation of resources.

Wakabayashi and Matsumoto (2012) suggested that the combination of ATT and an appropriate travel time reliability measure is very important for assessing the route reliability properly. Based on the findings from this research, it is also concluded that the combination of ATT, BT, and BTI is very important for motorists to plan their trips and for practitioners to assess the transportation system performance and efficiently allocate resources.

The sample size used in this research is reasonably large. Such a large sample size can create a lot of noise and scatter due to the influence of exogenous variables that vary from one link to another link in the transportation network (for example, traffic volume, number of lanes, lane widths, presence of driveways, etc.). These details were not readily available for most of the road links during the study years. Clustering data based on these influential exogenous variables and exploring the correlations might provide a better understanding of the effect of travel time-based measures on outputs, outcomes, and decisions. The applicability of a travel time-based measure could also depend on the type of transportation project/alternative (for example, increase capacity by adding a lane, toll road, etc.). Further, some relations could be non-linear and spatially dependent. These merit research in the future.

Acknowledgements

This paper is prepared using data collected for research projects supported by the United States Department of Transportation (USDOT) - Office of the Assistant Secretary for Research and Technology (USDOT/OST-R) and the North Carolina Department of Transportation (NCDOT). The authors acknowledge and thank the NCDOT and Regional Integrated Transportation Information System (RITIS) for their help with data required for this research.

Disclaimer

This paper is disseminated in the interest of information exchange. The views, opinions, findings, and conclusions reflected in this paper are the responsibility of the authors only and do not represent the official policy or position of the USDOT/OST-R, NCDOT, or any other State, or the University of North Carolina at Charlotte or other entity. This paper does not constitute a standard, specification, or regulation.

Disclosure statement

No potential conflict of interest was reported by the authors.

ORCID

Srinivas Pulugurtha http://orcid.org/0000-0001-7392-7227

References

Abdel-Aty, M. A., Kitamura, R., & Jovanis, P. P. (1995). Investigating effect of travel time variability on route choice using repeated-measurement stated preference data. *Transportation Research Record: A Journal of the Transportation Research Board*, *1493*(1), 39–45.http://onlinepubs.trb.org/Onlinepubs/trr/1995/1493/1493-005.pdf

Asakura, Y., & Kashiwadani, M. (1991). Road network reliability caused by daily fluctuation of traffic flow. In *19th PTRC Summer Annual Meeting*, University of Sussex, United Kingdom.

Chen, A., Ji, Z., & Recker, W. (2002). Travel time reliability with risk-sensitive travelers. *Transportation Research Record: A Journal of the Transportation Research Board*, *1783*(1), 27–33. https://doi.org/10.3141/1783-04

Du, Z-P.., & Nicholson, A. (1997). Degradable transportation systems: Sensitivity and reliability analysis. Transportation Research Part B: Methodological, 31(3), 225–2317 doi:10.1016/S0191-2615(96)00023-9

Federal Highway Administration (FHWA). (2006). *Travel time reliability: Making it there on time, all the time*. https://ops.fhwa.dot.gov/publications/tt_reliability/TTR_Report.htm#:~:text=The%20travel%20time%20index%20represents,travel%20time%20that%20is%20necessary

Haitham, A. D., & Emam, B. (2006). New methodology for estimating reliability in transportation networks with degraded link capacities. *Journal of Intelligent Transportation Systems*, *10*(3), 117–129. https://doi.org/10.1080/15472450600793586

Iida, Y., & Wakabayashi, H. (1989). An approximation method of terminal reliability of road network using partial minimal path and cut sets. In *Transport Policy, Management & Technology towards 2001: Selected Proceedings of the Fifth World Conference on Transport Research*, p. 4.

Lomax, T., Schrank, D., Turner, S., & Margiotta, R. (2003). *Selecting travel reliability measures*. Texas Transportation Institute, Texas A&M University.

Lomax, T., Turner, T., & Margiotta, R. (2004). *Monitoring urban roadways in 2002: Using archived operations data for reliability and mobility measurement*. Texas Transportation Institute, Texas A&M University.

Lyman, K., & Bertini, R. (2008). Using travel time reliability measures to improve regional transportation planning and operations. *Transportation Research Record*, *2046*(1), 1–10. https://doi.org/10.3141/2046-01

Masinick, J., Teng, H., & Orochena, N. (2014). The impact of rubbernecking on urban freeway traffic. *Journal of Transportation Technologies*, *4*(1), 116–125. https://doi.org/10.4236/jtts.2014.41012

Pu, W. (2011). Analytic relationships between travel time reliability measures. *Transportation Research Record: A Journal of the Transportation Research Board*, *2254*(1), 122–130. https://doi.org/10.3141/2254-13

Pulugurtha, S. S., Duddu, V. R., Puvvala, R., Thokala, V. R., & Imran., M. S. (2015). Commercial remote sensing & spatial information (CRS & SI) technologies program for reliable transportation systems planning: Volume 2 - comparative evaluation of travel time related performance measures. *Report No. RITARS-12-H-UNCC-2, Prepared for The United States Department of Transportation, Office of the Assistant Secretary for Research and Technology*.

Pulugurtha, S. S., Duddu, V. R., & Thokala, V. R. 2016, January 10–14). Travel-time-based performance measures: Examining interrelationships and recommendations for analysis. *Transportation Research Board 95th Annual Meeting, Compendium of Papers*, Washington, DC.

Pulugurtha, S. S., & Mahanthi, S. S. B. (2016). Assessing spatial and temporal effects due to a crash on a freeway through traffic simulation. *Case Studies on Transport Policy Journal*, *4*(2), 122–132. https://doi.org/10.1016/j.cstp.2015.12.001

Puvvala, R. K., Pulugurtha, S. S., & Duddu, V. R. (2015, January 11–15). Cronbach's Alpha as a performance measure to assess link-level reliability. *Transportation Research Board 94th Annual Meeting, Compendium of Papers, DVD-ROM*, Washington, DC.

Sisiopiku, V. P., Islam., M. D. S., & Freeway Travel, A. (2012). Time reliability study. *International Journal of Engineering Research and Development*, *3*(10), 83–101.https://www.academia.edu/28832446/A_Freeway_Travel_Time_Reliability_Study
Tu, H., van Lint, H., & van Zuylen, H. (2007). The influence of road geometry on travel time variability. In *Proceedings of the 3rd International Symposium on Transport Network Reliability*, Vol. 1, Network Design II.
Wakabayashi, H. (2010). Travel time reliability indexes for highway users and operators. In *The 4th International Symposium on Transportation Network Reliability*, Minneapolis, MN.
Wakabayashi, H., & Matsumoto, Y. (2012). Comparative study on travel time reliability indexes for highway users and operators. *Journal of Advanced Transportation*, *46*(4), 318–339. https://doi.org/10.1002/atr.1194
Williams, B. M., Chase, R. T., Xu, Y., Kim, S., Craft, D., Rouphail, N., & Encarnacion, A. (2013). Mobility and reliability performance measurement. *Final Report Submitted to the North Carolina Department of Transportation*.