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ORIGINAL ARTICLE

Using Link-Level Archived Automatic Vehicle Location Data to Assess Transit System LOS at Bus-Stop Level

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Abstract

The focus of this paper is on assessment of transit system level-of-service (LOS) at bus-stop level using the proposed percentage-based performance measure and compare it with the fixed-range-based performance measure. Data captured through automatic vehicle location (AVL) units installed on Charlotte Area Transit System (CATS) buses for 2012 and archived was used to develop query tools and compute link-level transit system performance measures, conduct analysis, and derive meaningful interpretations. The query tools developed computed performance measures 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 a year. Actual delay time and early arrivals as well as percentage of delays and early arrivals were computed to assist in the assessment. The analysis was conducted by time-of-the-day and day-of-the-week, for both travel directions, along selected bus routes/segments to assist in assessing the applicability of the measures. Findings from the research indicate that percentage-based performance measure is more reliable than fixed-range-based performance measure (delay or difference in travel time) for planning and assessment of operational performance by transit agencies.

Keywords Transit · LOS · AVL · Performance · Bus stop

Introduction

Public transportation or transit system helps reduce road congestion and travel time, thereby reducing energy consumption and air pollution. In addition, transit system provides people with mobility and access to employment, community resources, medical care centers, and recreational facilities in communities across America [1]. The performance of a transit system plays a vital role for over 90% of transit system passengers who do not own a car and rely on this system [1]. According to the Federal Highway Administration (FHWA), 50% of transit system passengers travel to or from work, 12% to or from college or school, and 4% to access medical services [1].

Travel time reliability, on-time performance, delay, safety, security, comfort, convenience, frequency, hours of service, service coverage, transfer time, and passenger environment are all vital to provide an amicable and attractive transit system to the passengers. The previously outlined statistics indicate that the reliability of transit system is important for at least 66% of transit system passengers who need to know their expected travel time to a given destination, to be on time. This research, therefore, focuses on on-time performance and travel time reliability as transit system performance measures to improve LOS.

According to the Highway Capacity Manual (HCM) and Transit Capacity & Quality of Service Manual (TCQSM), on-time performance is one of the most important measures to evaluate the LOS or quality of transit system performance,

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especially from passengers' perspective [2, 3]. In addition, it is the most widely used reliability measure in transit industry. According to Rietveld et al. [4], 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 traffic congestion, the number of passengers alighting and boarding the bus, service headway, and incidents [4]. The aforementioned factors also increase passengers waiting time [5].

Researchers are still trying to find an insightful definition for on-time performance. In Transit Cooperative Research Program (TCRP) Synthesis of Transit Practice [6], on-time performance standards of more than 80 agencies were reviewed. About 42% of these agencies allow buses to be more than 5 min late and account it as on-time, while 24% 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 min in advance and 5 min late) without considering the amount of delay or early departure [7].

Travel time reliability is vital for transit system passengers. Depending on the trip length and the total travel time, the cost of unreliable service may be greater than the cost of travel time [8]. 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 [8]. Various concepts of transportation reliability have been proposed in the past. These include connectivity reliability, capacity reliability, encountered reliability, performance reliability, flow decrement reliability, mode choice reliability, and travel time reliability [9]. The level of variability between the expected travel time (scheduled, average, or median travel time) and the actual travel time is defined as travel time reliability [10]. Researchers in the past have found that users prefer routes with higher mean travel times and smaller travel time variation to routes with a lower mean travel time and larger variability [11, 12].

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 influence the running time deviation from schedule, the variation in running time, and the variation in running time deviation from schedule [13]. While on-time performance is vital [14], transit service reliability [15], subway service performance [16], comparing regularity of transit service [17], and measuring service experienced by riders [18, 19] are equally important. As most of these performance measures do not have control on the size of headways and cannot be used to compare one route with another route, headway regularity index and passenger wait index were used to evaluate transit system performance [20]. Saberi et al. [20] proposed bus-stop-level reliability measures using empirical data from archived Bus Dispatch System (BDS) data in Portland, Oregon to evaluate and prioritize bus stops for operational improvement purposes such as bus holdings or schedule adjustments.

The NCHRP report on "Multimodal Level-of-Service Analysis for Urban Streets" describes various LOS criteria for transit system based on service quality and transit system elements such as bus-stop level, segment level, and system level [21]. For bus stops, the frequency of service is considered as the LOS criterion. For bus route segments and corridors, the hours of service are considered as the LOS criterion. At the system level, the service coverage area as a percentage of transit supportive area is considered as the LOS criterion. Availability, comfort, and convenience are considered as the LOS criteria to evaluate the service quality.

In this research, the reliability of link-level scheduled travel times is evaluated by time-of-the-day and day-of-the-week to assess the transit system performance. A new percentage-based on-time performance measure is introduced to serve as a more robust method to evaluate transit system reliability and LOS at bus-stop level. This is based on percentage of times travel time is different than scheduled travel time rather than just the differences.

Methodology

The AVL data collected at fixed bus stops during 2012 by Charlotte Area Transit System (CATS) were obtained and used in this research. Unlike other bus stops, where the bus driver decides to stop if requested by at least one alighting or boarding passenger, buses must stop at the fixed bus stops. The AVL data have stop-level data with times at each bus stop for all the days in the year 2012. Data for, both, inbound and outbound directions were considered for the analysis.

The data were categorized based on the direction (inbound and outbound), segment (between two consecutive fixed bus stops), day-of-the-week (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 develop a new database. Travel times (the travel time between two fixed bus stops), actual travel times (summation of dwell time and travel time), and scheduled travel times (summation of scheduled dwell time and scheduled travel time) for each segment were computed. In addition, various statistics (minimum, maximum, and average) of these travel time measures, for each segment, were computed based on the direction, time-of-the-day, and day-of-the-week.

The transit system performance of each route was evaluated by comparing actual travel times with scheduled travel times on each segment between the fixed bus stops. Transit system performance at each bus stop may have a strong correlation with the performance of the previous and next bus stop and road segments, as the delay at each bus stop will be added to the delays at following bus stops. Therefore, the performance of scheduled travel times was evaluated based on travel times between segments instead of considering performance at bus stops. Considering the transit system 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 system reliability was evaluated by assessing 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 system 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 at the following bus 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 at the following bus stop later than the expected time. This delay might be because of longer 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:

$$\begin{cases} \text{Scheduled travel time} - \text{actual travel time} > 0 : & \text{Early arrival} \\ \text{Scheduled travel time} - \text{actual travel time} < 0 : & \text{Delay} \end{cases}. \quad (1)$$

The definition of on-time performance based on TCQSM assumes that the severity of delay or early performance is the same without considering the amount of delay or early departure [5, 12]. 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:

$$-\delta \geq [\text{scheduled travel time} - \text{actual travel time}] \leq +\delta,$$

where $\delta = (1\text{ min},\ 2\text{ min},\ 3\text{ min},\ 4\text{ min},\text{ and } 5\text{ min})$.

The aforementioned conventional performance measure does not consider the length of the segment and categorize the performance 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, proposes a new set of on-time performance measure. In the proposed performance measure, instead of the values of 1, 2, 3, 4, or 5 min, a percentage of average travel time is applied to define the on-time performance. 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 expressed as follows:

$$-\delta(\text{aveTT}) \geq [\text{scheduled travel time} - \text{actual travel time}] \leq +\delta(\text{aveTT}),$$

where $\delta = (5\%,\ 10\%,\ 15\%,\ 20\%,\text{ and } 25\%)$.

New LOS criteria, to indicate transit system performance measure, are proposed based on the aforementioned percentage-based performance measure. Table 1 summarizes the proposed LOS based on the percentage-based performance measure.

The conventional and proposed on-time performance measures are evaluated based on their standard deviations to make meaningful interpretations. Higher standard deviation indicates over-dispersed values resulting in in-appropriate representation of the performance measure. On the other hand, the performance measure with smaller standard deviation is more homogenous and, therefore, more reliable for agencies 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. Table 2 summarizes the travel times, actual travel

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

TT travel time, *ATT* summation of actual dwell time and actual travel time, *STT* summation of scheduled dwell time and scheduled travel time

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 (s)			Scheduled travel time (s)		
		Minimum	Average	Maximum	Minimum	Average	Maximum
7–9	1296	612	1216	2748	660	1022	2460
9–11	1272	556	969	1827	780	987	2400
11–13	1269	616	974	1996	720	868	1920
13–15	1316	584	1517	3094	720	1425	1920
15–17	1188	610	1621	3119	780	1562	1920
17–19	1053	576	1160	3071	840	1368	3540
19–7	3861	430	1038	3636	720	955	1800

times and scheduled travel times for Route 11, segment 1, inbound direction during weekdays.

Transit System Performance

The transit system performance along Route 11 was evaluated by comparing actual travel times with scheduled travel times on each segment between the fixed bus stops. Figure 1 shows 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-of-the-week (weekdays and weekends). It is evident from Fig. 1 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 was always greater than the scheduled travel time. On the other hand, on some other segments (e.g., segment number 3), the scheduled travel time was higher than the actual travel time during weekdays, and was lower during weekends. Two interesting points can be noted from this figure. On almost all the segments, the weekday peak hour is between 15:00 and 17:00 for inbound direction. It is also clear that CATS tried to follow the trends in variation of actual travel time in their proposed scheduled travel time.

From Fig. 1, 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 did not have any service during weekends in 2012) have higher average scheduled travel times when compared to actual travel times. This indicates that the transit system travel time varies by area type (higher in downtown/core urban areas when compared to suburban areas). The weekday peak hour for outbound direction is from 17:00 to 19:00, which is different compared to weekday peak hour for the inbound direction. It is worth mentioning that the day-of-the-week influences 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. The congestion pattern during weekends is different than for 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.

Transit Schedule Reliability

Transit schedule reliability was evaluated considering the 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-min intervals. From Table 3, Segment 1, inbound direction has experienced major delays during morning peak hours (7:00–9:00) and 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 min for the entire day. Early arrivals greater than 1 min were observed less than 1 percent of the time. This indicates lower scheduled travel times during these periods for this segment. The inbound direction was also experiencing more than 5-min early arrivals frequently between 13:00 and 19:00, indicating higher scheduled travel times during these time periods.

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-min difference between scheduled travel times and actual travel times. Segment 1 was observed to have most unreliable scheduled travel times when compared to other considered 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

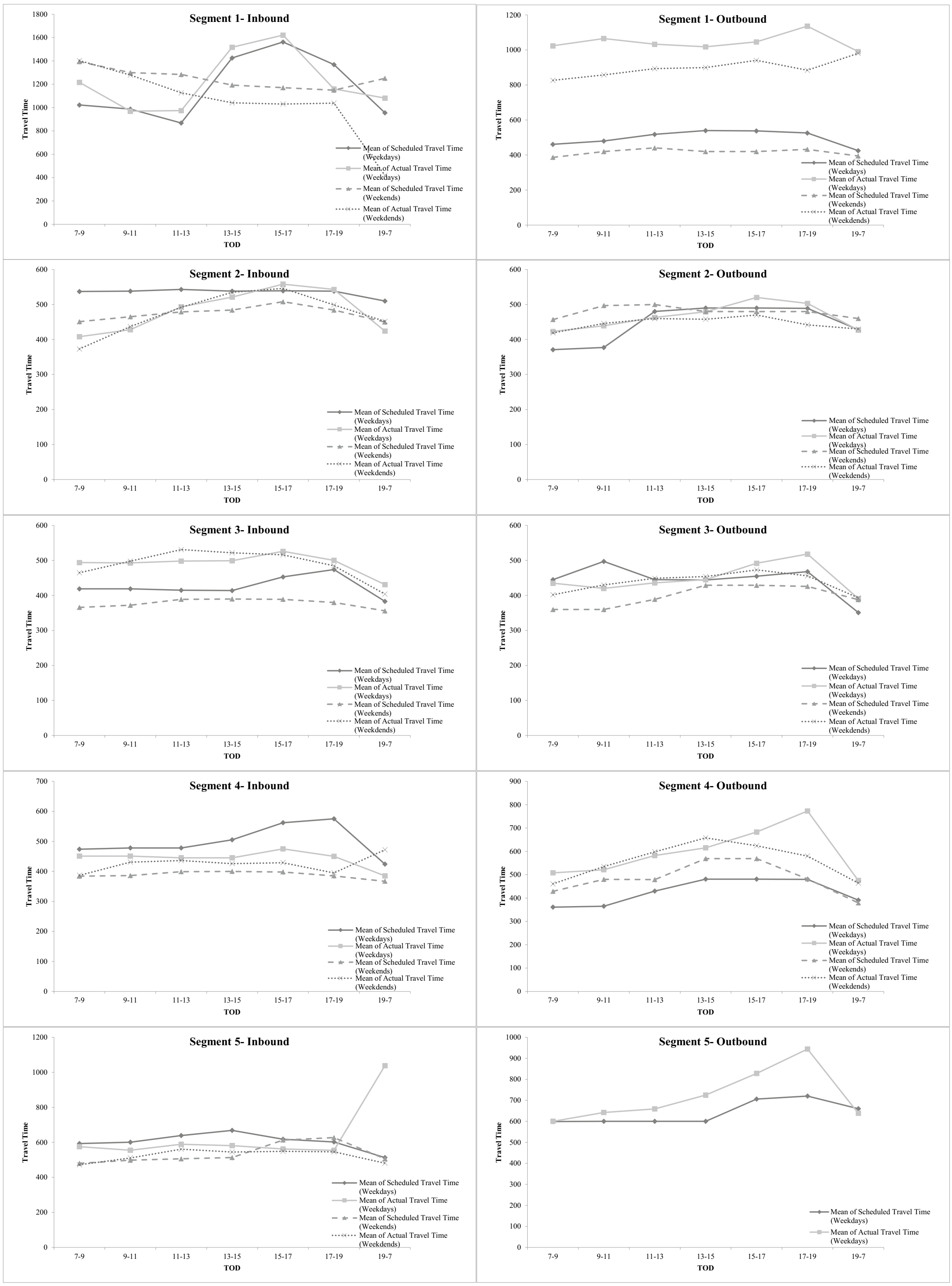

Fig. 1 Scheduled and actual travel times for inbound (left) and outbound (right) direction by time-of-the-day and day-of-the-week

Table 3 Percentage of delay and early arrivals for route 11, segment 1, inbound and outbound direction during weekdays in the year 2012

Time period	0–1 min	1–2 min	2–3 min	3–4 min	4–5 min	5–10 min
Inbound—Delay (%)						
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 (%)						
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 (%)						
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 (%)						
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

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.

The percentage-based proposed on-time performance measure for each segment along Route 11 was computed by time-of-the-day and day-of-the-week for the year 2012. Table 5 shows the computed percentage-based on-time performance measure for Route 11, inbound direction, during weekday's 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 based on percentage-based performance measures. From Table 6, none of the links along Route 11 have LOS 'B' or better. This indicates that the scheduled travel times and the actual travel times on Route 11 do not comply with each other resulting in early arrivals or late arrivals of buses at bus stops on Route 11.

Figure 2 shows the total percent of links in the study area (inbound and outbound) in each LOS category (LOS "A" to LOS "F") based on fixed-range-based and proposed percentage-based methods. From Fig. 2, based on the proposed percentage-based method, less than 20% of links have LOS 'B' or better during morning, mid-day, and evening peak hours, while ~ 35% of the links are performing at LOS 'F'. This indicates that, as observed in the case of Route 11, the scheduled times of arrivals at bus stops do not correlate with actual arrival times, resulting in early arrivals or late arrivals.

To evaluate the effectiveness of the percentage-based on-time performance measures, the standard deviation of both the conventional and proposed measures was computed. Table 7 shows the standard deviation for studied on-time

Table 4 Fixed-range-based on-time performance measure for route 11, 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

Table 5 Percentage-based on-time performance measure for route 11, 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

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.

Conclusions

Analysis was conducted using AVL data captured from buses to assess temporal variations in the performance measures. The arrival of a bus at a bus stop may have a strong correlation with travel time along the previous links and delays incurred at the previous bus stops, as the delay at each bus stop is propagated to the next 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 min) were, therefore, computed for each sample (link) to assist in the assessment of 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, 0.10, 0.15, 0.20, or 0.25 times of average travel time) between bus stops for use in assessing transit system

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

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. The results obtained show that the proposed 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 agencies to be considered as a measure for planning and assessment of operational performance. These measures can also be used for better scheduling of transit services by agencies for improved performance.

The frequency of transit could also play a significant role when, both, delayed and early arrivals are considered in evaluating the transit performance. The proposed percentage-based performance measures are defined as function of average travel times on the previous links considering both delayed and early arrivals. However, to incorporate wide variations in travel time into performance measures, the use of standard deviation/variance in travel times on the previous links along with frequency of transit in evaluating performance measures merits further investigation.

The perceptions of transit system passengers on on-time arrivals and sharing information related to arrival time is important and need to be accounted for when assessing transit system performance. LOS measures should be based on these perceptions and acceptable thresholds. Collecting such data and incorporating passenger's perceptions merit further investigation.

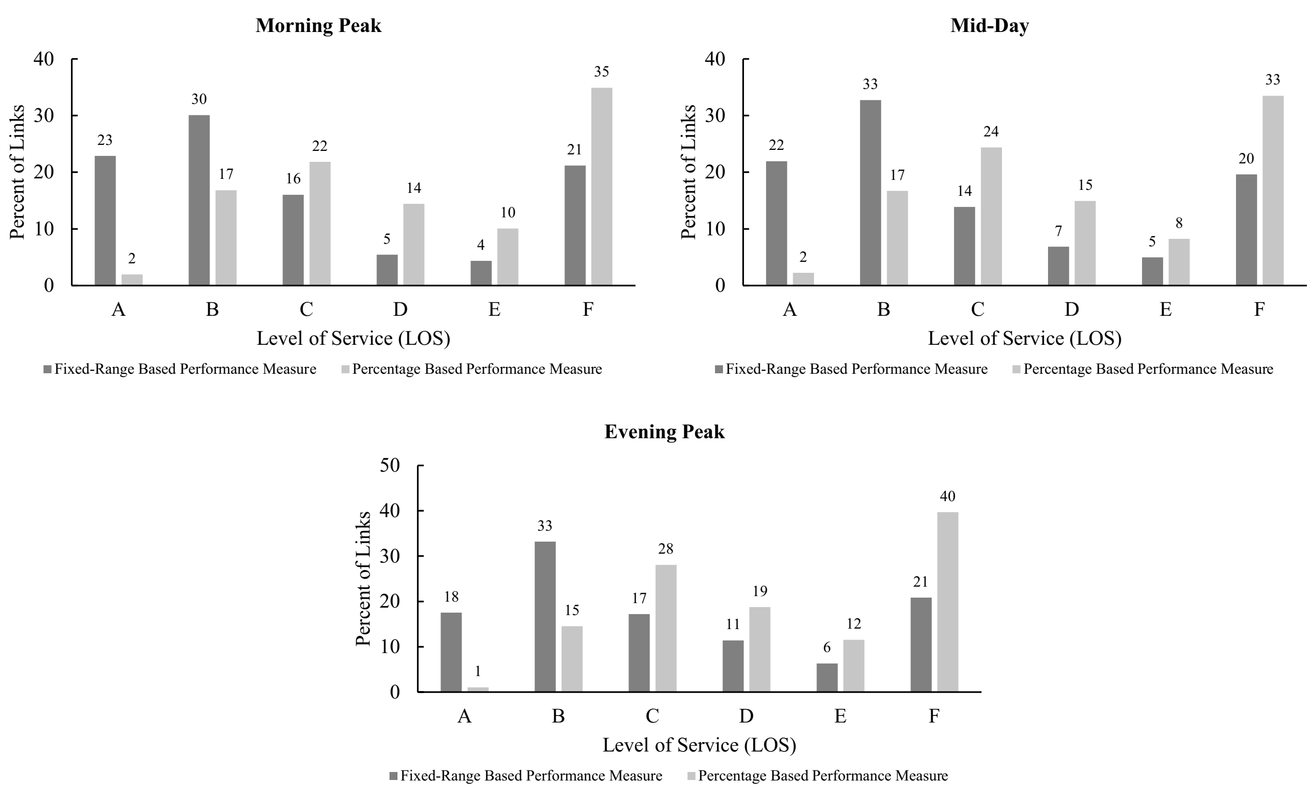

Fig. 2 Scheduled and actual travel times for outbound direction by time-of-the-day and day-of-the-week

Table 7 Comparison of on-time performance measures for route 11, segment 1, inbound direction based on time-of-the-day

	Standard deviation	
	Inbound	Outbound
Range-based on-time performance measures		
STT ± 1 min	13.49	21.27
STT ± 2 min	19.12	32.01
STT ± 3 min	18.47	34.25
STT ± 4 min	15.82	33.38
STT ± 5 min	13.05	31.67
Percentage-based on-time performance measures		
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

TT travel time, *STT* summation of scheduled dwell time and scheduled travel time

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References

1. FHWA (2002) The importance of public transportation. http://www.fhwa.dot.gov/policy/2002cpr/pdf/ch14.pdf. Accessed 30 Jul 2013
2. TRB. Highway Capacity Manual 2010 (2010) Transportation Research Board of the National Academies, Washington, DC
3. TCRP (1999) Transit capacity and quality of service manual. http://onlinepubs.trb.org/onlinepubs/tcrp/tcrp100/part%203.pdf. Accessed on 30 Jul 2013
4. Rietveld P, Bruinsma FR, Van Vuuren DJ (2001) Coping with unreliability in public transport chains: a case study for Netherlands. Transp Res Part A 35:539–559
5. Shuai D, Hao L, and Yanyan C (2008) Time reliability of urban public transit. In: The Eighth International Conference of Chinese Logistics and Transportation Professionals, Published by American Society of Civil Engineers, China
6. TCRP (2003) Traveler response to transportation system changes: an interim introduction to handbook. http://gulliver.trb.org/publications/tcrp/tsyn10.pdf. Accessed 30 Jul 2013
7. Camus R, Longo G, and Macorini C (2005) Estimation of transit reliability level-of-service based on automatic vehicle location data. In: Transportation research record, no. 1927, p 277–286
8. NCTR (2010) Transit ridership, reliability, and retention, Center for Urban Transportation Research, Final Report # FDOT BD-549-32
9. Wakabayashi H (2010) Travel time reliability indexes for highway users and operators. In: The 4th international symposium on transportation network reliability, Minneapolis, USA
10. Elefteriadou L and Cui X (2005) Review and definitions of travel reliability. http://www.dot.state.fl.us/planning/statistics/mobilitymeasures/define-ttr.pdf. Accessed 30 Jul 2013
11. Lyman K, Bertini RL (2008) Using travel time reliability measures to improve regional transportation planning and operations. In: Transportation research board 87th annual meeting, Washington, DC
12. van Lint JWC, van Zuylen HJ (2005) 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, Washington, DC
13. Bates JW (1986) Definition of practices for bus transit on-time performance: preliminary study, transportation research circular, no. 300
14. Diab EI, El-Geneidy AM (2013) Variation in bus transit service: understanding the impacts of various improvement strategies on transit service reliability. In: Transportation research board 92nd annual meeting, Washington, DC
15. Furth P, and Muller T (2006) Service reliability and hidden waiting time: insights from automatic vehicle location data. In: Transp. Res. Record, No. 1955, pp 79–87
16. Levine B, Lu A, and Reddy AV (2013) 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, Washington, DC
17. Trompet M, Liu X, Graham DJ (2011) Development of key performance indicator to compare regularity of service between urban bus operators. In: Transportation research record, no. 2216, pp 33–41
18. Henderson G, Adkins H, Kwong P (1990) Toward a passenger oriented model of subway performance. In: Transportation research record, no. 1266, pp 221–228
19. Uniman DL, Attanucci J, Mishalani RG, Wilson NHM (2010) Service reliability measurement using automated fare card data: application to the London underground. In: Transportation research record, no. 2143, pp 92–99
20. Saberi M, Zockaie KA, Feng W, El-Geneidy A (2013) Definition and properties of alternative bus service reliability measures at the stop level. J Public Transport 16(1):97–122
21. Dowling R, Reinke D, Flannery A et al (2008) Multimodal level of service analysis for urban streets. In: NCHRP Report 616, Transportation Research Board of the National Academies of Sciences, Washington, DC