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Model-Based Urban Road Network Performance Measurement Using Travel Time Reliability: A Case Study of Addis Ababa City, Ethiopia

Seada Mohammed Assen[1,*], Emer Tucay Quezon[2]

[1]MSc in Road & Transport Engineering, College of Engineering & Architecture,
Addis Ababa Science & Technology University, Addis Ababa, Ethiopia
[2]Civil and Construction Engineering & Management Streams, Institute of Technology, Awaro Campus,
Ambo University, Ambo City, Oromia Region, Ethiopia
*Corresponding author: seadamohammed69@yahoo.com, quezonet09@gmail.com

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Abstract In heterogeneous traffic conditions, the performance of the road network is described by vehicles and driver characteristics. Nowadays, traffic congestion, delay, and unreliability are terms that are most associated with present-day travel, in which transport users spend their precious time on long traffic queues. Due to this, late arrival at the workplace and appointment for social or business activities have become a perennial problem in the study area. In addition, during traffic queues, vehicle fuel emission increases in congested traffic segments affecting the environment, particularly the issue of global warming. This research study evaluated the performance of the road network in terms of travel time reliability in order to determine the main factors affecting travel time reliability. Ten road segments were selected to analyze the performance level and efficiency of the road network, considering the travel time probability distribution, and reliability of road segments in Addis Ababa City. From these road segments, nine were selected to formulate the model, and one road segment considered for validation of the result. The reliability of the road segments was analyzed using travel time reliability measures such as buffer time, buffer time index, planning time index, and the travel time index. It was used a multiple linear regression model to predict the travel time reliability of the road segments with R^2_{adj} =0.936. In this research study, there were 1,141 samples considered for the analysis. A cross-validation analysis conducted on the models to estimate how accurately a predictive model will perform in practice. Hence, it is concluded that the regression analysis showed all variables found to have statistically significant to predict the travel time reliability of a road segment.

Keywords: *Buffer time index, Congestion, Regression analysis, Travel time index, Travel time reliability*

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1. Introduction

Travel time, a fundamental measure in transportation, is the total elapsed time necessary for a vehicle to traverse from one point to another over a specified route under existing traffic conditions. Delay, on the other hand, is the time lost to travel because of traffic frictions and traffic control devices [1,2].

Traffic congestion impacts the movement of people and freight transportation. It is significantly related to the level of accessibility and mobility, and it becomes a common characteristic of an urban road transportation system of cities in developing countries, which resulted in high operating costs, loss of users' productive time, and more fuel consumption among others [3]. Traffic congestion wastes time and energy, which causes pollution and stress, decrease productivity, and imposes costs on society. It directly affects the commuters with increased travel time, excessive delay in a queue, increased fuel cost, delay for a necessary appointment and job, loss in productive hours, and indirectly affects the living standard and the environment as well. Congestion, delay, and unreliability are terms that are most associated with present-day- travel. Increasing mobility and congestion results in an increase in travel time variability and a decrease in reliability. Reliability becomes an important performance measure for transportation facilities [4].

According to Asakura Y. (2006), the travel time distribution or variability in travel time is the most useful indicator to measure the performance and reliability of a transportation system. Travel time reliability is significant to many transportation system users, whether they are vehicle drivers, transit riders, or freight shippers. Travel time is a critical measure and an important measure used to evaluate the effectiveness of the road. Reliability is important for transportation system users, transportation planners, and decision-makers should consider travel time reliability as a key performance measure. Traffic professionals recognized the importance of travel time reliability because it better quantifies the benefit of traffic management and operational activities [5].

On the other hand, Chen, A., Ji Zhaowang and Recker, W. (2003) stated that travel time reliability is "an important measure of service quality for travelers [6]." Recently, various empirical travel time reliability studies have extensively used travel time distribution as a tool for developing various reliability indices such as planning time (95th % travel time), Buffer time index, and planning time index. All these reliability indices are useful to improve regional transportation planning [7,8,9].

Travel time-based performance measurement is probably the most familiar and straight forward measures for road users than the other road network reliability measurement (i.e., Connectivity reliability or capacity reliability). Most of the studies in the literature used a deterministic approach to model Travel time variation under the influence of various factors from the supply-side and demand side of the system. Development of suitable metrics for travel time reliability and, then, ranking the different links according to the performance will be important to transport planners in order to priorities the improvements to road corridors and to implement mitigation strategies [10,11].

In this research study, some applications of travel time reliability as a performance measure to evaluate the operational conditions of highway segments by using travel time-based performance measures performed. The travel time reliability on an arterial segment is usually not only a function of traffic flow, driver behavior, traffic composition, link capacity, and speed limit, but also a function of the roadway and intersection geometries, media type, pedestrian activities, and traffic conflict. So, this research study sought a linear relationship (regression model) between those factors that have a great impact on travel time reliability of urban road networks and developed a distribution probability model for a dominant vehicle type in order to understand the nature of the distribution.

2. Study Area and Research Methods

2.1. Study Area

Addis Ababa is the capital city of Ethiopia, which is located within the horn of Africa with geographical coordinates of 9º 1’ 48” and 38º 44’ 24” east and with an average elevation of 2355m above sea level. The city has a total land area of about 530.14km^2. Two corridors selected for the study, as shown in Figures 2 & 3.

2.2. Data Requirements

The following data are needed for the analysis:

1. Traffic-related data
   - Travel time data, Traffic volume data, Average speed data, Percent (%) of heavy vehicle data
2. Segment Geometry Data
   - Segment Length, Average segment width, Number of lanes, Crosswalk
3. Road user data
   - Number of pedestrians, Average headway time data

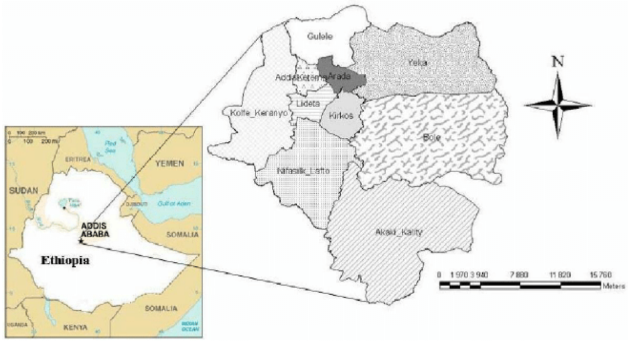

Figure 1. Map of Addis Ababa City (Source: Google Map 2019)

Figure 2. Corridor -1, from Torhailoch to AU square through Sost Kutr Mazoria Square

Figure 3. Corridor -2, from Summit Square to Unity University (Gerji) through Safari- Figa

2.3. Data Collection Techniques

The following surveys were conducted during peak hours from 7:00 A.M - 9:00 A.M on Tuesday, Wednesday, and Thursday (May 14-16, 2019 GC), namely: manual vehicle license plate Survey, manual Traffic volume count, and pedestrian count survey. There were four (4) data collectors assigned to each corridor and the road segments. The data had recorded at the entry and exit of each segment for travel time data, traffic volume data, and pedestrian volume, vehicle headway, including travel time survey at mid-block.

The number of pedestrians collected at the marked crossing that are given priority over entering vehicles, which is one of the contributory factors that affect travel time reliability of the vehicles. Also, field measurements performed to gather data on geometrical features of road segments such as a number of lanes and width per lane and segment length to supplement the regression model development. Prior to developing the model, travel time data, pedestrian crossing data, and traffic volume data were extracted manually from the data collection sheets. For the traffic volume, the license plate between entry and exit points were matched and determined the travel time based on the difference between each vehicle's arrival time.

2.4. Data Analysis

2.4.1. Probability Distribution Modeling

In this research study, the probability distribution model was developed based on the collected travel time data. SPSS (Statistical Package for the Social Sciences) Software used as a major data analysis and manipulation tool. A probability distribution is fitted to departure data for each vehicle type and flow movement type. Before fitting any probability distribution, the data is tested for outliers using Grubbs' test (Grubbs 1969 and Stefansky 1972) and removed from the analysis. Then tested the data for normality using the Kolmogorov-Smirnov normality test, and for non-normal data, other probability distributions are fitted. The probability-probability (p-p) plots and Kolmogorov-Smirnov test was considered for testing the existing distribution models.

Grubbs' test with the following Null and Alternate Hypotheses used to determine the selected (car and minibus) vehicle travel time data outliers:

Ho: If there are no outliers in the data set.

Ha: If there is exactly one outlier in the data set.

Anderson- Darling test with the following Null and Alternate hypothesis is used to test for normality.

Ho: If the data follow a specified distribution.

Ha: If the data does not follow the specified distribution.

2.4.2. Analysis of Travel time Reliability

Travel time reliability is defined as the consistency of a given trip travel time. More formally, it is said to be "the consistency or dependability in travel times, as measured from day to day and/or across different times of the day [12]. The 95th percentile travel time ($TT_{95\%}$), planning time (PT), planning time index (PTI), buffer time (BT), and buffer time index (BTI) are used as performance indicators. Below are the equations used:

$$BT = PTT_{95\%} - ATT \quad (1)$$

$$BTI = \frac{\mathrm{PTT}_{95\%} - ATT}{ATT}[\frac{1}{100}\%] \quad (2)$$

$$PTI = \frac{\mathrm{PTT}_{95\%}}{FTT} \quad (3)$$

$$TTI = \frac{\mathrm{ATT}}{FTT} \quad (4)$$

Travel time threshold (reliability) $\leqslant$ (BT + ATT)

Where: BT - Buffer time (Sec); BTI - buffer time index (%); $PTT_{95\%}$ - 95th percentile travel time; PT- planning time (Sec); ATT-Average Travel Time (Sec); PTI- Planning Time Index; TTI- Travel Time Index; FTT- Free Flow Travel Time

A 2012 Maryland State Highway Mobility Report utilizes the planning time index and the travel time index to measure the travel time reliability of the highway system. The planning time index (PTI) is computed as the 95th percentile travel time divided by the free-flow travel time, as shown in equation (3). While, the travel time index (TTI) is the ratio of the average travel time to the mean free-flow travel time, as shown in (4) [13,14].

2.4.2.1. Travel time Reliability Regression Modeling

The following variables of the study were identified to develop the model:

Dependent variables

- Travel time

Predictor variables

- Traffic volume, Number of the pedestrian crossing, Travel speed, Number of lanes, Segment length, Average segment width, Average headway time, % of heavy vehicles, Crosswalk

Multiple linear regression assumptions were checked for any violation before performing the regression analysis, and development of the model.

3. Analysis, Results, and Discussion

3.1. Travel Time Reliability Measurement Analysis

Travel time reliability reflects the overall operating conditions of a road segment; most transportation agencies used to compare the performance of several road segments along a roadway. It would help them to identify some issues to provide countermeasures or improvements within the problematic areas.

Results indicated in Table 1, the ranked buffer time index (BTI) with the corresponding segment number using equations (1)-(4). The BTI represents the additional time that is necessary above the average peak travel time. The highest BTI value of 0.98 represented segment-1, followed by 0.92 for segment-8, 0.89 for segment-3, 0.77 for segment-9, and the other six segments with BTI value ranges from 0.68 to 0.61. It can be seen that the lowest BTI value of 0.61 for segment 2. These results showed that among all ten road segments, segments 1, 8, 3 & 9 are the worst conditions during the peak hour travel time of the day.

Likewise, the travel time index (TTI) represents the average additional time required during peak times as compared to times of the normal light traffic condition. The TTI for Segment-2 and Segment-6 were 1.50 and 1.35, respectively. It means that travel time during peak hours, approximately 50% & 35% longer than that during an off-peak period or free-flow conditions. These measures of analysis are also applied to the other road segments within the study area.

Table 1. Ranked BTI for Travel Time Reliability Measure of the Selected Road Segments

Segment (No.)	Segment Length (m)	95th Percentile travel time ($PTT_{95\%}$)	ATT (Sec)	FTT (Sec)	BT (Sec)	Reliability measures		Congestion measures
						BTI (Ranked)	PTI	TTI
1	2100.0	623.7	314.5	300.00	309.2	0.98	2.08	1.05
8	1400.0	346.4	180.2	160.00	166.2	0.92	2.17	1.13
3	1200.0	235.2	124.3	120.00	110.9	0.89	1.96	1.04
9	1800.0	432.9	244.8	239.97	188.1	0.77	1.80	1.02
6	850.0	204.5	121.4	90.01	83.1	0.68	2.27	**1.35**
7	1700.0	431.6	256.7	240.04	174.9	0.68	1.80	1.07
10	800.0	312.6	186.9	179.97	125.7	0.67	1.74	1.04
4	800.0	118.5	72.1	60.00	46.4	0.64	1.98	**1.20**
5	450.0	111.9	68.1	60.00	43.8	0.64	1.87	1.14
2	700.0	144.7	89.9	59.99	54.8	0.61	**2.41**	**1.50**

3.2. Travel time Distribution Modeling

To better understand the travel time variability, travel time is fitted to specific distribution functions and evaluate the goodness of fit, the distribution modeling value of each distribution needed. In this research study, the distribution model is developed for the collected travel time data. SPSS software is used as the major data analysis and manipulation tool. Since the traffic flow condition at the selected road segment was heterogeneous, it would not be reasonable to treat all vehicle types under the same category. So, the travel time data distributions could be fitted for each vehicle type. For this study, the distribution modeling was not fit for a segment with five cars and minibus vehicles.

Likewise, there are possible probability distributions that could be used to test fit travel time data for cars such as Lognormal, Laplace, Logistic, Pareto, student t-test, Weibull, Uniform, Half normal, Gamma, Exponential, and Chi-square. In the process of the analysis, Laplace distribution found out to show the best fit for the data.

3.3. Travel Time Regression Modeling

There were 1,147 travel time data samples extracted from corridors-1 & 2, which are used for multiple linear regression modeling.

(a) **Predictors**: Constant were crosswalk, average time headway, traffic speed, segment length, traffic volume, number of the pedestrian crossing at the segment, average segment width, and percent (%) of heavy vehicles.

(b) **Dependent Variable**: Travel time (Sec)

The final regression analysis had been processed to predict travel time from the indicated predictors or independent variables, as shown in section (a). The predictor variables were found to predict travel time statistically significant at $P < 0.05$ and $R^2_{adj} = 0.936$, and it was applied to all predictor variables, which were added statistically.

Table 2. Correlation Matrix between Independent Variables

Variables	Reliable travel time (Sec)	No. of lanes	Segment length	Average Segment Width	No. of Pedestrian Crossing	Traffic volume	Traffic speed	% of Heavy Vehicles	Average Time Headway (Sec)	Crosswalk
Reliable Travel time (Sec)	1.000									
No. of lanes	-.343	1.000								
Segment length	.072	-.254	1.000							
Average segment width	-.343	1.000	-.254	1.000						
No. of the Pedestrian crossing	.784	.011	.799	.011	1.000					
Traffic volume	.095	.339	.266	.339	.220	1.000				
Traffic speed	-.488-	.368	-.290-	.368	-.246-	.467	1.000			
% of heavy vehicles	.459	-.506-	.412	-.506-	.370	.172	-.193-	1.000		
Average time headway (Sec)	.102	.218	.121	.218	.105	.022	-.217-	-.730-	1.000	
Crosswalks	.176	.661	.247	.661	.413	.616	.203	.201	-.115-	1.000

Table 3. Predictor Variable Variance Inflation Factor(VIF)

Predictors	Available	No. of lanes	Average segment width	No. of pedestrian crossing	Traffic volume	Traffic speed	% of heavy vehicle	Average time headway
VIF	1.069	1.069	2.76	1.076	1.092	1.204	1.015	1.065

Table 4. Description of Model Summary

Model	R	R^2	Adjusted R^2	Std. Error of Estimate	Change Statistics				
					R^2	F Change	df_1	df_2	Sig. F Change
1	0.972	0.944	0.936	22.72461	0.944	118.012	8	0	0.000

Table 5. Final Regression Output

Travel Time Reliability Model	Coefficients		t	Sigma (p-value)	95th Confidence interval	
	Beta	Std. Error			Lower bound	Upper bound
Constant (a)	89.571	22.999	3.895	0.008	33.294	145.848
Segment length (SL)	-0.155	0.014	1.656	0.000	0.121	0.188
Average segment width (SW)	0.010	0.006	-1.142	0.297	0.001	0.0910
No. of lanes (NL)	0.103	0.024	-1.142	0.297	0.098	0.201
No. of pedestrian crossing (NPC)	-0.023	0	0.142	0.892	-0.031	-0.013
Traffic volume (TV)	-0.576	0.002	-2.514	0.046	-0.619	-0.406
Average travel speed (ATS)	0.225	0.025	-5.378	0.002	0.073	0.307
% of heavy vehicles (HV)	-0.071	0.039	0.692	0.515	-0.036	-0.093
Average headway time (ATH)	-0.016	0.003	-0.169	0.872	-0.102	-0.002
Crosswalk (CW)	-0.068	0.022	-0.715	0.502	-0.129	-0.021

In the analysis, travel time data were assigned as the dependent variable, and it was transformed into a natural logarithm, which resulted in the prediction equation formulated below:

$$\begin{aligned} TTR = {} & 89.57 - 0.155SL + 0.010SW + 0.103NL \\ & - 0.023NPC - 0.576TV + 0.225ATS \\ & - 0.071HV - 0.016ATH - 0.068CW \end{aligned} \tag{5}$$

Where: TTR is travel time reliability, SL is segment length, SW is the average segment width, NL is the number of lanes, NPC is a number of pedestrian crossing, TV is the traffic volume, ATS is average travel speed, HV is % of heavy vehicles, ATH is average headway time, CW is a crosswalk

3.4. Model Interpretation

In the above equation, the variable crosswalk was considered categorical as a dummy variable, and it was taken a value 0 and 1. This means, ‘1' for crosswalk available, while ‘0' for no crosswalk. From the above results, the p-value of all predictor variables is less than the significance level, $P<0.05$. Hence, all predictor variables, when added, it showed statistically significant to the prediction of the variable. All selected variables, segment length, average width, number of the lane, number of a pedestrian crossing, travel speed, traffic volume, % of heavy vehicle, average headway time, and crosswalk, indicated 94.4% of observed data.

Using equation (5), the average segment width, the number of lanes, and average travel speed provided an appositive coefficient expressing a positive relationship with travel time reliability. From the point of view of segment width, the drivers could get more space to speed up, which resulted in shorter travel time along the road, but when the lane width decreases, the drivers will no longer free to maneuver and speed up.

3.5. Model Validation

The R^2_{adj} value described how well the regression model performs over the tailing data set. A validation analysis was necessary to determine the performance of the model in predicting future response values. External model validation used to validate the predictive regression model. In this research study, the researcher selected road corridor-1 for validation of the study. One hundred twenty-seven samples considered, taken from Jacros to Unity University. These samples used as test data set to determine the predictive ability of the model. It was found out that R^2_{adj} value indicated 0.873, as shown in Figure 4 below. Hence, it confirmed that the outputs of a statistical model are acceptable with respect to the real data-generating process of this study.

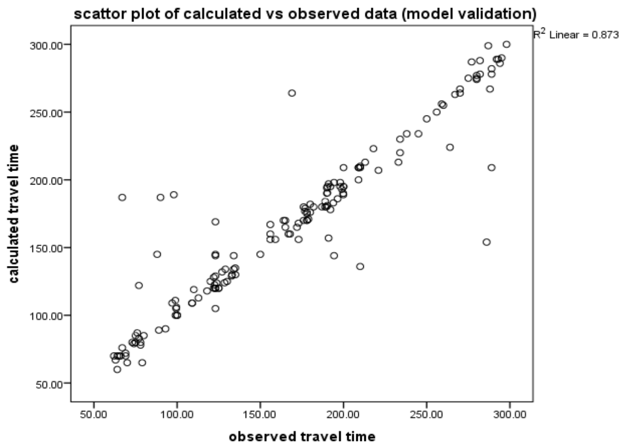

Figure 4. Validation result

4. Conclusion

Travel time reliability measures such as Buffer time index (BTI), and the Travel time index (TTI) carried out on selected road segments, considering cars and minibuses during peak periods from 7:00 A.M - 9:00 A.M in three consecutive days (Tuesday, Wednesday & Thursday) the morning. The travel time distribution model was developed, based on two road corridors with ten selected road segments in the study area. From the selected vehicle types, the distribution parameters were estimated from the data for the selected probability distribution.

From the probability distribution analysis, it indicated the travel time data for car and minibus did not follow the same probability distribution. A Normal probability distribution was found to fit Travel time data for cars and fitted for segments 1-9.

Based on travel time reliability measurements such as buffer time index, buffer time, and 95th percentile travel time for all segments showed the reliability of getting a worse condition as its values in ascending order. Road segment-2 has a high-performance level and efficiency than the other segments due to its low BTI value.

In addition, a multiple linear regression model developed to predict the travel time reliability of urban road segments. From the statistical analysis performed, all variables were found statistically significant to the model at a 95% confidence level, and the calculated R^2_{adj} for the regression was 94.4%. On the other hand, the pedestrian movements by crossing the segment, and the maneuver of drivers have a great impact on travel time reliability on the road network.

It is therefore concluded that the regression analysis showed all variables found to have statistically significant to predict the travel time reliability of a road segment.

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