New Transit Performance Measures and LOS Criteria for Link-level Assessment
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New Transit Performance Measures and LOS Criteria for Link-level Assessment

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ABSTRACT

The focus of this research is to assess link-level transit performance measures using data captured through Automatic Vehicle Location (AVL) units installed on Charlotte Area Transit System (CATS) buses for year 2012. Query tools were developed to compute link-level transit system performance measures, conduct analysis, and derive meaningful interpretations. The link-level transit system performance measures were computed by comparing actual bus travel time along selected links (between two consecutive fixed bus stops) with the scheduled-travel-time along the same link for each run in the year. Actual delay time and early arrivals as well as percentage of times delay and early arrival was observed were computed to assist in the assessment. New level-of-service (LOS) criteria, to indicate link-level transit system performance, based on percentage-based measure are proposed. The analysis was conducted by time-of-the-day and day-type (weekday or weekend), for both travel directions, along selected transit segments to assist in assessing the applicability of the measures. Findings from the research indicate that percentage-based performance measures would be more reliable than fixed range-based measures (delay or difference in travel time) for planning and assessment of operational performance by transit system operators.

Keywords: Transit, Performance, Reliability, Travel Time, On-time

INTRODUCTION

Public transportation helps reduce road congestion and travel time, thereby reducing energy consumption and air pollution. In addition, "public transportation provides people with mobility and access to employment, community resources, medical care centers, and recreational facilities in communities across America *(1)*." The performance of transit system plays a vital role for over 90 percent of public transportation users who do not own a car and have to rely on public transportation *(1)*.

Travel time reliability, on-time performance, delay, safety, security, comfort, convenience, frequency, hours of service, service coverage, transfer time, and passenger environment are some of the transit performance measures. Fifty percent of transit system users

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travel to or from work, 12 percent to or from college or school, and 4 percent to access medical services *(1)*. These statistics show that the reliability of transit system is important for at least 66 percent of users who need to know their expected travel time to a given destination, to be on time. This research focuses on on-time performance and travel time reliability as the transit performance measures for improved quality of service.

According to Highway Capacity Manual (HCM) and Transit Capacity & Quality of Service Manual (TCQSM) *(2)*, on-time performance is one of the most important measures to evaluate the level-of-service (LOS) or quality of transit system performance, especially from passengers' perspective. In addition, it is the most widely used reliability measure in transit industry. According to Rietveld et al. *(3)*, the waiting time at bus stops is valued 1.5 times more than in-vehicle time. Even though scheduled frequencies between buses are fixed, the actual arrival time may fluctuate based on several uncertain factors such as congestion, the number of passengers alighting and boarding the bus, transit service headway, and incidents. The aforementioned factors could increase passengers waiting time *(4)*.

Researchers are still trying to find an insightful definition for on-time performance. In Transit Cooperative Research Program (TCRP) Synthesis of Transit Practice (*2*, *5*), on-time performance standards of more than 80 agencies were reviewed. Forty-two percent of these agencies allow buses to be more than 5 minutes late and account it as on-time, while twenty-four percent of them allow some early buses to be considered on-time. To evaluate the LOS, TCQSM defines a fixed schedule range for an on-time trip (i.e., 3 minutes in advance and 5 minutes late) without considering the amount of delay or early departure *(6)*.

Travel time reliability is another important measure for transit passengers. Depending on trip length and total travel time, the cost of unreliable service may actually be greater than the cost of travel time *(7)*. Since the variation in travel time during a segment of a trip increases the risk of missing connection between bus stops, it is very important to have a reliable travel time and service *(7)*. Bus waiting time at a stop, on-time performance, frequency of bus services, and even the number of passengers in each bus is affected from travel time reliability *(6)*. Several factors affect the transit travel time reliability. They include traffic congestion, traffic signal delay, incidents, work zones, mechanical breakdown of the bus, vehicle and staff availability, existence of exclusive bus lanes, traffic signal priority when a bus is behind schedule, schedule achievability and quality, passenger demand, wheelchair lift, route length, and the number of stops *(2)*.

In this research, the reliability of link-level scheduled-travel-times is evaluated to assess the transit system performance. The performance of transit system is also studied by time-of-the-day and day-type (weekday or weekend) from passengers' and operators' perspective. In addition, a new on-time performance measure is introduced to serve as a more robust measure to evaluate the reliability of link-level scheduled-travel-time. This is based on a range of percentage of times travel time was different than scheduled-travel-time rather than the differences. Finally, the characteristics of these transit system reliability measures are assessed to evaluate and identify the best transit system reliability measure.

LITERATURE REVIEW

Researchers in the past have proposed various concepts of transportation reliability. These include connectivity reliability, capacity reliability, encountered reliability, performance reliability, flow decrement reliability, mode choice reliability, and travel time reliability *(8)*. The level of variability between the expected travel time (scheduled, average or median travel time) and the actual-travel-time is travel time reliability *(9)*.

Travelers prefer routes with higher mean travel times and smaller travel time variation to routes with a lower mean travel time and larger variability *(10, 11)*. They remember not only the average travel time, but also the worst few days they experienced. The concept of reliability could provide a different perspective to help agencies or operators measure and improve the travel time on those worst days, by decreasing average travel time and increasing travel time reliability *(12)*.

Reliability can be defined as the probability of reaching a destination within an acceptable range of time that takes no longer than the expected travel time plus a certain acceptable additional time *(9)*. In this definition, the three major components are expected travel time, acceptable additional time, and the actual-travel-time. The acceptable additional travel time is the additional travel time that a traveler would find acceptable during an on-time performance *(9)*. The buffer time is the amount of extra time that must be allowed for the traveler to reach their destination in a high percentage of the trips *(9)*.

It is worth mentioning that the expected travel time would be high for some links that are congested for a large portion of the time. Consequently, the variability between the expected travel time and actual-travel-time may be small. In such situations, the facility is considered as reliable, though the links are congested *(9)*. However, for a regular facility without continuous congestion, the variability for non-congested travel times is smaller when compared to congested travel times *(9)*.

The measures of reliability are different in passengers' and operators' perceptions. Transit passengers expect day-to-day consistency in bus performance; however, operators consider reliability over longer periods of time *(7)*. Schedule adherence is one of the most important measures of reliability for passengers. Transit passengers will have more reliable on-time arrivals when buses conform to schedule *(7)*. For services with the headways of 10 minutes or less, the headway delay (difference between actual headway and scheduled headway) is an indicator of reliability *(7)*.

Passengers and transit operators also differ in their perceptions on schedule adherence. Generally, transit operators use on-time performance measure to assess schedule adherence. They consider the percentage of buses that depart a certain location within a predetermined range of time, generally no more than one minute early or five minutes late as on-time performance *(7)*. One of the main limitations of this definition from passengers' perspective is that it assumes that all early and late departures are of equal consequence, regardless of the delay's severity or the time-of-the-day *(7, 13)*.

Strategies such as the implementation of a smart card fare collection system, operation of a reserved bus lane, introduction of limited-stop bus service, use of articulated buses, and operation of transit signal priority could have an affect on running time deviation from schedule, variation in running time, and variation in running time deviation from schedules *(14)*. While on-time performance is vital *(15)*, researchers in the past have also considered and evaluated various other transit performance measures such as transit service reliability *(16)*, subway service performance (17), comparing regularity of transit service *(18)*, and measuring service experienced by riders *(19, 20)*. As most of these performance measures do not control for the size of headways and cannot be used to compare one route with another, headway regularity index and passenger wait index were proposed and used to evaluate transit performance *(21)*. In another effort, Seberi et al. *(22)* proposed and used stop level reliability measures using empirical data from archived Bus Dispatch System (BDS) data in Portland, Oregon to evaluate and prioritize stops for operational improvement purposes such as bus holdings or schedule adjustments.

Rietveld et al. *(3)* have introduced different ways to define the transit reliability based on the distribution of departure and arrival times. Probability of an early departure, the mean difference between the expected travel time and scheduled arrival time, the mean delay of late arrivals, the mean delay of more than "x" minutes late arrivals, the standard deviation of arrival time, and the standard deviation of arrival time without considering the early arrivals are a few examples to define transit reliability *(3)*. Most of public transit user's travel in a chain using more than one bus route (transfer passengers). Therefore, delay on one route would result in missing next connections *(3)*.

Shuai et al. *(4)* divided transit reliability into two different parts: transit travel time reliability and passengers waiting time reliability. They indicated that the first measure is useful to consider bus scheduling management, operation validity, and route accessibility. Rietveld et al. *(3)* mentioned that the reliability of passenger arrival time should be considered rather than the reliability of vehicle arrival time, since the concept of trip chain is directly related to each traveler rather than each vehicle. Schil *(23)* measured journey time reliability for transit systems with several transportation modes for customers and operators. They tried to consider the passengers' experience from origin to destination including all interchanges between different modes (London's rail and bus systems).

Bunker *(24)* used risk assessment to quantify transit system reliability where the main aim was to identify high-risk segments in the entire transit system for decision-makers and operators. They considered morning and evening peak hours on weekdays as conditions are relatively uniform during these time periods. Also, passengers are most vulnerable to unreliability during these time periods. Their study concluded that combining transit productiveness with risk assessment is useful for transit planning and operational management.

PROPOSED METHODOLOGY

The AVL data collected at fixed bus stops during 2012, collected and stored by Charlotte Area Transit System (CATS), was obtained and used in this research. Unlike other bus stops, where the bus driver makes decision to stop if requested by at least one alighting or boarding passenger, buses must stop at these fixed bus stops. The AVL data consists of stop-level data with times at each stop for all the days in the year 2012.

Data for inbound and outbound directions was considered for the analysis. The data was categorized based on the direction (inbound, outbound), segment (between two consecutive fixed bus stops), day-type (weekday or weekend), and time-of-the-day (7:00 - 9:00, 9:00 - 11:00, 11:00 -13:00, 13:00 - 15:00, 15:00 - 17:00, 17:00 - 19:00, and 19:00 - 7:00) to make up a new database. Travel times (the travel time between two fixed bus stops), actual-travel-times (summation of actual-dwell-time and actual-travel-time) and scheduled-travel-times (summation of scheduled-dwell-time and scheduled-travel-time) for each segment were computed. Also, various statistics (minimum, maximum, and average) of these time measures, for each segment, were computed based on the direction, time-of-the-day, and day-type.

The transit performance on each route is evaluated by comparing actual-travel-times with scheduled-travel-times on each segment between the fixed bus stops. Transit performance at each bus stop may have a strong correlation with the performance of previous and next bus stops and roadway segments, as the delay at each bus stop will be added to the delays at next bus stops. So, the performance of scheduled-travel-times was evaluated based on travel times between segments instead of considering performance at bus stops. Considering the transit performance for each segment between two fixed bus stops will make it possible to focus just on evaluating the reliability of scheduled-travel-time for each segment on a route. Such a procedure will be useful to assess from both passengers' and operators' perspective.

In this research, transit schedule reliability is evaluated considering the link-level on-time performance measures. The scheduled-travel-times and actual-travel-times from AVL data were used to evaluate the measure. If these two values are same, the transit has an on-time performance for that segment based on the schedule. If the scheduled-travel-time is greater than the actual-travel-time, the bus will arrive to the second stop sooner than the expected time. This early arrival might be because of less dwell time at the previous bus stops or less travel time between the previous bus stops. If the actual-travel-time is greater than the scheduled-travel-time, the bus will arrive to the next stop later than the expected time. This delay might be because of higher stop time at the previous bus stops or higher travel time between the previous bus stops compared with expected travel time (i.e., scheduled-travel-time). Equation (1) summarizes the aforementioned discussion.

$$\begin{cases} [\text{scheduled} - \text{travel} - \text{time} - \text{actual} - \text{travel} - \text{time}] > 0: & \mathit{Early\ Arrival} \\ [\text{scheduled} - \text{travel} - \text{time} - \text{actual} - \text{travel} - \text{time}] < 0: & \mathit{Delay} \end{cases} \quad (1)$$

The definition of on-time performance based on TCQSM *(2)* assumes that the severity of delay or early performance is same without considering the amount of delay or early departure *(4, 10, 11)*. To overcome this problem, this research has tried to consider five different ranges of conventional delay or earlier performance measures (fixed range-based on-time performance measures) rather than just one specific range:

$$-\delta \geq [\text{scheduled} - \text{travel} - \text{time} - \text{actual} - \text{travel} - \text{time}] \leq +\delta$$
$$\text{where, } \delta = (1\text{ min}, 2\text{ min}, 3\text{ min}, 4\text{ min}, \&\ 5\ min)$$

The aforementioned conventional performance measures do not consider the length of the segment and categorize the performance of transit system based on specific pre-defined ranges of travel time. These estimates may or may not account for all the uncertain factors (say, due to congestion). This research, therefore, tries to define a new set of on-time performance measures. In the proposed definition, instead of the values of 1, 2, 3, 4, or 5 minutes, a percentage of average travel time is applied to define the on-time performance measures. The effect of segment's length, congestion, the number of lanes, and several other traffic characteristics are considered incidentally as the average travel time is strongly correlated with these factors. The percentage-based on-time performance measures proposed in this research are:

$$-\delta\ (\text{aveTT}) \geq [\text{scheduled} - \text{travel} - \text{time} - \text{actual} - \text{travel} - \text{time}] \leq +\delta\ (\text{aveTT})$$
$$\text{where, } \delta = (5\%, 10\%, 15\%, 20\%, \&25\%)$$

New level-of-service (LOS) criteria, to indicate transit system performance measures, are proposed based on the aforementioned percentage-based performance measure. Table 1 shows the proposed LOS based on the percentage-based performance measures.

TABLE 1 Proposed LOS Criteria

LOS	Range
A	If at least 50% of times, (STT-ATT) is within ±5% of average TT
B	If at least 50% of times, (STT-ATT) is within ±10% of average TT
C	If at least 50% of times, (STT-ATT) is within ±15% of average TT
D	If at least 50% of times, (STT-ATT) is within ±20% of average TT
E	If at least 50% of times, (STT-ATT) is within ±25% of average TT
F	If 50% of times, (STT-ATT) is not within ±25% of average TT

Note: TT is travel time, ATT is summation of actual-dwell-time & actual-travel-time and STT is summation of scheduled-dwell-time & scheduled-travel-time.

To assess the effectiveness of the proposed percentage-based measure, the conventional and proposed on-time performance measures are evaluated based on their standard deviations. Higher standard deviations indicate over-dispersed values resulting in in-appropriate representation of performance measures. On the other hand, the performance measures with smaller standard deviation values contain more homogenous values and are more reliable for operators to be considered as measures for planning.

CASE STUDY

Transit bus Route 11 in the Charlotte metropolitan area, which runs between Transit City Center and the University of North Carolina at Charlotte, was considered as the case study to illustrate and test the measures proposed in this research. Route 11 is 12 miles long, has 55 stops in the inbound direction and 56 stops in the outbound direction. The total number of fixed bus stops for inbound and outbound directions is 6; including bus start point and end point. Figure 1 shows Route 11 with fixed bus stops for both inbound (i.e., towards downtown) and outbound (i.e., away from downtown) directions. For illustration purposes, Table 2 summarizes the statistics of travel times, actual-travel-times and scheduled-travel-times for Route 11, segment 1, inbound direction during weekdays.

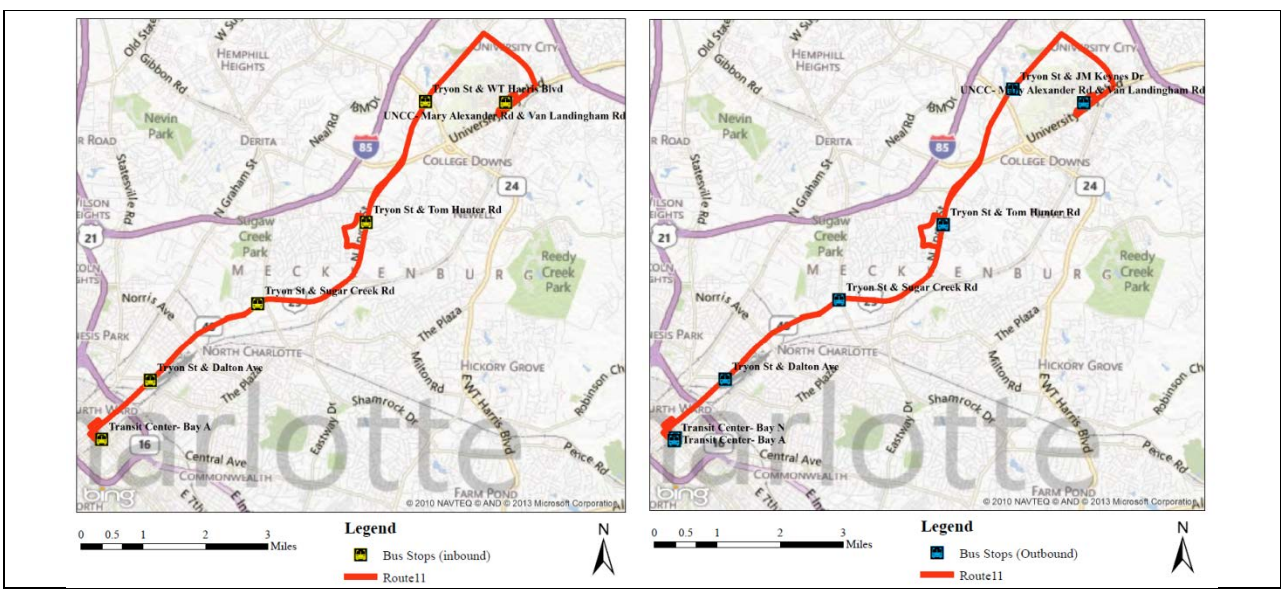

FIGURE 1 Route 11 with fixed bus stops - inbound (left) and outbound (right).

TABLE 2 Summary of Weekday Travel Times for Route 11, Segment 1, Inbound Direction for the Year 2012 based on Time-of-the-day

Time Period	Sample Size	Actual-Travel-Time (sec)			Scheduled-Travel-Time (sec)		
		Minimum	Average	Maximum	Minimum	Average	Maximum
7-9	1,296	612	1,216	2,748	660	1,022	2,460
9-11	1,272	556	969	1,827	780	987	2,400
11-13	1,269	616	974	1,996	720	868	1,920
13-15	1,316	584	1,517	3,094	720	1,425	1,920
15-17	1,188	610	1,621	3,119	780	1,562	1,920
17-19	1,053	576	1,160	3,071	840	1,368	3,540
19-7	3,861	430	1,038	3,636	720	955	1,800

Transit System Performance

The transit system performance along Route 11 is evaluated by comparing actual-travel-times with scheduled-travel-times on each segment between the fixed bus stops. Figure 2 and Figure 3 show the average values of scheduled-travel-time and the average values of actual-travel-times of Route 11 in the year 2012 for inbound and outbound directions, respectively. The travel time values are presented in these figures by the time period (7:00 - 9:00, 9:00 - 11:00, 11:00 - 13:00, 13:00 - 15:00, 15:00 - 17:00, 17:00 - 19:00, and 19:00 - 7:00) and the day-type (weekdays and weekends). It is evident from Figure 2 that there is no specific trend between scheduled-travel-times and actual-travel-times. On some segments (e.g., segment numbers 3 and 5), the actual-travel-time is always greater than the scheduled-travel-time. On the other hand, on some other segments (e.g., segment number 3) the scheduled-travel-time is higher than the actual-travel-time during weekdays, and is lower during weekends. Two interesting points can be noted from this figure. It is clear that almost on all the segments the weekdays' peak hour is located between 15:00 - 17:00 for inbound direction. It is also clear that CATS has tried to follow the trend of variations of actual-travel-time in the proposed scheduled-travel-time.

From Figure 3, the mean of actual-travel-time is observed to be greater than the mean of scheduled-travel-time in the downtown area (i.e., segment 1). Segments 4 and 5 (segment 5 does not have any service on weekends) have higher average scheduled-travel-times when compared to actual-travel-times. The weekdays' peak hour for outbound direction is from 17:00 - 19:00, which is different compared to weekdays' peak hour for the inbound direction. It is worth mentioning that the day-type has an important effect on the travel time. The average actual-travel-time (i.e., sum of travel time and dwell time) of weekends is higher than the average actual-travel-time of weekdays on all segments along Route 11. However, after 13:00, the condition is vice-versa. In fact, the congestion pattern during weekends is different than from weekdays (higher travel time during weekdays after 13:00, and higher travel time during weekends before 13:00). In addition, there is no specific peak hour over weekends.

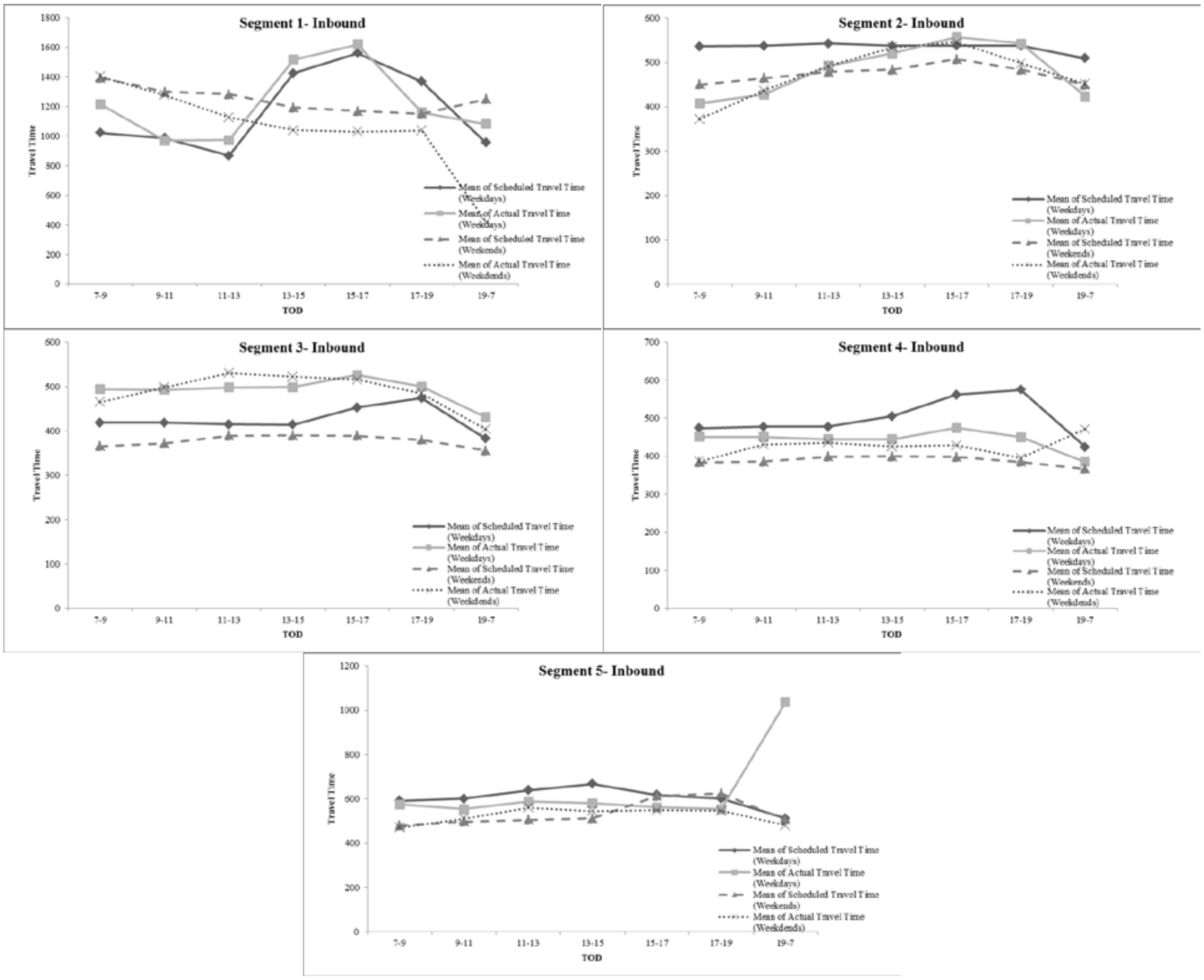

FIGURE 2 Scheduled- and actual-travel-times for inbound direction by time-of-the-day and day-type.

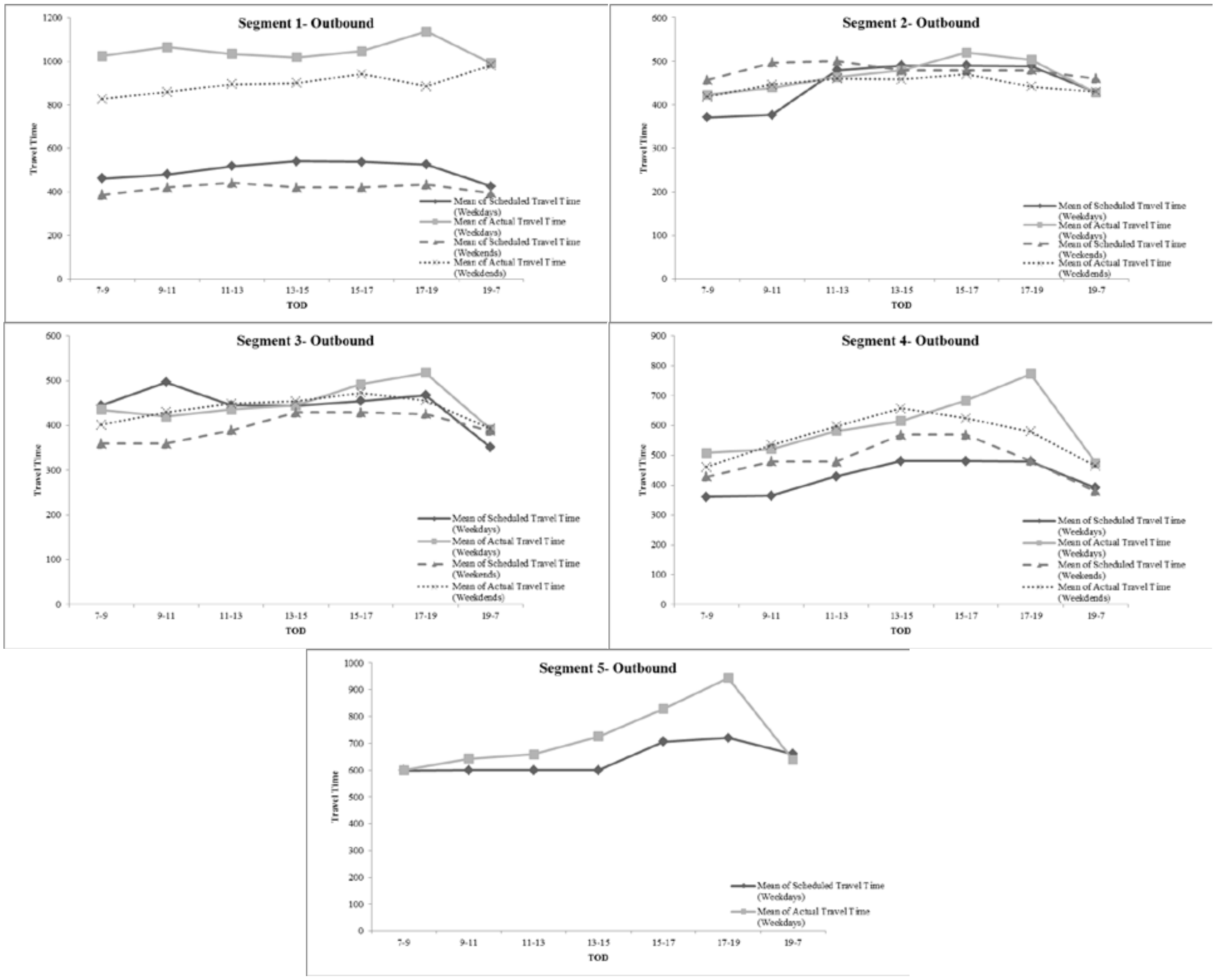

FIGURE 3 Scheduled- and actual-travel-times for outbound direction by time-of-the-day and day-type.

Transit Schedule Reliability

Transit schedule reliability was evaluated considering the link-level on-time performance measures. Table 3 shows the percentage of delays and early arrivals for Route 11. The measures are categorized into 0-1, 1-2, 2-3, 3-4, 4-5, and 5-10 minute intervals. From Table 3, Segment 1, inbound direction is experiencing major delays during morning peak hours (7:00 - 9:00) and also after 19:00 and before 7:00. Similarly, in the outbound direction, more than 30 percent of the times, Segment 1 has delays greater than 5 minutes for the entire day. Early arrivals greater than 1 minute are observed less than 1 percent of the time. This indicates lower scheduled-travel-times during these periods for this segment. The inbound direction is also experiencing more than 5-minute early arrivals frequently in between 13:00 and 19:00, indicating higher scheduled-travel-times during these time periods.

TABLE 3 Percentage of Delay and Early Arrivals for Route 11, Segment 1, Inbound and Outbound Direction during Weekdays in the Year 2012

Inbound – Delay (%)						
Time Period	0-1 Min	1-2 Min	2-3 Min	3-4 Min	4-5 Min	5-10 Min
7-9	9.34	8.49	7.33	7.25	6.40	20.91
9-11	12.97	8.18	9.43	5.90	4.40	4.72
11-13	11.51	14.74	10.72	11.82	6.70	13.32
13-15	4.94	6.08	5.70	5.24	4.03	7.60
15-17	5.30	3.70	4.46	2.27	2.36	6.57
17-19	5.32	3.42	3.13	3.61	2.66	7.12
19-7	7.64	7.49	6.55	6.03	5.83	20.49
Outbound – Delay (%)						
Time Period	0-1 Min	1-2 Min	2-3 Min	3-4 Min	4-5 Min	5-10 Min
7-9	0.68	1.28	3.12	2.96	4.28	40.39
9-11	1.49	2.21	2.48	3.62	3.01	33.31
11-13	1.95	2.58	3.82	5.92	5.88	37.26
13-15	2.86	3.77	4.42	6.21	4.73	39.12
15-17	1.99	2.69	3.24	4.88	6.13	44.16
17-19	2.60	3.13	3.26	5.20	4.33	30.45
19-7	2.11	3.00	4.05	4.33	4.79	36.78
Inbound - Early Arrival (%)						
Time Period	0-1 Min	1-2 Min	2-3 Min	3-4 Min	4-5 Min	5-10 Min
7-9	9.80	7.56	6.10	4.71	2.01	3.01
9-11	12.11	12.34	9.51	6.68	6.45	7.00
11-13	9.38	8.51	6.07	3.47	2.05	0.55
13-15	5.85	4.48	6.46	3.34	5.24	11.32
15-17	3.28	7.15	4.63	5.22	5.39	17.59
17-19	5.70	4.27	6.17	6.65	7.22	26.02
19-7	7.64	6.97	6.14	4.95	4.71	9.76
Outbound - Early Arrival (%)						
Time Period	0-1 Min	1-2 Min	2-3 Min	3-4 Min	4-5 Min	5-10 Min
7-9	0.00	0.00	0.00	0.00	0.00	0.00
9-11	1.03	0.69	0.19	0.08	0.04	0.04
11-13	1.27	0.64	0.40	0.08	0.04	0.00
13-15	2.21	1.30	0.50	0.04	0.08	0.00
15-17	1.05	0.70	0.35	0.04	0.04	0.00
17-19	1.13	0.47	0.40	0.00	0.00	0.00
19-7	1.14	0.45	0.22	0.04	0.02	0.02

Using each fixed range-based on-time performance measures mentioned in the methodology section, the percentage-based on-time performance measures for each segment of Route 11 is evaluated based on time-of-the-day and day-type for the year 2012. Table 4 shows the on-time performance measures for Route 11, inbound direction during weekday morning peak period (7:00 - 9:00), mid-day peak period (11:00 - 13:00), and evening peak period (17:00 -

19:00). Each cell in this table represents the percentage of observations that followed the defined range of on-time performance measure. From Table 4, more than 50% of the time, none of the segments on Route 11 have less than 1 minute difference between scheduled-travel-times and actual-travel-times. Segment 1 is observed to have most unreliable scheduled-travel-times when compared to other segments. This unreliability of scheduled-travel-time for segment 1 leads to delay/early arrival at subsequent stops affecting the reliability and performance of the entire route. Similarly, Segment 2 during morning peak period and Segment 4 during evening peak period follow a similar trend as segment 1, indicating that the scheduled-travel-times vary based on time-of-the-day for reliable transit services.

TABLE 4 Fixed-range based On-time Performance Measure for Route 11, Segment 1, Inbound Direction based on Time-of-the-day

Segment	Time Period	Fixed-range based On-time Performance Measure (%)				
		1 min	2 min	3 min	4 min	5 min
1	Morning peak	19.10	35.20	48.60	60.60	69.00
	Mid-day	20.90	44.10	60.90	76.20	84.90
	Evening peak	11.00	18.70	28.00	38.30	48.10
2	Morning peak	18.60	41.70	71.00	85.70	98.00
	Mid-day	35.60	69.10	92.30	98.70	99.70
	Evening peak	44.10	81.50	90.50	97.40	98.40
3	Morning peak	41.60	70.20	86.40	95.10	98.30
	Mid-day	39.00	66.60	83.70	92.30	96.50
	Evening peak	38.60	68.60	87.00	93.90	97.40
4	Morning peak	52.60	86.50	97.40	99.20	99.50
	Mid-day	45.10	80.50	94.90	98.00	99.10
	Evening peak	18.10	43.30	65.90	89.90	99.10
5	Morning peak	41.80	77.80	91.40	95.60	97.20
	Mid-day	34.50	64.30	86.10	95.00	97.70
	Evening peak	29.80	59.30	81.00	93.40	96.80

Similarly, the percentage-based proposed on-time performance measure for each segment along Route 11 was evaluated based on time-of-the-day and day-type for the year 2012. Table 5 shows the computed percentage-based on-time performance measure for Route 11, inbound direction, during weekdays during morning peak period (7:00 - 9:00), mid-day peak period (11:00 - 13:00) and evening peak period (17:00 - 19:00). Table 6 shows the LOS of each segment during the morning peak period, mid-day peak period and evening peak period, which is based on percentage-based performance measures.

To evaluate the effectiveness of the percentage-based on-time performance measures, the standard deviation of both the conventional and proposed measures are computed. Table 7 shows the standard deviation for studied on-time performance measures. From Table 7, the percentage-based measures have lower standard deviation values when compared with the fixed range-based measures indicating that the percentage-based performance measures are better than the fixed range-based measures in evaluating transit system reliability and performance.

TABLE 5 Percentage-based On-time Performance Measure for Route 11, Segment 1, Inbound Direction based on Time-of-the-day

Segment	Time Period	Proposed Percentage-based On-time Performance Measure (%)				
		5%	10%	15%	20%	25%
1	Morning peak	19.10	35.60	48.80	60.90	69.50
	Mid-day	18.00	35.10	53.00	64.80	76.80
	Evening peak	10.60	18.30	27.10	36.40	46.80
2	Morning peak	6.70	13.50	18.90	26.30	33.50
	Mid-day	15.90	29.90	43.40	58.30	71.30
	Evening peak	12.20	36.70	66.10	79.90	82.50
3	Morning peak	14.60	32.60	50.90	62.70	71.40
	Mid-day	15.80	32.80	47.60	59.00	67.70
	Evening peak	16.50	33.00	47.50	60.90	69.70
4	Morning peak	20.60	40.80	57.00	73.20	84.20
	Mid-day	16.50	33.00	49.70	64.10	76.60
	Evening peak	6.00	12.10	21.10	29.20	39.30
5	Morning peak	24.70	40.60	61.20	76.40	84.20
	Mid-day	17.70	33.60	49.00	63.40	75.60
	Evening peak	13.30	26.50	41.60	54.80	66.30

TABLE 6 LOS based on Percentage-based On-time Performance Measure

Segment	Time Period	LOS
1	Morning peak	D
	Mid-day	C
	Evening peak	F
2	Morning peak	F
	Mid-day	D
	Evening peak	C
3	Morning peak	C
	Mid-day	D
	Evening peak	D
4	Morning peak	C
	Mid-day	D
	Evening peak	F
5	Morning peak	C
	Mid-day	D
	Evening peak	D

TABLE 7 Comparison of On-time Performance Measures for Route 11, Segment 1, Inbound Direction based on Time-of-the-day

Range-Based On-time Performance Measures	Standard Deviation	
	Inbound	Outbound
STT ± 1 Minutes	13.49	21.27
STT ± 2 Minutes	19.12	32.01
STT ± 3 Minutes	18.47	34.25
STT ± 4 Minutes	15.82	33.38
STT ± 5 Minutes	13.05	31.67
Percentage-Based On-time Performance Measures	Inbound	Outbound
STT ± 5% of Average TT	4.86	9.45
STT ± 10% of Average TT	8.74	16.8
STT ± 15% of Average TT	12.01	22.57
STT ± 20% of Average TT	13.98	26.61
STT ± 25% of Average TT	14.33	28.61

Note: TT is travel time and STT is summation of scheduled-dwell-time & scheduled-travel-time.

CONCLUSIONS

Analysis was conducted using AVL data captured from buses to assess temporal variations in the performance measures. The actual-travel-times were computed for each run on each link and compared with the scheduled-travel-time. The computed travel times varied from one link to another link. They also tend to vary by the area type (downtown / core urban area to suburban area). Traffic volume, time-of-the-day and day-type (weekday or weekend), as expected, were observed to influence bus travel times along a link.

The arrival of a bus at a bus stop has a strong correlation with travel time along the previous links and delays incurred at the previous bus stops. Five different ranges of delay or early arrival time (difference between the scheduled-travel-time and actual arrival time; ± 1/2/3/4 or 5 minutes) were, therefore, computed for each sample (link) to assist in the assessment of link-level transit system performance. As this performance measure does not consider the effect of length and other traffic characteristics of the segment, this research recommends using the percentage of times the actual-travel-times and scheduled-travel-times differ (± 0.05/0.1/0.15/0.2 or 0.25 times of average travel time) between bus-stops for use in assessing transit system performance. Transit performance LOS criteria were proposed for this percentage-based performance measure.

To evaluate the effectiveness of the proposed percentage-based on-time performance measures, standard deviation was computed and compared for the percentage-based and range-based performance measures. Results show that defined percentage-based on-time performance measure has lower standard deviation values for all directions, study durations, and segments considered in this research. Therefore, the proposed percentage-based performance measures and LOS criteria are more reliable than fixed range-based measures for operators to be considered as a measure for planning and assessment of operational performance at link-level.

The tolerance level and expectations of passengers may vary based on their trip length (example, longer delay for a longer trip compared to longer delay for a shorter trip). This might play a vital role in evaluating transit LOS from passengers’ perspective. Incorporating these aspects in evaluating LOS measures based on passengers’ perspective merit an investigation.

The study was performed using data for one mode (bus) in a medium-density city. Further research is needed in a variety of settings considering data for different modes before the method or LOS criteria could be adopted by transit operators.

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DISCLAIMER

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REFERENCES

1. Status of the Nation’s Highways, Bridges, and Transit: 2002 Conditions and Performance Report, Chapter 14: Transit User Characteristics and System Benefits, FHWA. http://www.fhwa.dot.gov/policy/2002cpr/pdf/ch14.pdf. Accessed on July 30, 2013.
2. Transit Capacity and Quality of Service Manual - 2nd Edition, Part 3: Quality of Service. Published by the Transportation Research Board. http://onlinepubs.trb.org/onlinepubs/tcrp/tcrp100/part%203.pdf. Accessed on July 30, 2013.
3. Rietveld, P., F. R. Bruinsma, and D. J. Van Vuuren. Coping with Unreliability in Public Transport Chains: A Case Study for Netherlands. Transportation Research Part A, Vol. 35, 2001, pp. 539-559.
4. Shuai, D., L. Hao, and C. Yanyan. Time Reliability of Urban Public Transit. The Eighth International Conference of Chinese Logistics and Transportation Professionals, Published by American Society of Civil Engineers, China, 2008.
5. Benn, H. P. TCRP Synthesis of Transit Practice 10: Bus Route Evaluation Standards. Transportation Research Board of the National Academies, Washington, DC, 1995. http://gulliver.trb.org/publications/tcrp/tsyn10.pdf. Accessed on July 30, 2013.
6. Camus R., G. Longo, and C. Macorini. Estimation of Transit Reliability Level-of-Service Based on Automatic Vehicle Location Data. In Transportation Research Record: Journal of the Transportation Research Board, No. 1927, Transportation Research Board of the National Academies, Washington, DC, 2005, pp. 277–286.
7. National Center for Transit Research, Center for Urban Transportation Research. Transit Ridership, Reliability, and Retention. Final Report # FDOT BD-549-32, 2010.
8. Wakabayashi, H. Travel Time Reliability Indexes for Highway Users and Operators. The 4th International Symposium on Transportation Network Reliability, Minneapolis, USA, 2010.

9. Elefteriadou, L., and X. Cui. Review of Definitions of Travel Time Reliability. 2005. http://www.dot.state.fl.us/planning/statistics/mobilitymeasures/define-ttr.pdf. Accessed July 30, 2013.
10. Lyman, K., and R. L. Bertini. Using Travel Time Reliability Measures to Improve Regional Transportation Planning and Operations. In Transportation Research Board 87th Annual Meeting, Transportation Research Board of the National Academies, Washington, DC, 2008.
11. van Lint, J. W. C., and H. J. van Zuylen. Monitoring and Predicting Freeway Travel Time Reliability Using Width and Skew of the Day-to-Day Travel Time Distribution. In Transportation Research Board 84th Annual Meeting Compendium of Papers, Transportation Research Board of the National Academies, Washington, DC, 2005.
12. Travel Time Reliability. Federal Highway Administration, Report # FHWA-HOP-06-070, US Department of Transportation.
13. Kimpel, T. J. Time Point-Level Analysis of Transit Service Reliability and Passenger Demand. Ph.D. dissertation, Portland State University, 2001.
14. Bates, J. W. Definition of Practices for Bus Transit On-time Performance: Preliminary Study. Transportation Research Circular, No. 300, 1986.
15. Diab, E. I. and A. M. El-Geneidy. Variation in Bus Transit Service: Understanding the Impacts of Various Improvement Strategies on Transit Service Reliability. In Transportation Research Board 92nd Annual Meeting Compendium of Papers, Transportation Research Board of the National Academies, Washington, DC, 2013.
16. Furth, P., and T. Muller. Service Reliability and Hidden Waiting Time: Insights from Automatic Vehicle Location Data. In Transportation Research Record: Journal of the Transportation Research Board, No. 1955, Transportation Research Board of the National Academies, Washington, DC, 2006, pp. 79-87.
17. Levine, B., A. Lu, and A. V. Reddy. Measuring Subway Service Performance at New York City Transit: A Case Study Using Automated Train Supervision (ATS) Track-Occupancy Data. In Transportation Research Board 92nd Annual Meeting Compendium of Papers, Transportation Research Board of the National Academies, Washington, DC, 2013.
18. Trompet, M., X. Liu, and D. J. Graham. Development of Key Performance Indicator to Compare Regularity of Service Between Urban Bus Operators. In Transportation Research Record: Journal of the Transportation Research Board, No. 2216, Transportation Research Board of the National Academies, Washington, DC, 2216, 2011, pp. 33-41.
19. Henderson, G., H. Adkins, and P. Kwong. Toward a Passenger Oriented Model of Subway Performance. In Transportation Research Record: Journal of the Transportation Research Board, No. 1266, Transportation Research Board of the National Academies, Washington, DC, 1990, pp. 221-228.
20. Uniman, D. L., J. Attanucci, R. G. Mishalani, and N. H. M. Wilson. Service Reliability Measurement Using Automated Fare Card Data: Application to the London Underground. In Transportation Research Record: Journal of the Transportation Research Board, No. 2143, Transportation Research Board of the National Academies, Washington, DC, 2010, pp. 92-99.
21. Henderson, G., P. Kwong, and H. Adkins. Regularity Indices for Evaluating Transit Performance. In Transportation Research Record: Journal of the Transportation Research Board, No. 1297, Transportation Research Board of the National Academies, Washington, DC, 1297, 1991, pp. 3-9.

22. Saberi, M., K. A. Zockaie, W. Feng, and A. El-Geneidy. Definition and Properties of Alternative Bus Service Reliability Measures at the Stop Level. Journal of Public Transportation, Vol. 16, Issue 1, 2013, pp. 97-122.
23. Schil, M. Measuring Journey Time Reliability in London Using Automated Data Collection Systems. M.Sc. Thesis, Massachusetts Institute of Technology, 2012.
24. Bunker, J. Planning for Transit System Reliability Using Productive Performance and Risk Assessment. In Transportation Research Board 92th Annual Meeting Compendium of Papers, Transportation Research Board of the National Academies, Washington, DC, 2013.