Average Speed Reliability Analysis Methods Applied on Las Vegas Arterials

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Abstract

Traffic conditions on arterials tend to be consistent during peak hours; yet, non-recurring events unpredictably affect these conditions. It is vital, however, for transportation planners as well as users of the facility to be able to assess traffic conditions. Therefore, a reliability performance measure is essential for evaluation. Reliability can take many measures. Various measures are chosen depending on the evaluation criteria. In this study, average speed as well as number of stops data for arterials in Las Vegas is used for evaluating reliability. Reliability assessment is conducted using five different approaches. Variability based on normalized standard deviation, analysis of variance (ANOVA), average time mean estimation, reliability as a measure of non-failures, and information Theory based approach are proposed. Each of which addresses a different measure of reliability.

INTRODUCTION

Travel time is the period of time spent by the road user traveling from one location to another. Travel times on arterials vary based on recurring or nonrecurring events. “Travel time reliability” is considered a good indication and performance measure describing the consistency of travel times on a certain roadway. Travel times were converted to average speeds in this study in order to eliminate the variability in distances among the different tested road segments. Traffic congestion on roadways not only increases travel time but also makes it more variable and unpredictable. It is considered to be one of the most important factors influencing the departure time of drivers (*4*). Study of travel time reliability can help in understanding this variation in travel time and create dependability and thereby aid in transportation system management (*5*) (*10*). Literature review suggests that statistical methods for defining reliability have been employed by many researchers and transportation agencies. In addition to the traditional reliability measures, this paper introduces confidence intervals, failure analysis method and information theory based approach. Section 2 describes the literature review. The analysis methods are explained in section 3 and are applied to two arterials in Las Vegas Charleston Boulevard and Craig. Section 4 and 5 summarize the results and conclusions respectively.

LITERATURE SURVEY

Transportation planning and operations performance measures have become vital for assessment (*1*). Berkow in (*2*) introduced new performance measures related to variability of service. Buffer and planning time indices were used as statistical reliability methods in a report prepared by Cambridge Systematic (*6*). An adaptive routing strategy, the stochastic on-time arrival (SOTA) algorithm, is developed by Nie and Fan in (*9*), which introduces least-expected travel time as a reliability performance measure. The relationship between travel time and level of service is studied by Chen et. al. in (*5*). It was discussed that the 90 percentile travel integrates the average and variability into a single measure. Furthermore, travel uncertainty reduction by travel time information was attempted using ITS.

Oh and Chung (*10*) address travel time variability using data from Orange County, California. Their study was conducted for day-to-day variability, within-day variability, and spatial variability. They also found correlation between travel time and standard deviation. Various reliability measures were studied by Bogers in (*4*). Furthermore, it was noted that the application criteria is to determine what reliability measure should be considered. Lam (*12*) uses the median of travel times as a measure of reliability. A travel time reliability ratio is defined in Black’s study (*3*). It gives an assessment of the extra time travelers should buffer based on variance (*4*). Skew is defined in Van Lint’s paper (*8*) as a measure of the asymmetry of the travel time distribution. Such measure was found to be significant in this study.

Various measures can be drawn from travel times; the appropriate measure must be chosen based on the assessment criteria of the system to be evaluated. In this study, travel times are converted to average speeds. Five different reliability approaches are used to analyze average speed data on the arterials in Las Vegas area. Variance, ANOVA, confidence intervals, failure analysis, and information theory based approaches will be used and results will be analyzed.

CASE STUDY-AVERAGE SPEED RELIABILITY ON ARTERIALS IN THE LAS VEGAS AREA

Map of Arterials Covered

Data Description

The operations data for some major street segments in the Las Vegas Metropolitan area were collected by the Regional Transportation Commission of Southern Nevada- FAST. FAST staff makes several travel runs with Jamar GPS equipment on a particular arterial. Travel run reports are made using the Jamar software and are printed to a pdf file. The data collected summarizes the details accumulated for the various runs used in this study. Information recorded include travel times (start and stop times), length of the segment, number of stops, average speed and total delay for each section within the tested segment for every run. The time

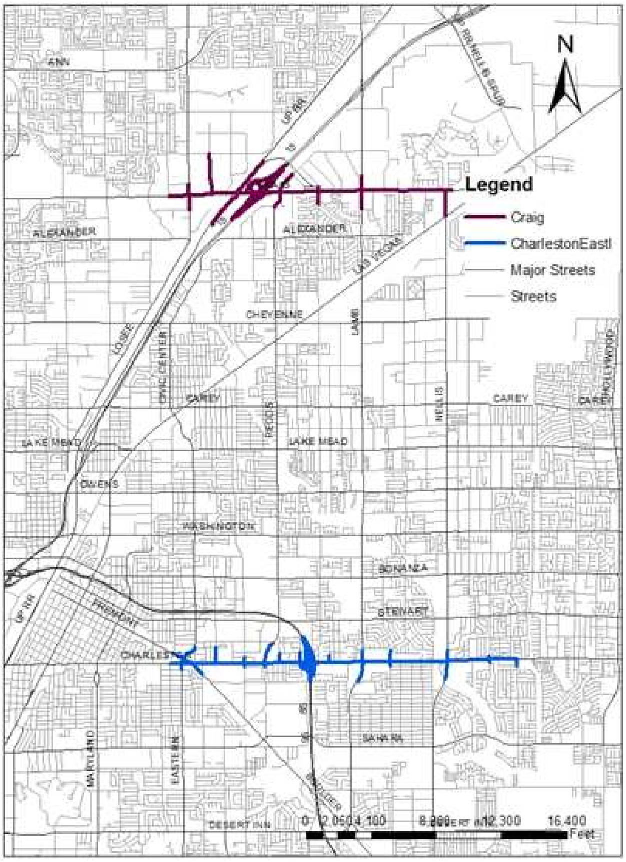


FIGURE 1 Arterials Covered in the Las Vegas Area

period of runs spans three different time of day AM, Midday and PM for the year 2008. For the purpose of this study, two arterials were chosen for analysis based on data availability, Craig and Charleston East as shown in the Map in Figure 1.

Data Reliability Analysis

The term “Reliability” suggests repeatability or dependability. For a random experiment this would mean that the results of an experiment are repeatable. In terms of average speed, this would mean that if average speed is measured repeatedly on a section we get comparable values. In general, repeatability of travel time on arterials could be framed in terms of segments, runs, etc. Thus, average speed reliability is determined by conducting analysis on data measured for a certain roadway.

In this study five different approaches are used in obtaining various reliability measures:

- Variability, based on normalized standard deviation,
- Analysis of Variance (ANOVA)
- Average Speed Mean Estimation,
- Reliability as a measure of non-failures, and
- Information Theory based Approach

Variability, Based on Normalized Standard Deviation (NSTD)

For a given set of average speed data on an arterial, statistical mean can be calculated given by Equation 1. however, average speed mean is not sufficient since it does not convey any information about how volatile the average speeds are on the studied highway segment. Therefore, calculations of the standard deviation given in Equation 2 are necessary in order to understand the distributive nature of avrage speeds (*13*). Clearly, a lower standard deviation indicates a higher concentration of data about the mean illustrating closer values to the mean; thus a more reliable roadway segment.

$$\bar{v} = \frac{\sum_{i=0}^{n} v_i}{N} \tag{1}$$

$$\sigma = \sqrt{\frac{\sum_{i=0}^{n}(v_i - \bar{v})^2}{N}} \tag{2}$$

$$\sigma_N = \frac{\sigma}{\bar{v}} \tag{3}$$

where

v_n : Average speed on a certain highway segment
$\bar{v}$: Average speed for the given data set
σ : Standard deviation of avrage speeds for the given data set
N : Total number of data points in the data set
σ_N : Normalized standard deviation

Tables 1(a) and 1(b) show the mean, variance, standard deviation, and normalized standard deviation for various segments and runs, respectively, on Charleston and Craig. Figures 2(a) and 2(b) show the normalized standard deviation.

The graphs in Figures 2(c) and 2(d) illustrate the trend of the normalized standard deviation with respect to various runs at three different times of day AM, Midday, and PM.

Number of stops were also analyzed. Variability for segments and runs are shown in Tables 2(a) and 2(b)

Analysis of Variance (ANOVA)

Using ANOVA, the mean of various data sets were compared for hypothesis testing. A null hypothesis is defined by determining a desired α value representing the variation between the various groups tested. If the ratio of the variance among the samples means to the variance within the samples F is less than F critical F_α value, then the null hypothesis (H_0) is accepted indicating that the variation in mean falls within the desired regions. Otherwise, the alternate hypothesis (H_1)is accepted.

$$\begin{aligned} \mathrm{H}_0&: \mathrm{F} \leq \mathrm{F}_\alpha \\ \mathrm{H}_1&: \mathrm{F} > F_\alpha \end{aligned} \tag{4}$$

where:

H_0 : Null hypothesis
H_1 : Alternative hypothesis

In this study, the null hypothesis tested stated that average speeds for all considered data sets are very close in value for all runs. Table 3(a) shows that the hypothesis was accepted for run analysis; however, it is rejected for segment analysis for α = 0.05. Conclusion can be drawn that average speeds for runs

TABLE 1 Statistical values for Charleston and Craig

(a) Segments

		Segment															
	Statistics	Estrn	Fremont	28th	Mojave	Pecos	Sandhill	95 W	95 E	Sacr.	Lamb	Marion	Nellis	Christy	Sloan	Tree Ln	Hlywd
Charleston	Mean		26.10	36.79	30.43	36.98	36.49	26.98	30.96	30.79	21.43	32.50	31.23	37.50	31.21	31.34	35.77
	V		16.55	26.11	74.85	40.71	45.36	184.66	109.32	143.02	96.88	38.35	54.32	27.33	92.44	76.81	41.05
	Std		4.07	5.11	8.65	6.38	6.74	13.59	10.46	11.96	9.84	6.19	7.37	5.23	9.61	8.76	6.41
	N-Std		0.16	0.14	0.28	0.17	0.18	0.50	0.34	0.39	0.46	0.19	0.24	0.14	0.31	0.28	0.18
		Losee	Berg	Donovan	Donovan	W. I-15	E. I-15	Pecos	Walnut	Lamb	Nellis	-	-	-	-	-	-
Craig	Mean		23.20	15.11	25.07	28.97	27.77	17.36	36.05	38.43	34.72	-	-	-	-	-	-
	V		105.94	100.78	29.06	45.26	68.52	99.16	66.60	65.93	40.88	-	-	-	-	-	-
	Std		10.29	10.04	5.39	6.73	8.28	9.96	8.16	8.12	6.39	-	-	-	-	-	-
	N-Std		0.44	0.66	0.21	0.23	0.30	0.57	0.23	0.21	0.18	-	-	-	-	-	-

(b) Runs

		Runs																					
		AM							Midday								PM						
	Statistics	1.0	2.0	3.0	4.0	5.0	6.0	7.0	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	1.0	2.0	3.0	4.0	5.0	6.0	7.0
Charleston	Mean	29.6	34.0	33.8	30.8	33.1	34.5	32.5	36.1	34.7	30.9	30.9	28.1	29.3	35.7	36.0	26.5	28.3	27.7	34.6	30.5	31.1	30.1
	V	38.9	45.5	63.2	89.5	45.5	43.2	65.7	46.6	68.4	99.0	65.3	148.3	125.9	38.9	71.6	157.1	164.9	129.0	90.2	97.3	88.4	86.2
	Std	6.2	6.7	7.9	9.5	6.7	6.6	8.1	6.8	8.3	9.9	8.1	12.2	11.2	6.2	8.5	12.5	12.8	11.4	9.5	9.9	9.4	9.3
	N-Std	0.2	0.2	0.2	0.3	0.2	0.2	0.2	0.2	0.2	0.3	0.3	0.4	0.4	0.2	0.2	0.5	0.5	0.4	0.3	0.3	0.3	0.3
		AM							Midday							PM							
		1.0	2.0	3.0	4.0	5.0	6.0	7.0	1.0	2.0	3.0	4.0	5.0	6.0	7.0	1.0	2.0	3.0	4.0	5.0	6.0	7.0	
Craig	Mean	28.6	29.0	21.7	22.7	26.7	22.8	23.0	23.3	24.2	25.5	26.3	27.7	23.7	30.2	31.3	29.8	25.1	30.3	35.0	35.3	33.4	
	V	271.0	186.0	168.4	161.8	15.5	129.0	70.9	172.9	148.5	186.6	161.1	61.9	67.7	76.5	72.1	103.3	176.6	132.1	118.0	130.1	78.5	
	Std	11.6	13.6	13.0	12.7	3.9	11.4	8.4	13.1	12.2	13.7	12.7	7.9	8.2	8.7	8.5	10.2	13.3	11.5	10.9	11.4	8.9	
	N-Std	0.4	0.5	0.6	0.6	0.1	0.5	0.4	0.6	0.5	0.5	0.5	0.3	0.3	0.3	0.3	0.3	0.5	0.4	0.3	0.3	0.3	

are very close in value; yet, variances of segments averages for the arterial as a whole are not consistant. Analysis of variance for number of stops are presented in 3(b). It shows that number of stops for segments is not reliable due to significant variations in mean. However, when the whole street is considered in runs, then on average number of stops is similar.

Average Speed Estimation

Average of measured average speeds of the sample data $\bar{v}$ may or may not reflect an accurate measure of the actual population mean μ (absolutely every average speed that existed). The actual average speed mean can be estimated using t distribution (since actual population variance is unknown) with a certain confidence interval as in Equation 5

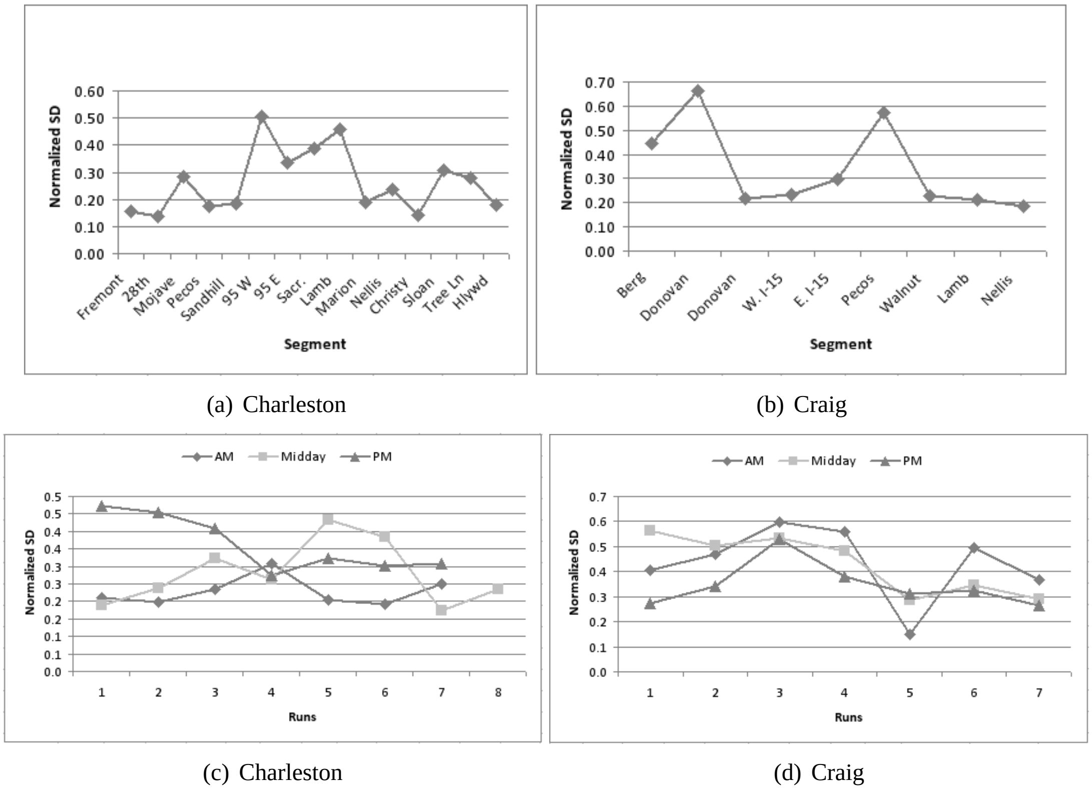
$$1-\alpha = 95\%$$
$$t = \frac{\bar{v}-\mu}{\sigma/\sqrt{n}}$$
95% Confidence intervals:
$$\Pr(\bar{v} - t_{\alpha/2}\frac{\sigma}{\sqrt{n}} < \mu < \bar{v} + t_{\alpha/2}\frac{\sigma}{\sqrt{n}}) = 0.95 \quad (5)$$

where

$\bar{v}$: Average speed for the given data set

σ : Standard deviation of average speeds for the given data set

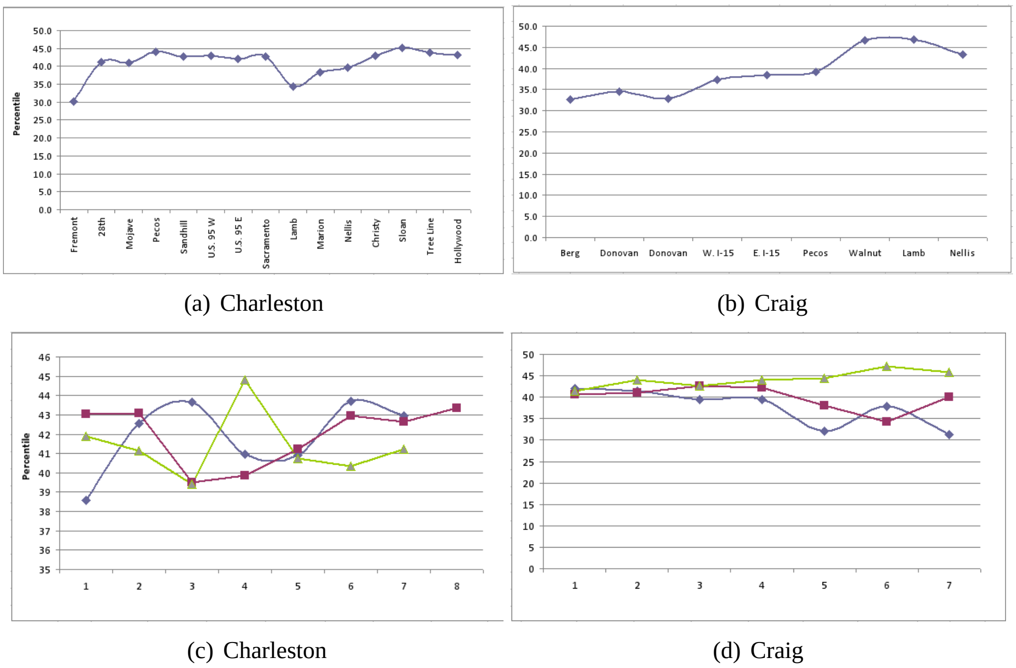
Table 4(a) shows the estimation of average speeds with 95 percent confidance and the 95th percentile for the various segments and runs of Charleston and Craig. The 95th percentiles for both streets are depicted in Figures 3(a), 3(b), 3(c), and 3(d).



(a) Charleston (b) Craig

(c) Charleston (d) Craig

FIGURE 2 Normalized standard deviation for segments and runs



(a) Charleston (b) Craig

(c) Charleston (d) Craig

FIGURE 3 The 0.95 percentile for segments and runs

Reliability as a measure of non-failures

One can perceive average speed reliability, R, as the probability of success of a certain route. This method provides probability of the extremes (pass or fail) defined in Equation 7. Success can take various meanings;

TABLE 2 Statistical values for stops on Charleston and Craig

(a) Segments

		Segment							
	Statistics	Eastern	Fremont	28th	Mojave	Pecos	Sandhill	U.S. 95 W	U.S. 95 E
Charleston	Mean		0.00	0.05	0.41	0.05	0.18	0.23	0.05
Charleston	V		0.00	0.05	0.25	0.05	0.16	0.18	0.05
Charleston	STD		0.00	0.21	0.50	0.21	0.39	0.43	0.21
Charleston	NSTD		0.00	4.69	1.23	4.69	2.17	1.89	4.69
		Losee	Berg	Donovan	Donovan	W. I-15	E. I-15	Pecos	Walnut
Craig	Mean		0.76	1.14	0.00	0.05	0.38	0.86	0.24
Craig	V		1.49	0.73	0.00	0.05	0.25	0.13	0.19
Craig	STD		1.22	0.85	0.00	0.22	0.50	0.36	0.44
Craig	NSTD		1.60	0.75	0.00	4.58	1.31	0.42	1.83
		Sacrame	Lamb	Marion	Nellis	Christy	Sloan	Tree Line	Hlywd
Charleston	Mean	0.32	0.86	0.09	0.64	0.14	0.55	0.55	0.64
Charleston	V	0.51	0.41	0.09	0.34	0.12	0.26	0.26	0.24
Charleston	STD	0.72	0.64	0.29	0.58	0.35	0.51	0.51	0.49
Charleston	NSTD	2.25	0.74	3.24	0.91	2.58	0.93	0.93	0.77
		Lamb	Nellis	-	-	-	-	-	-
Craig	Mean	0.29	0.57	-	-	-	-	-	-
Craig	V	0.21	0.26	-	-	-	-	-	-
Craig	STD	0.46	0.51	-	-	-	-	-	-
Craig	NSTD	1.62	0.89	-	-	-	-	-	-

(b) Runs

	Statistics	**Runs**							
		AM							
		1	2	3	4	5	6	7	
Charleston	Mean	0.40	0.20	0.13	0.40	0.13	0.20	0.40	
Charleston	V	0.2571	0.17	0.12	0.26	0.12	0.17	0.26	
Charleston	STD	0.5071	0.41	0.35	0.51	0.35	0.41	0.51	
Charleston	NSTD	1.2677	2.07	2.64	1.27	2.64	2.07	1.27	
		AM							
		1	2	3	4	5	6	7	
Craig	Mean	0.3333	0.44	0.78	0.78	0.44	0.89	0.56	
Craig	V	0.5	1.03	0.94	1.19	0.28	0.61	0.53	
Craig	STD	0.7071	1.01	0.97	1.09	0.53	0.78	0.73	
Craig	NSTD	2.1213	2.28	1.25	1.41	1.19	0.88	1.31	
		Midday							
		1	2	3	4	5	6	7	8
Charleston	Mean	0.07	0.33	0.27	0.33	0.47	0.47	0.27	0.13
Charleston	V	0.07	0.24	0.21	0.38	0.27	0.27	0.21	0.12
Charleston	STD	0.26	0.49	0.46	0.62	0.52	0.52	0.46	0.35
Charleston	NSTD	3.87	1.46	1.72	1.85	1.11	1.11	1.72	2.64
		Midday							
		1	2	3	4	5	6	7	
Craig	Mean	0.89	0.56	0.56	0.56	0.22	0.56	0.22	
Craig	V	1.11	0.53	0.53	0.53	0.19	0.28	0.19	
Craig	STD	1.05	0.73	0.73	0.73	0.44	0.53	0.44	
Craig	NSTD	1.19	1.31	1.31	1.31	1.98	0.95	1.98	
		PM							
		1	2	3	4	5	6	7	
Charleston	Mean	0.33	0.53	0.40	0.27	0.47	0.40	0.33	
Charleston	V	0.24	0.70	0.40	0.21	0.41	0.40	0.24	
Charleston	STD	0.49	0.83	0.63	0.46	0.64	0.63	0.49	
Charleston	NSTD	1.46	1.56	1.58	1.72	1.37	1.58	1.46	
		PM							
		1	2	3	4	5	6	7	
Craig	Mean	0.33	0.22	0.67	0.33	0.22	0.22	0.22	
Craig	V	0.25	0.19	0.50	0.25	0.19	0.19	0.19	
Craig	STD	0.50	0.44	0.71	0.50	0.44	0.44	0.44	
Craig	NSTD	1.50	1.98	1.06	1.50	1.98	1.98	1.98	

in terms of average speed, a roadway segment success can be defined as whether the actual average speed is below or above a desired average speed v_d defined in Equation 6.

TABLE 3 Analysis of variance

(a) Speeds

Street	ANOVA results	Segment	Run
Charleston	F_{obs}	6.41	1.48
	P	2.40E-11	0.08
	F_{crit}	1.72	1.59
Craig	F_{obs}	20.03	1.27
	P	1.82E-21	0.20
	F_{crit}	1.99	1.63

(b) Stops

Street	ANOVA (	Segment-w	Run-wise
Charleston	F_{obs}	8.34	0.96
	P	2.88E-15	0.52
	F_{crit}	1.72	1.59
Craig	F_{obs}	8.10	1.14
	P	3.81E-09	0.31
	F_{crit}	2.00	1.64

$$v_d = v_{ff} + v_{th} \tag{6}$$

$$R_i = \frac{S_T}{N} \tag{7}$$

where

v_d : Desired average speed
v$_{ff}$: Free flow average speed
v_{th} : Average speed Threshold, ex: 5 min
N : Sample size
S_T : Total number of successes, where v $\geq v_d$

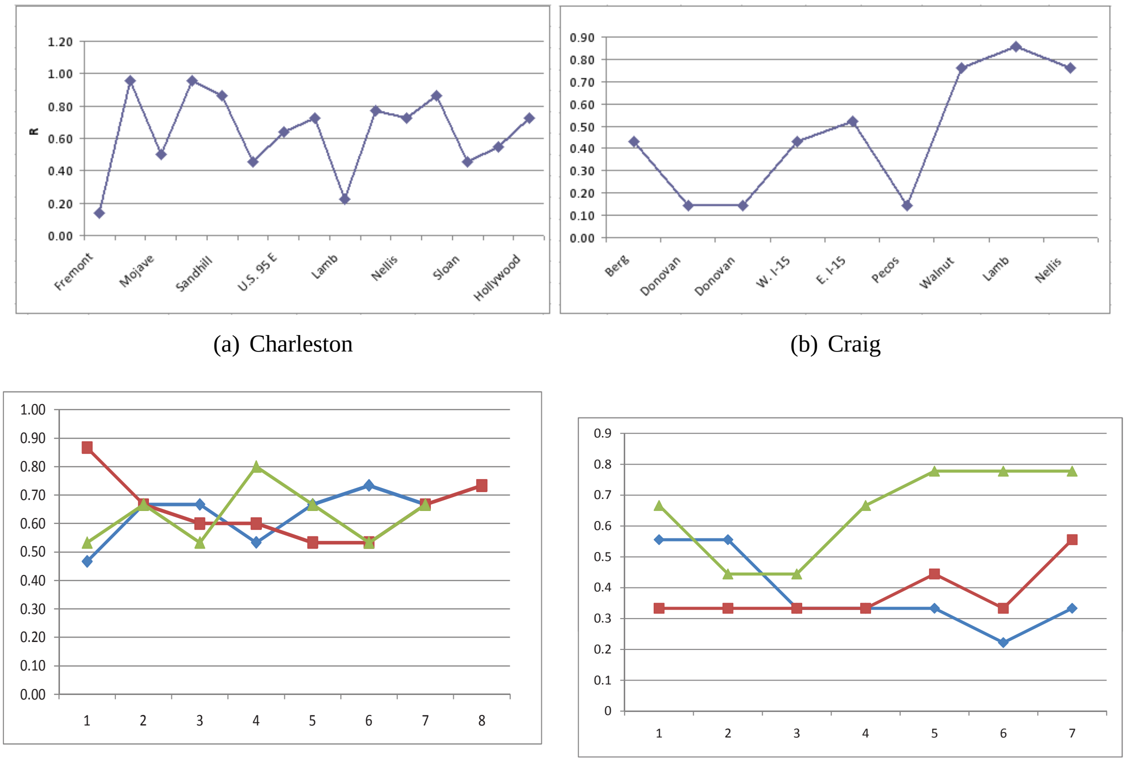
Using this method, reliability of a roadway segment R_s that consists of multiple contiguous segments R_1, $R_2 \ldots R_n$ is determined as implied by Equation 8 (7). However, this is true only if the roadway segments are independent. Therefore, further analysis must be performed in order to determine the reliability of a network.

$$R_s = \prod_{i=1}^{n} R_i \tag{8}$$

Tables 5(a) and 5(b) show the reliability obtained as a result of non-failure analysis. The plots in Figures 4(a), 4(b), 4(c), and 4(d) show the trend of the reliability for segments and runs for both arterials (Charleston boulevard and Craig road).

Number of stops are analyzed in Figure 6

Information Theory Based Approach
In information theory, the information content, H(n), contained in a certain massage is given by Equation 9 (*11*)



(a) Charleston (b) Craig

(c) Charleston (d) Craig

FIGURE 4 Reliability as a non failure measure

$$H(n) = \sum_{i=1}^{n} -P_i \log_2 P_i$$
$$P_i = n_i/n \tag{9}$$
$$n = \sum_{i=1}^{k} n_i$$

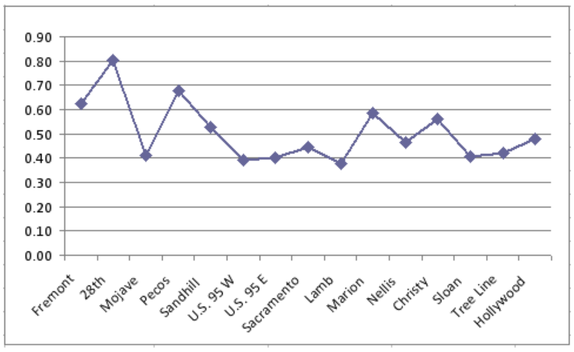
where
$H(n)$: Information Content
n : Total number of various average speeds
n_i : Frequency of average speeds that lie within a specified interval

In terms of average speeds, high information content indicates high variability in the considered segment of the roadway. Therefore, an inverse relation of the information content would be a reasonable measure of reliability. Such relation is given by Equation 10

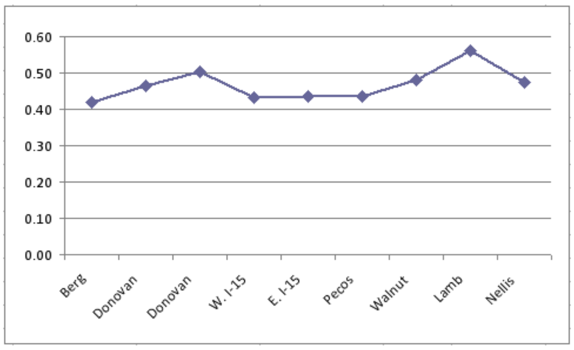
$$R = 1/H(x) \tag{10}$$

The results for Charleston boulevard and Craig road are shown in Tables 7(a) and 7(b). Information theory based reliability is depicted in the plots in Figures 5(a), 5(b), 5(c), and 5(d).

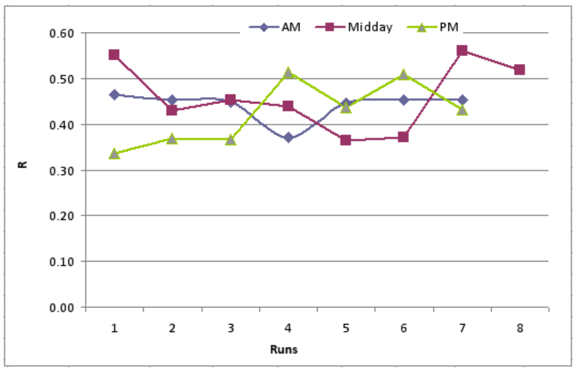
Number of stops are analyzed in Figure 8



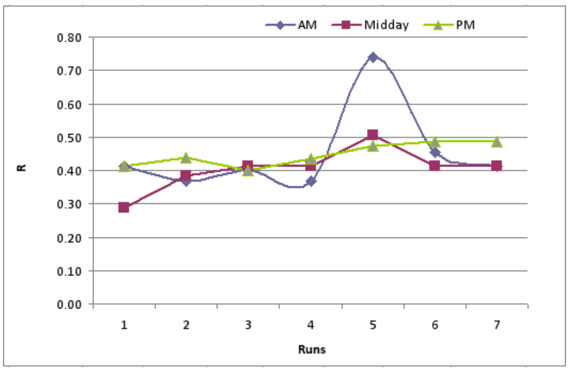
(a) Charleston



(b) Craig



(c) Charleston



(d) Craig

FIGURE 5 Reliability obtained from information theory methods

RESULTS AND DISSCUSSION

As depicted in the plots in figure 2, normalized standard deviation is relatively low (between 0.1 and 0.3) for some segments. However, it goes up to 0.5 and 0.7 in both Charleston and Craig, respectively, indicating inconsistency in average speeds within the segments as well as between segments. Normalized standard deviation varies taking values in ranges 0.2-0.5 and 0.1-0.6 for Charleston and Craig, respectively. This indicates a more consistent average speeds for Charleston, therefore higher reliability.

The plots in Figure 3 indicate the value below which 95 percent of the data fall. Charleston clearly shows a very low percentile for runs three and five for various times of day. It is also highly inconsistent. Craig shows consistency for some of the runs; yet, it becomes inconsistent after the fourth run.

The reliability within the segments as the success of the extreme measure highly varies. For certain segments in Charleston boulevard, reliability is higher than 0.8; however, it could be as low as 0.18 where as in Craig road, most segments reliability is less than 0.4. Even though previous results showed more consistency in average speeds for Craig, this reliability method addresses reliability in terms of success with respect to a desired average speed.

Plots in Figure 5 show consistency in reliability for Craig road ranging from 0.4 to 0.6 obtained from information theory based approach. However, reliability for Charleston varies highly ranging from 0.39 to 0.81. When considering runs, reliability for Charleston ranges between 0.33 to 0.6 and 0.3 and 0.72. Clearly, it is highly inconsistent among the various runs.

Clearly various reliability measures differ in results since every method evaluates different criteria. Variability, based on normalized standard deviation analyzes consistency in average speeds for a given road segment. Analysis of Variance (ANOVA) compares the various segments indicating any possible consistency between them. Average speed mean estimation predicts average speeds with a certain confidence level for the analyzed segment based on data history. Reliability as a measure of non-failures indicates success of a roadway segment with respect to a desired value. Finally, reliability based on information theory approach indicates the level of inconsistency by evaluating the frequency of data.

CONCLUSIONS

Five different methods were introduced in this paper as reliability measures, variability, based on normalized standard deviation, analysis of variance (ANOVA), average speed mean estimation, reliability as a measure of non-failures, and information theory based approach. The first method is a measure of variability which indicates consistency of average speeds for the studied segment. The second approach is hypothesis based that compares the means of all data sets obtained and accepts or rejects the hypothesis accordingly. Based on data history and its statistical values, the third approach provides means for estimating average speeds with a certain confidence. The fourth approach is the test of the extremes, where the reliability measure depends on the researcher's perspective or the group of interest's perspective. Finally, the information theory based approach examines frequency of tested values (average speeds in this paper) and defines reliability as the inverse relation of the information content lays in a highway segment. These methods were used to analyze average speeds and number of stops for two arterials in the Las Vegas area, Charleston Boulevard and Craig. Results have demonstrated the differences in the various reliability approaches conducted.

REFERENCES

[1] Mathew Berkow, Ahmed M. El-Geneidy, Robert L. Bertini, and David Crout. Generating Transit Performance Measures with Archived Data. *Transportation Research Board*, (1841):109–119, 2003.

[2] Mathew Berkow, Ahmed M. El-Geneidy, Robert L. Bertini, and David Crout. Beyond Generating Transit Performance Measures: Visualizations and Statistical Analysis Using Historical Data. *Transportation Research Board*, (1945):12–23, 2009.

[3] I.G. Black and J.G. Towriss. Demand Effects of Travel Time Reliability. *Final report prepared for London assessment division. UK Department of transport*, 1993.

[4] Enide A.I. Bogers, Hans WC Van Lint, and HENK J Van Zuylen. Travel Time Reliability: Effective Measures from a Behavioral Point of View. *Transportation Research Board*, page 1Ű14, 2008.

[5] Chao Chen, Alexander Skabardonis, and Pravin Varaiya. Travel-Time Reliability as a Measure of Service. *Transportation Research Record: Journal of the Transportation Research Board*, (1855):74Ű79, 2003.

[6] Cambridge Systematics Inc. Traffic Congestion and Reliability Trends and Advanced Strategies for Congestion Mitigation. *Prepared for Federal Highway Administration*, page 140, 2005.

[7] Richard A. Johnson. *Miller and Freund's Probability and Statistics for Engineers*. Prentice Hall, 1994.

[8] J.W.C. Van Lint and H.J. Van Zuylen. Monitoring and Predicting Freeway Travel Time Reliability. *Transportation Research Record*, (1917):54–62, 2005.

[9] Yu Nie and Yueyue Fan. Arriving-on-Time Problem, Discrete Algorithm That Ensures Convergence. *Transportation Research Record: Journal of the Transportation Research Board*, (1964):193Ű200, 2006.

[10] Jun-Seok Oh and Younshik Chung. Calculation of Travel Time Variability from Loop Detector Data. *Transportation Research Record: Journal of the Transportation Research Board*, (1945):12Ű23, 2006.

[11] Gordon Raisbeck. *Information Theory*. The MIT Press, 1964.

[12] Lam S.H., M. Jing, and A.A. Memon. Effects of Real-Time Information on Route Choice Behavior: New Modeling Framework and Simulation Study in Behavioral Responses to ITS. *Eindhoven*, 2003.

[13] Ronald E. Walpole. *Introduction to Statistics*. Macmillan Publications, 1968.

TABLE 4 Mean Estimation with 95% confidence and the 95th percentiles

(a) Segments

	Statistics	Segment								
		Eastern	Fremont	28th	Mojave	Pecos	Sandhill	U.S. 95 W	U.S. 95 E	Sacramento
Charleston	Cnfd.Intrvl		24.6<v<27.6	34.9<v<38.7	27.3<v<33.6	34.6<v<39.3	34<v<39	22<v<32	27.1<v<34.8	26.4<v<35.2
	Percentile		30.2	41.1	40.9	44.1	42.8	42.9	42.0	42.8
			Lamb	Marion	Nellis	Christy	Sloan	Tree Line	Hollywood	
			17.8<v<25	30.2<v<34.8	28.5<v<33.9	35.6<v<39.4	27.7<v<34	28.1<v<34.5	33.4<v<38.1	
			34.4	38.3	39.7	42.9	45.1	43.9	43.1	
		Losee	Berg	Donovan	Donovan	W. I-15	E. I-15	Pecos	Walnut	Lamb
Craig	Cnfd.Intrvl		19.3<v<27.1	11.3<v<18.9	23<v<27.1	26.4<v<31.5	24.7<v<30	13.6<v<21.1	33<v<39.1	35.4<v<41.5
	Percentile		32.7	34.6	32.8	37.4	38.4	39.2	46.6	46.8
			Nellis							
			32.3<v<37.1							
			43.2							

(b) Runs

	Statistics	Runs							
		AM							
		1	2	3	4	5	6	7	
Charleston	Cnfd.Intrvl	25.9<v<33.2	30.1<v<38	29.2<v<38.5	25.2<v<36.3	29.2<v<37.1	30.7<v<38.3	27.8<v<37.2	
	Percentile	38.57	42.54	43.68	40.96	40.93	43.70	42.94	
		AM							
		1	2	3	4	5	6	7	
Craig	Cnfd.Intrvl	21.5<v<35.8	20.7<v<37.4	13.7<v<29.6	14.9<v<30.5	24.3<v<29.1	15.9<v<29.8	17.8<v<28.1	
	Percentile	41.96	41.36	39.42	39.54	31.98	37.76	31.24	
		Midday							
		1	2	3	4	5	6	7	8
Charleston	Cnfd.Intrvl	32.2<v<40.1	29.8<v<39.5	25.1<v<36.7	26.2<v<35.6	21<v<35.2	22.8<v<35.9	32<v<39.3	31.1<v<40.9
	Percentile	43.06	43.08	39.50	39.88	41.21	42.95	42.63	43.36
		Midday							
		1	2	3	4	5	6	7	
Craig	Cnfd.Intrvl	15.2<v<31.3	16.8<v<31.7	17.2<v<33.9	18.5<v<34	22.9<v<32.5	18.7<v<28.7	24.9<v<35.6	
	Percentile	40.58	40.98	42.60	42.26	38.14	34.26	39.98	
		PM							
		1	2	3	4	5	6	7	
Charleston	Cnfd.Intrvl	19.1<v<33.8	20.8<v<35.8	21.1<v<34.3	29<v<40.2	24.8<v<36.3	25.7<v<36.6	24.7<v<35.5	
	Percentile	41.91	41.14	39.42	44.82	40.73	40.35	41.25	
		PM							
		1	2	3	4	5	6	7	
Craig	Cnfd.Intrvl	26.1<v<36.5	23.6<v<36	17<v<33.2	23.3<v<37.3	28.3<v<41.6	28.4<v<42.3	28<v<38.8	
	Percentile	41.52	44.10	42.7	44.08	44.36	47.2	45.84	

TABLE 5 Reliability as a non failure measure

(a) Segments

	Statistics	Segment							
Charleston		Eastern	Fremont	28th	Mojave	Pecos	Sandhill	U.S. 95 W	U.S. 95 E
	R		0.14	0.95	0.50	0.95	0.86	0.45	0.64
Craig		Losee	Berg	Donovan	Donovan	W. I-15	E. I-15	Pecos	Walnut
	R		0.43	0.14	0.14	0.43	0.52	0.14	0.76
Charleston		Sacramento	Lamb	Marion	Nellis	Christy	Sloan	Tree Line	Hollywood
	R	0.73	0.23	0.77	0.73	0.86	0.45	0.55	0.73
Craig		Lamb	Nellis	-	-	-	-	-	-
	R	0.86	0.76	-	-	-	-	-	-

(b) Runs

	Statistics	Runs							
Charleston		AM							
		1	2	3	4	5	6	7	
	R	0.47	0.67	0.67	0.53	0.67	0.73	0.67	
Craig		AM							
		1	2	3	4	5	6	7	
	R	0.56	0.56	0.33	0.33	0.33	0.22	0.33	
Charleston		Midday							
		1	2	3	4	5	6	7	8
	R	0.87	0.67	0.60	0.60	0.53	0.53	0.67	0.73
Craig		Midday							
		1	2	3	4	5	6	7	
	R	0.33	0.33	0.33	0.33	0.44	0.33	0.56	
Charleston		PM							
		1	2	3	4	5	6	7	
	R	0.53	0.67	0.53	0.8	0.67	0.53	0.67	
Craig		PM							
		1	2	3	4	5	6	7	
	R	0.67	0.44	0.44	0.67	0.78	0.78	0.78	

TABLE 6 Reliability for number of stops as a non failure measure

		Segments															
Charleston		Estrn	Frmnt	28th	Mojave	Pecos	Sndhll	U.S. 95	U.S. 95	Scrmnt	Lamb	Mrn	Nellis	Christy	Sloan	Tree Line	Hlywd
	R		1.00	0.95	0.59	0.95	0.82	0.77	0.95	0.77	0.27	0.91	0.41	0.86	0.45	0.45	0.36
Craig		Losee	Brg St.	Dnvn W	Dnvn	W. I-15	E. I-15	Pecos Rd	Wlnt Rd.	Lamb	Nellis	-	-	-	-	-	-
	R		0.67	0.29	1.00	0.95	0.62	0.14	0.76	0.71	0.43	-	-	-	-	-	-

Runs		1	2	3	4	5	6	7	8
		AM							
Ch	R	1.00	1.33	1.44	1.00	1.44	1.33	1.00	
Cr	R	0.78	0.78	0.44	0.56	0.56	0.33	0.56	
		Midday							
Ch	R	1.56	1.11	1.22	1.22	0.89	1.22	1.44	1.11
Cr	R	0.44	0.56	0.56	0.56	0.78	0.44	0.78	
		PM							
Ch	R	1.00	1.11	1.22	1.00	1.00	1.11	1.11	
Cr	R	0.67	0.78	0.44	0.67	0.78	0.78	0.78	

TABLE 7 Information theory based reliability

(a) Segments

	Statistics	Segment							
Charleston		Eastern	Fremont	28th	Mojave	Pecos	Sandhill	U.S. 95 W	U.S. 95 E
	R		0.62	0.80	0.41	0.68	0.53	0.39	0.40
Craig		Losee	Berg	Donovan	Donovan	W. I-15	E. I-15	Pecos	Walnut
	R		0.42	0.46	0.50	0.43	0.44	0.44	0.48
Charleston		Sacramento	Lamb	Marion	Nellis	Christy	Sloan	Tree Line	Hollywood
	R	0.45	0.38	0.59	0.46	0.56	0.41	0.42	0.48
Craig		Lamb	Nellis	-	-	-	-	-	-
	R	0.56	0.47	-	-	-	-	-	-

(b) Runs

	Statistics	**Runs**							
Charleston		AM							
		1	2	3	4	5	6	7	
	R	0.47	0.45	0.45	0.37	0.45	0.45	0.45	
		AM							
Craig		1	2	3	4	5	6	7	
	R	0.41	0.37	0.40	0.37	0.74	0.46	0.41	
Charleston		**Midday**							
		1	2	3	4	5	6	7	8
	R	0.55	0.43	0.45	0.44	0.36	0.37	0.56	0.52
		Midday							
Craig		1	2	3	4	5	6	7	
	R	0.29	0.39	0.41	0.41	0.51	0.41	0.41	
Charleston		**PM**							
		1	2	3	4	5	6	7	
	R	0.34	0.37	0.37	0.51	0.44	0.51	0.43	
		PM							
Craig		1	2	3	4	5	6	7	
	R	0.41	0.44	0.40	0.44	0.47	0.49	0.49	

TABLE 8 Reliability from information theory

		Segments															
Charleston		Eastern	Frmnt	28th	Mojave	Pecos	Sndhll	U.S. 95	U.S. 95	Scrmnt	Lamb	Mrn	Nellis	Christy	Sloan	Tree Line	Hllyw
	R		-	1.00	1.00	1.00	1.00	1.00	1.00	0.63	0.63	1.00	0.63	1.00	1.00	1.00	1.00
Craig		Losee	Brg St.	Dnvn W	Dnvn Wy	W. I-15	E. I-15	Pecos R	Wlnt Rd.	Lamb	Nellis	-	-	-	-	-	-
	R		0.50	0.63	-	1.00	1.00	1.00	1.00	1.00	1.00	-	-	-	-	-	-

Runs		1	2	3	4	5	6	7	8
		AM							
Ch	R	1.00	1.00	1.00	1.00	1.00	1.00	1.00	
Cr	R	0.63	0.63	0.63	0.50	1.00	0.63	0.63	
		Midday							
Ch	R	1.00	1.00	1.00	0.63	1.00	1.00	1.00	1.00
Cr	R	0.50	0.63	0.63	0.63	1.00	1.00	1.00	
		PM							
Ch	R	0.63	0.63	1.00	0.63	0.63	0.63	0.63	
Cr	R	1.00	1.00	0.63	1.00	1.00	1.00	1.00	