# Route performance evaluation of a closed bus rapid transit system using GPS data

*Ankit Kathuria*, M. Parida and Ch. Ravi Sekhar*

*GPS-fitted buses operating in bus rapid transit systems (BRTS) of India make it easier to collect a wealth of travel-time data from them. This article evaluates the operational performance of BRTS routes based on GPS data. First, various simplified statistical range parameters, viz. coefficient of variation percentile travel time, travel-time distributions, etc. are selected for route evaluation. Then, two bus routes of the Ahmedabad BRTS are selected as case study to develop and validate a methodology for evaluating the performance of these routes based on selected parameters. Weekday bus travel-time data for one direction accounting for 2124 bus trips are used in the study. The study then compares travel-time reliability-based performance of a BRT and a non-BRT route. Further, the study proposes an approach to measure a shift in BRTS network level of service based on two indices – average travel time per kilometre, and travel-time coefficient of variation. A left shift in cumulative plot indicates an improvement in the BRTS network level of service in the year 2016 compared to 2013.*

**Keywords:** Bus rapid transit systems, GPS data, route performance, statistical parameters.

PUBLIC transportation systems like bus rapid transit system (BRTS) are becoming popular all over the world because of their strong identity and low initial investment[1,2]. Satiennnam *et al.*[3] reported that BRTS has the capability of bringing a significant modal shift from private vehicles. BRTS are running in eight cities of India[4]; buses running in these systems are mostly GPS-fitted which helps in collecting a wealth of travel-time data, but the methodologies to use the same for performance evaluation and system monitoring are limited. This article evaluates the performance of BRTS using the aforesaid GPS data for two routes in Ahmedabad. Both the selected routes operate from the innermost part of the city and then extend to the outer areas. These routes are majorly segregated from the normal traffic, but wherever sufficient right of way was not available, the buses were running with mixed traffic. It is thus important to evaluate the performance of such routes and carry out a segment-level analysis. Further, we have compared travel-time reliability of a BRTS and a non-BRTS route having similar characteristics in terms of land use and right of way. This was done to show the advantage of BRTS corridor in terms of travel-time reliability. Finally, after route evaluation we present a travel-time reliability and stability-based network level of service analysis. This was based on two indices, i.e. how the level of service had changed from 2013 to 2016 with the changing corridor length from 61 to 89 km.

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## Literature review

Studies in the past have reported using GPS data for various analyses in a bus transit system. The initial studies used GPS data to estimate travel time from the bus location data[5]. After developing techniques for travel-time estimation from GPS data, historical data were utilized for predicting travel time using artificial neural network and Kalman filter method[6,7]. Using the travel-time estimation, average commercial speed of the buses was also estimated[8]. After the travel-time estimation and prediction studies, the travel-time variability (TTV) and reliability studies were reported[5,9–12]. Day-to-day and period-to-period travel-time reliability analysis was also carried out earlier[13]. GPS data were used to develop transit level of service based on the criterion of 'on time performance', in which the percentage of vehicles not arriving on time was computed by considering a vehicle to be on time if it was not more than 5 min late or 3 min early[14]. In another study, a new form of level of service (LOS) criterion was suggested based upon the weighted delay and acted as improvement over the conventional Transit Capacity and Quality Service Manual (TCQSM)[14] level of service ranges[15]. GPS data were also used to evaluate bus priority system; for which they were fed into a simulation software for carrying out sensitivity analysis[16].

The present study is different from the above-mentioned studies as it first evaluates performance based on the two perspectives, i.e. transit operation and transit regulation. The performance evaluation based on transit operation uses indices like percentile travel time, coefficient of variation (COV) of travel-time, average journey speed and travel-time distribution, whereas transit regulation uses indices like schedule adherence and headway regularity. Further, segment-level analysis is carried out for the BRTS corridors as these are partly segregated and partly unsegregated. Hence it is of practical significance to study how travel time varies among different segments. After a thorough route-level analysis, the present study also carries out a network-level LOS analysis.

## Identifying performance indices

### *Route performance indices*

For evaluating BRTS route performance, the user and operators perspectives have to be clearly understood. Users seek performance in terms of punctuality of the buses, which is further linked with the waiting time at stops. Some other factors like cleanliness inside the bus and at the stop, seat availability, ride comfort, etc. are also part of the users' perceived performance measurement. Since the present study is based on the use of GPS data, only measures using the same will be discussed.

Punctuality as perceived by the users can be measured in terms of schedule adherence and headway regularity. Here schedule adherence implies the percentage of buses reaching a stop at a pre-determined schedule. Headway regularity helps understand whether the time gap between the transit units is maintained every day, or not. Irregularity in headways can cause bus bunching at the stops leading to more waiting time for the passengers on stop. Osuna and Newell[17] reported that if the frequency of transit units in a system is higher, then the passengers start arriving randomly and the aggregated waiting of the passengers is reduced. Therefore, schedule adherence and headway regularity can be used as measures reflecting the level of service from the users' point of view.

On the other hand, operators are concerned with actual operating conditions. The operational reliability can be measured within a day or day to day. Various statistical range parameters used to evaluate it are presented below.

First COV, which is the ratio of standard deviation to mean of the travel time, helps in standardizing the TTV so that it can be compared between the routes and the segments. Greater the COV value, more will be the TTV. In the present study, COV-based monochromatic TTV maps have been developed using MATLAB software. Secondly, 95th percentile travel time or the planning time is used as a measure to evaluate reliability. The 95th percentile travel time denotes how bad the transit delay can be during the worst-case scenarios. Thirdly, T90 – T10, i.e. the difference of the 90th percentile and the 10th percentile value of travel time is used to get the spread of the travel-time distribution. Fourth, planning time index (PTI), i.e. the ratio of planning time to free-flow travel time is used as a performance measure[18]. For example, a PTI value of 1.30 indicates that the travellers should plan for an additional 30% travel time above the off-peak hour travel time to ensure 95% on-time arrival.

Further, average journey or commercial speed is also used as a performance measure in the present study. It is considered as an important parameter to estimate the performance of a route[12]. The journey speed is the average speed of a bus including all stop times, for instance, stop delays due to dwell time and intersection delays. Additionally, travel-time distribution is also used as a performance measure as it presents the nature and pattern of reliability.

### *Network performance indices*

There are various factors that affect LOS of a public transit network. This study focuses on two of them, viz. average travel time per kilometre and COV of travel time. The former is used to evaluate the efficiency of the public transport (PT) network, whereas the latter is used to evaluate the reliability of the network.

## BRTS route description and data collection

Ahmedabad BRTS is now considered as a model of efficient transit system for developing countries[19]. Ahmedabad city located in Gujarat, western part of India has a population of 5.5 million. BRTS began in Ahmedabad in 2009. The operations of the system are handled by Ahmedabad Janmarg Limited, which is a part of Ahmedabad Municipal Corporation.

The present study considers two routes of the Ahmedabad BRTS. This is a closed BRTS having the following characteristics: (i) segregated busways for majority of the network length; (ii) bus station and busway are located on the median; (iii) provides a good integration of network of routes and corridors; (iv) BRT stations are secure, comfortable and are protected from different kinds of weather; (v) implementation of pre-board fare collection system; (vi) integration with the feeder services; (vii) entry to any other kind of bus, rather than the one prescribed is restricted; (viii) having a distinctive marketing identity comparable to mass rapid transit system.

Figure 1 *a* and *b* shows two routes considered in the present study. Route 1 runs from Maninagar to ISKON, starting from the southeastern part of the city and leading to the western part. This route has a length of 12.1 km.

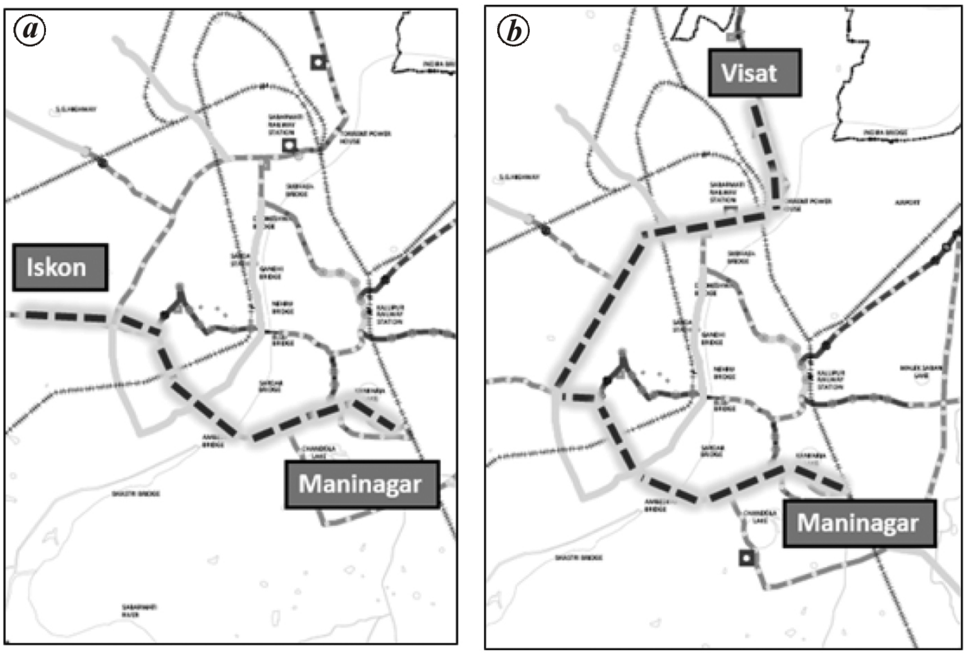


**Figure 1.** Routes of Ahmedabad bus rapid transit system (BRTS): (***a***) route 1 and (***b***) route 2.

| STOPS: | STOP 1 (000- 29, Maninagar) | | | STOP 2 (001-30, Swaminarayan Mandir) | | |
|---|---|---|---|---|---|---|
| Service | Scheduled departure time | Real departure time | Difference | Scheduled arrival | Real arrival | Difference |
| SM1 - B 60 - 06:41:00 | 06:41:00 | 06:38:18 | -00:02:42 | 06:41:00 | 06:42:16 | 00:01:16 |
| S_SM1 - 06:41:00 | | | | | | |
| SM2 - B 133 - 06:53:00 | 06:53:00 | 06:40:47 | -00:12:13 | 06:53:00 | 06:54:04 | 00:01:04 |
| S_SM2 - 06:53:00 | | | | | | |
| SM3 - B 66 - 07:05:00 | 07:05:00 | 06:50:34 | -00:14:26 | 07:05:00 | 07:06:42 | 00:01:42 |
| S_SM3 - 07:05:00 | | | | | | |
| SM4 - B 55 - 07:17:00 | 07:17:00 | 07:05:00 | -00:12:00 | 07:17:00 | 07:18:24 | 00:01:24 |

**Figure 2.** Snapshot of GPS data retrieved from the different BRT buses.

There are in total 22 bus stops and 25 intersections (both signalized and unsignalized) in this route. Route 2 runs from Maninagar to Visat, and connects the southwestern part of the city to the north. This route also acts as a connection between inner-city and outer ring road. With a total length of 22 km, this route has 36 bus stops and 31 intersections.

Buses moving in Ahmedabad BRTS are equipped with GPS devices. When the bus stops at the BRT stop, its arrival and departure times are recorded and presented in the form of Excel sheet (Figure 2).

A total of 2125 bus trip data are used in the present study. These data are for a single direction, i.e. half cycle or only for the upstream of both the routes. The upstream for routes 1 and 2 are from Maninagar to ISKON, and Maninagar to Visat respectively.

## Route performance evaluation

### *Within a day travel-time variation*

Figure 3 *a* and *b* illustrates the travel-time observations considering 30 min of departure time-window to club complete trips for two weeks of weekday data for routes 1 and 2. In Figure 3, four distinct periods can be observed, i.e. morning peak, inter-peak, evening peak, evening off-peak. It can be seen that the travel time varies from 43 min to 88 min, and from 24 to 58 min for routes 1 and 2 respectively. Apart from travel-time plots, Figure 3 also presents T90 and T10 plots. A greater difference between them indicates that the TTV is high. For both the routes it can be seen that there is a high TTV during the morning (7 : 00 to 10 : 00) and evening (16 : 00

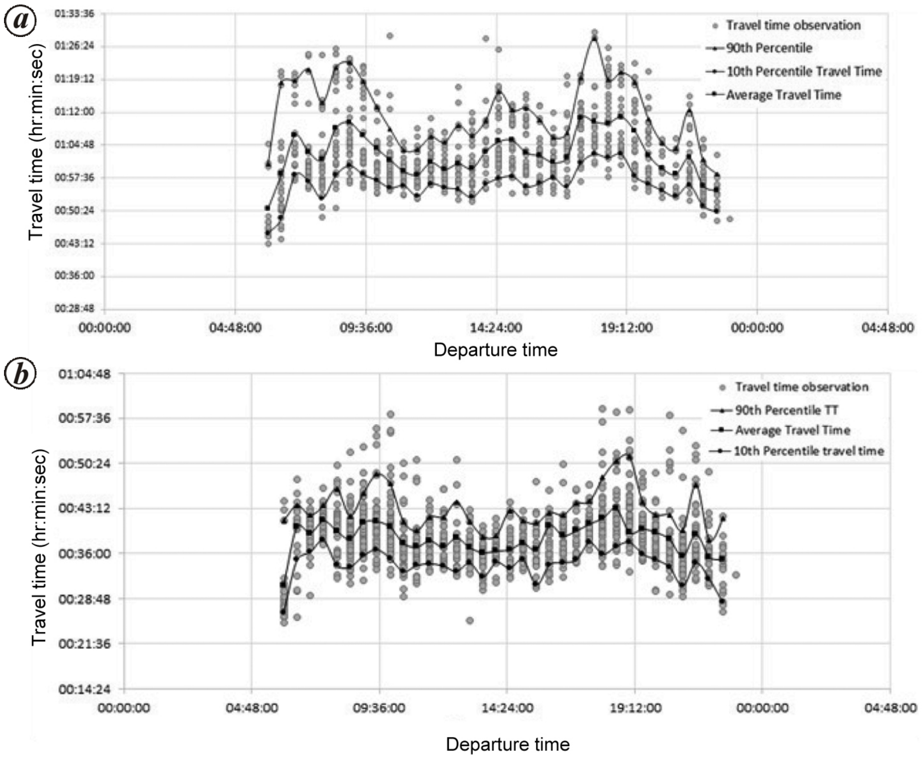


**Figure 3.** Travel-time variation (TTV) for every 30 min departure time-window. ***a***, Within-a-day TTV of route 1. ***b***, Within-a-day TTV of route 2.

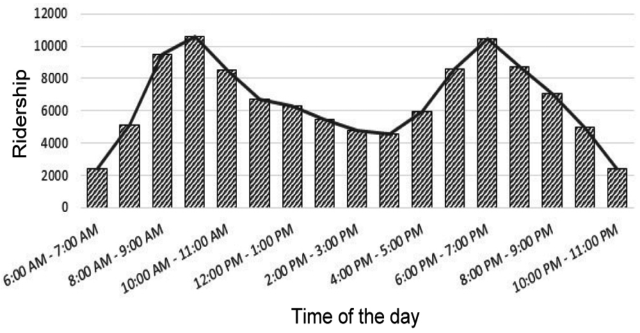


**Figure 4.** Weekday ridership of Ahmedabad BRTS.

to 20 : 00) periods. TTV can be caused by both lateness and earliness of the trips. In the evening, it could be seen in both the routes that few buses show very high travel time. The reason for this is because there is no check on the last buses of the day.

In case of BRTS, the peak and off-peak periods are decided based on the ridership of the system. Therefore in present study, this was decided after collecting the ridership data for a weekday. Figure 4 presents the ridership data of each hour throughout the day based on which the morning off-peak (6 : 00 to 8 : 00), morning peak (8 : 00 to 11 : 00), inter-peak (11 : 00 to 17 : 00), evening peak (17 : 00 to 20 : 00) and evening off-peak (20 : 00 to 23 : 00) were decided (Table 1).

One can visually understand TTV within a day from Figure 3, but this has to be further analysed statistically during different times of the day for both the routes as presented in Table 1. The table shows travel time across the day for different peak and off-peak periods. For route 1, it can be observed that mean travel time varies across the day ranging from 37.25 min in inter-peak to 41.17 min in evening peak whereas for route 2 mean travel time varies from 59 min in evening off-peak to 69.58 min in evening peak periods. The difference can be attributed to variation in level of congestion for unsegregated segments in different periods. Therefore, different scheduled travel-time values should be used for different periods. Trends of T10 and T50, i.e. the 10th and 50th percentile travel time are parallel to mean travel time for route 1. Whereas trends of T10, T50 and T90 are parallel to mean travel time for the case of route 2. High value of (T90 – T10)/T50 during morning peak and evening off-peak of route 1, and morning peak and evening peak of route 2 suggests unstable travel times during these periods. COV was observed to be the highest during evening off-peak and morning off-peak for routes 1 and 2 respectively, which indicates an increase in TTV when compared to other periods. The highest 95th percentile travel time is observed as 50.36 and 79.51 min for routes 1 and 2 respectively. These high values indicate how worst can be the travel times during certain periods of the day. The average journey speed is observed highest

**Table 1.** Descriptive statistics for within-the-day travel time of routes 1 and 2

| Descriptive statistics | Morning off-peak | Morning peak | Inter-peak | Evening peak | Evening off-peak |
|---|---|---|---|---|---|
| Route 1 | | | | | |
| Mean travel time (min) | 38.03 | 39.51 | 37.25 | 41.17 | 34.27 |
| Average journey speed (km/h) | 19.1 | 18.4 | 19.5 | 17.6 | 21.2 |
| Standard deviation (min) | 4.16 | 6.23 | 3.4 | 4.03 | 6.25 |
| COV (%) | 11 | 15 | 9 | 9 | 16 |
| T10 (min) | 34.53 | 36.36 | 36.4 | 40.01 | 33.54 |
| T50 (min) | 38.31 | 41.02 | 40.14 | 42.52 | 39.44 |
| T90 (min) | 42.35 | 49.16 | 43.31 | 47.16 | 45.33 |
| T95 (min) | 43.3 | 50.36 | 44.03 | 48.07 | 46.45 |
| T90 – T10/T50 (%) | 21.0 | 31.0 | 17.0 | 17.0 | 29.0 |
| Route 2 | | | | | |
| Mean travel time (min) | 60 | 66.4 | 61.56 | 69.58 | 59 |
| Average journey speed (km/h) | 22.0 | 19.9 | 21.4 | 19.0 | 22.4 |
| Standard deviation (min) | 8.22 | 8.23 | 5.02 | 7.34 | 5.09 |
| COV (%) | 14 | 13 | 8 | 11 | 9 |
| T10 (min) | 52.22 | 57.06 | 55.57 | 60.23 | 53.45 |
| T50 (min) | 57.21 | 62.45 | 60.38 | 67.45 | 57.41 |
| T90 (min) | 74.54 | 76.3 | 68.44 | 78.57 | 65.25 |
| T95 (min) | 76.16 | 78.59 | 70.12 | 79.51 | 67.06 |
| T90 – T10/T50 (%) | 39.01 | 30.80 | 21.3 | 27.019 | 20.5 |

**Table 2.** Comparison of scheduled travel time and percentile travel time of routes 1 and 2

| Percentile value | Morning off-peak | Morning peak | Inter-peak | Evening peak | Evening off-peak |
|---|---|---|---|---|---|
| Route 1 | | | | | |
| T10 (min) | 34.53(31) | 36.36(35) | 36.4(31) | 40.01(36) | 33.54(30) |
| T50 (min) | 38.31 | 41.02 | 40.14 | 42.52 | 39.44 |
| T95 (min) | 43.3 | 50.36 | 44.03 | 48.07 | 46.45 |
| Route 2 | | | | | |
| T10 (min) | 52.22(52) | 57.06(56) | 55.57(52) | 60.23(56) | 53.45(56) |
| T50 (min) | 57.21 | 62.45 | 60.38 | 67.45 | 57.41 |
| T95 (min) | 76.16 | 78.59 | 70.12 | 79.51 | 67.06 |

during evening off-peak for both routes, suggesting that the route service condition is fairly good during this period. On the other hand, this speed is minimum during evening peak for both routes, indicating poor level of service during this period. This implies that although a segregated bus lane is present in a BRTS corridor, the evening peak goes through the poorest transit service condition across the day.

Further, an analysis was done to understand what value of travel time percentile matches with the actual scheduled travel time. Table 2 presents the comparison between the scheduled travel time and the percentile value. The scheduled travel times are shown in brackets, which are either close to or less than the 10th percentile travel time value. This indicates that using the present schedule time will result in only 10% of the buses reaching on time. By understanding this, operators should change the scheduled time based on the GPS data.

## *Day-to-day travel time variation*

The day-to-day TTV for routes 1 and 2 has been analysed for five weekdays. Travel-time variability maps based on COV were developed in MATLAB software (Figure 5 *a* and *b*). All dark areas in the figure depict unreliable service times. These reliability maps can be useful for the operators to visually identify the unreliable periods for different days and at different periods. Based on these maps, further operational improvements can be suggested. After the visual analysis for day-to-day TTV, descriptive statistics of travel time was considered (Table 3) and is explained as under.

The average journey speed on Monday is less than the other days for route 1. A small variation in journey speed is observed for all the days on route 2. Journey speed of route 1 corresponds to 'barely acceptable condition' of LOS according to the ranges suggested by Cortés *et al.*[8].

**Table 3.** Descriptive statistics of travel time for routes 1 and 2

| Descriptive statistics | Monday | Tuesday | Wednesday | Thursday | Friday |
|---|---|---|---|---|---|
| Route 1 | | | | | |
| Number of observations (#) | 172 | 170 | 169 | 173 | 178 |
| T95 (min) | 41.26 | 40.49 | 41.25 | 40.56 | 41.26 |
| Standard deviation (min) | 4.46 | 2.53 | 3 : 07 | 2 : 35 | 3 : 08 |
| Mean (min) | 40.52 | 37.48 | 38.12 | 37.55 | 38.22 |
| Average journey speed (km/h) | 17.9 | 19.4 | 19.0 | 19.3 | 19.0 |
| Coefficient of variation (%) | 12 | 8 | 8 | 7 | 8 |
| Planning time index | 1.13 | 1.13 | 1.08 | 1.07 | 1.07 |
| T90 – T10 | 8.54 | 5.10 | 5.26 | 4.52 | 4.56 |
| T90 – T10/50 (%) | 22 | 13 | 14 | 13 | 13 |
| Route 2 | | | | | |
| Number of observations (#) | 142 | 133 | 148 | 162 | 135 |
| T95 (min) | 66.43 | 66.58 | 67.41 | 68.31 | 68.51 |
| Standard deviation (min) | 5.24 | 4.52 | 4.55 | 4.59 | 5.39 |
| Mean (min) | 60.5 | 62.09 | 62.37 | 62.58 | 63.39 |
| Average journey speed (km/h) | 21.8 | 21.3 | 21.2 | 21.1 | 20.8 |
| Coefficient of variation (%) | 9 | 8 | 8 | 8 | 9 |
| Planning time index | 1.09 | 1.08 | 1.08 | 1.09 | 1.08 |
| T90 – T10 (min) | 9.24 | 8.23 | 8.37 | 8.42 | 8.27 |
| T90 – T10/50 (%) | 15 | 13 | 14 | 14 | 13 |

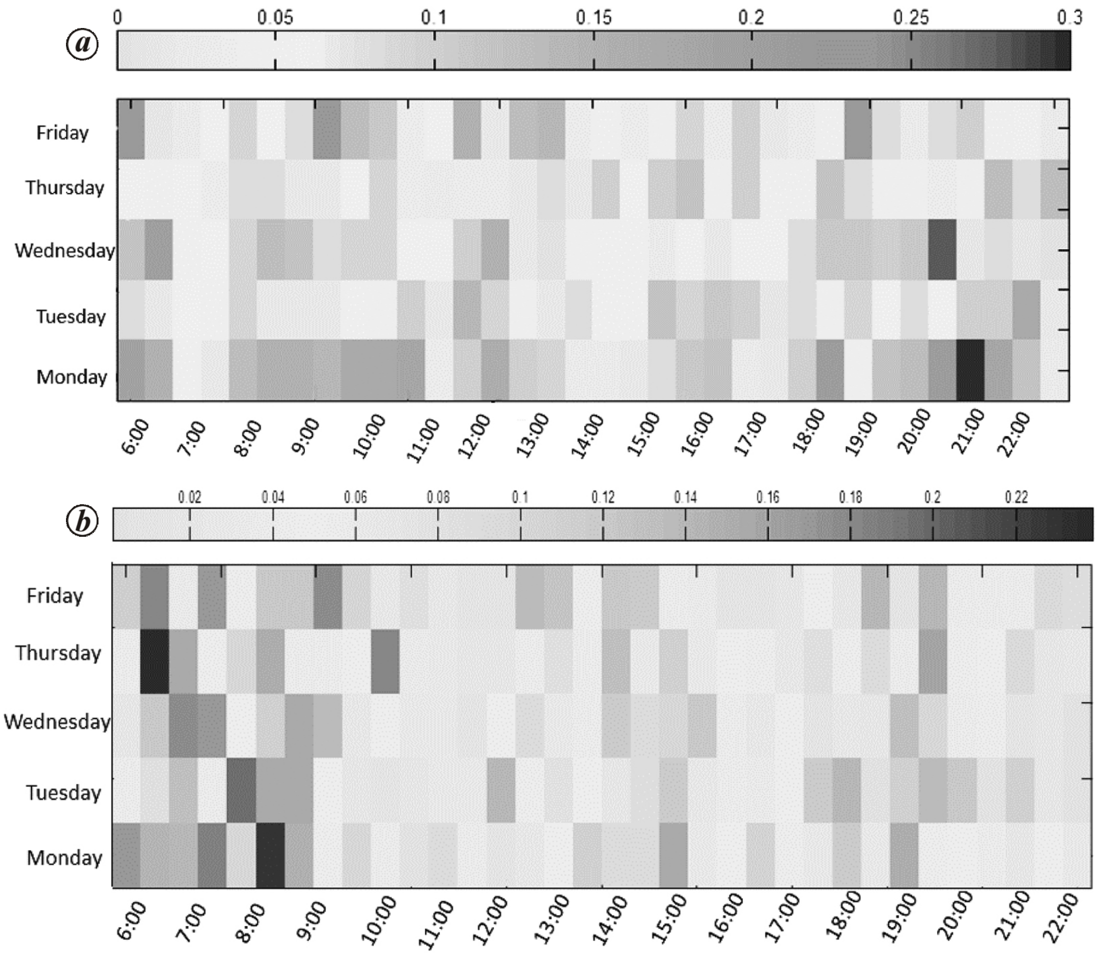


**Figure 5.** Coefficient of variation based reliability map of (***a***) route 1 and (***b***) route 2.

**Table 4.** Travel-time distribution fit of routes 1 and 2

| Day | Travel-time distribution (best fit) | KS statistics value | Critical value (5% level of significance) |
|---|---|---|---|
| Route 1 | | | |
| Monday | log-Normal | 0.040 | 0.116 |
| Tuesday | Logistic | 0.039 | 0.109 |
| Wednesday | log-Logistic | 0.052 | 0.119 |
| Thursday | log-Logistic | 0.382 | 0.098 |
| Friday | Logistic | 0.065 | 0.122 |
| Route 2 | | | |
| Monday | log-Normal | 0.093 | 0.1139 |
| Tuesday | Log-logistic | 0.07 | 0.1239 |
| Wednesday | log-Normal | 0.11015 | 0.11163 |
| Thursday | Log-logistic | 0.06184 | 0.10669 |
| Friday | Weibull | 0.1318 | 0.14274 |

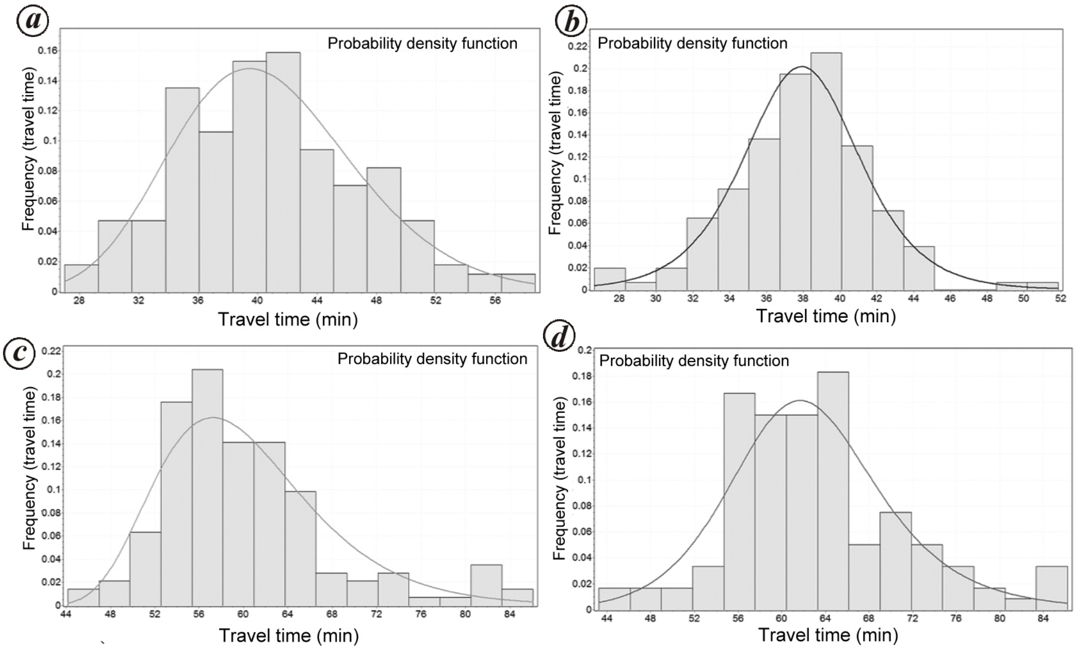


**Figure 6.** Travel-time distribution on Monday and Tuesday for routes 1 and 2. ***a***, Travel-time distribution for route 1 on Monday. ***b***, Travel-time distribution for route 1 on Tuesday. ***c***, Travel-time distribution for route 2 on Monday. ***d***, Travel-time distribution on route 2 on Tuesday.

Whereas in route 2, BRT service is poor only on Friday; for rest of the days, it is fairly good as the journey speed is more than 21 km/h (ref. 8).

The COV value is highest for route 1 on Monday, and for route 2 on both Monday and Friday. This implies that TTV is highest during these days. The same can be supported by the standard deviation values for the same days of both the routes. (T90 – T10)/T50 value represents the width of the travel time distribution relative to the median[20]. T90 and T10 remove the extremely high and low values of travel time. From a high value of T90 – T10 parameter on Monday it can be comprehended that the travel time fluctuation is high this day for both the routes. The PTI was observed highest (1.13) on Monday and Tuesday for route 1, and on Monday and Thursday for route 2 (1.09). A value of 1.13 implies that travellers should plan for an additional 13% travel time above the free-flow travel time to ensure 95% on-time arrival. Further, the day-to-day TTV analysis of routes was done by fitting the distribution to the travel-time values of all weekdays. Table 4 shows the best-fit distribution for routes 1 and 2. In route 1 mainly three types of distributions were seen, i.e. log-normal, log-logistic and logistic, whereas for route 2 it was log-normal, log-logistic and Weibull. Table 4 also presents the KS statistics and the corresponding critical values.

Figure 6 shows the distribution fit on Monday and Tuesday for routes 1 and 2. The distribution along different days cannot be compared by just mentioning its type. Therefore, a two-sample KS test was performed for two independent samples of travel time for two different weekdays set. Table 5 shows the $P$-value of the KS test for different weekday combinations.

The null hypothesis for this test is that the travel-time data for two weekdays are from the same continuous distribution, and alternate hypothesis is that the travel-time data for two weekdays are from different continuous distributions. If the $h$ value (Table 5) is '0', then it means that the null hypothesis is accepted; if the value is '1', then the null hypothesis is rejected and corresponding alternate hypothesis is accepted.

## BRT route segment travel-time analysis

The segment analysis is pertinent for giving specific improvements for a particular section. It might happen that 80% of a route is performing well, but a small segment is causing problems. The selected BRTS routes are majorly segregated, but part of them are unsegregated and buses move with mix traffic. In such cases, the segment travel-time analysis will help planners and operators for better management of routes. In the present study, route 1 is divided into 7 segments with 3 bus stops in each segment, and route 2 is divided into 11 segments with 3 bus stops in each segment, except the last section. Table 6 shows descriptive statistics of segment travel time for the evening peak period to understand the operations at discrete segment level. The average speed is highest in segment 5 and lowest in segment 1 for route 1. Additionally, the highest COV value is observed for segment 1. Accordingly, it can be comprehended that the buses usually face problem in segment 1 of route 1.

Route 1 starts from segment 1; there is a bus terminal and a railway station on the opposite side of the first stop of this segment. A large number of passengers board from this stop, thus increasing the dwell time during the evening peak. Further, part of segment 1 moves with normal traffic, and thus another cause of variability in travel time is traffic congestion. Further, a low average journey speed was observed in segment 6. This segment of route 1 passes through the busiest BRTS corridor. The three stops in this segment are common to nine BRT routes of the system, and hence bus bunching is observed at these stops, resulting in more journey time. In route 2, segment 1 has the lowest journey speed and highest COV value. The reason for this is the same as that for segment 1 of route 1. The decision-makers should account for the delay in segment 1 for both the routes before finalizing the schedule. Also at origin stop, i.e. Maninagar, the

**Table 5.** Two-sample KS test for different days of routes 1 and 2

| Days | KS test ($P$-value) | Hypothesis (h) |
|---|---|---|
| Route 1 | | |
| Monday–Tuesday | 0.0000013 | 1 |
| Monday–Wednesday | 0.000057 | 1 |
| Monday–Thursday | 0.0000020 | 1 |
| Monday–Friday | 0.00024 | 1 |
| Tuesday–Wednesday | 0.615 | 0 |
| Tuesday–Thursday | 0.837 | 0 |
| Tuesday–Friday | 0.697 | 0 |
| Wednesday–Thursday | 0.984 | 0 |
| Wednesday–Friday | 0.968 | 0 |
| Thursday–Friday | 0.636 | 0 |
| Route 2 | | |
| Monday–Tuesday | 0.098 | 0 |
| Monday–Wednesday | 0.075 | 0 |
| Monday–Thursday | 0.0003 | 1 |
| Monday–Friday | 0.008 | 1 |
| Tuesday–Wednesday | 0.098 | 0 |
| Tuesday–Thursday | 0.098 | 0 |
| Tuesday–Friday | 0.099 | 0 |
| Wednesday–Thursday | 0.126 | 0 |
| Wednesday–Friday | 0.561 | 0 |
| Thursday–Friday | 0.935 | 0 |

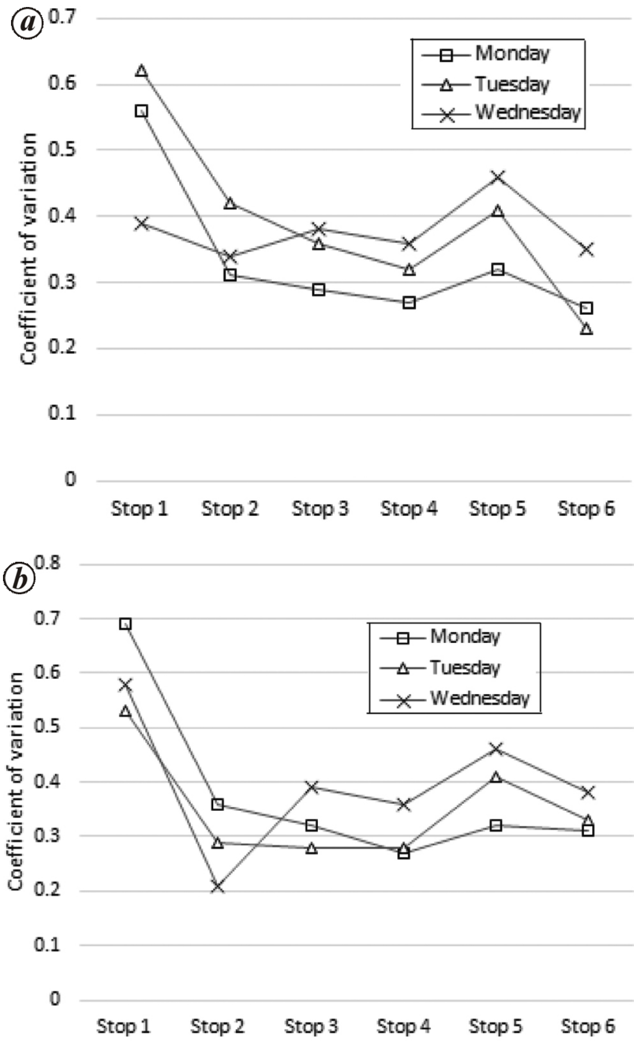


**Figure 7.** Headway COV at different stops: (***a***) route 1 and (***b***) route 2.

**Table 6.** Descriptive statistics of segment travel time of routes 1 and 2

| Segment | Mean travel time (min) | Distance (km) | Average journey speed (km/h) | Standard deviation (min) | Coefficient of variation (%) |
|---|---|---|---|---|---|
| Route 1 | | | | | |
| 1 | 11 | 1.86 | 10.46 | 1.85 | 16.8 |
| 2 | 4.78 | 1.85 | 23.47 | 0.49 | 10.3 |
| 3 | 4.55 | 1.90 | 25.21 | 0.40 | 8.7 |
| 4 | 5.97 | 2.70 | 27.25 | 0.46 | 7.8 |
| 5 | 5.32 | 2.42 | 27.55 | 0.54 | 10.2 |
| 6 | 4.03 | 1.30 | 19.32 | 0.36 | 9.7 |
| 7 | 4.04 | 1.64 | 24.54 | 0.34 | 8.5 |
| Route 2 | | | | | |
| 1 | 11.4 | 1.86 | 10.25 | 2.36 | 20.7 |
| 2 | 4.4 | 1.85 | 25.12 | 0.48 | 10.9 |
| 3 | 4.3 | 1.90 | 26.83 | 0.51 | 11.7 |
| 4 | 5.6 | 2.70 | 29.25 | 0.41 | 7.3 |
| 5 | 5.0 | 2.42 | 29.15 | 0.45 | 9.1 |
| 6 | 4.4 | 1.87 | 25.55 | 0.38 | 8.7 |
| 7 | 4.1 | 1.75 | 25.65 | 0.29 | 6.9 |
| 8 | 4.1 | 1.86 | 27.17 | 0.46 | 11.1 |
| 9 | 4.6 | 1.76 | 23.21 | 0.37 | 8.2 |
| 10 | 5.3 | 2.69 | 31 | 0.59 | 11.2 |
| 11 | 3.5 | 1.46 | 25.47 | 0.44 | 12.6 |

buses were seen waiting for more passengers to board apart from those standing on the platform. Hence proper enforcement is also required so that bus drivers adhere to their respective schedule.

## BRT – adherence to schedule and headway regularity

Schedule adherence analysis is done to analyse the on-time performance of a route. TCQSM[14] reports that the buses coming more than 5 min late and more than 3 min early should be considered as late and early respectively, and not adhering to the schedule. The same criterion was used in the present study. Data for one weekday data (Monday) were analysed. On route 1, a total of 3% of buses arrived early and 41% arrived late, whereas on route 2%, 4% and 38% of the buses were seen arriving early and late respectively. Based on the LOS reported in TCQSM[14], it was observed that both the routes showed poor LOS in terms of scheduled adherence.

Headway irregularity directly impacts the waiting time of passengers and hence is a key element of BRT reliability and performance. A day-to-day variation in headway can impact the reliability of the system to a great extent. Figure 7 *a* and *b* represents the COV of headway for six bus stops of routes 1 and 2 (the same can be done for all the bus stops).

Fluctuations in the COV values of the headway can majorly occur due to the variation in dwell time at the stops and the intersection delay, apart from the other supply-side factors.

## Comparing reliability of BRTS versus non-BRTS routes

Two routes, one segregated BRT and the other unsegregated with conventional buses moving on it were selected for comparing travel-time reliability. It was made sure that both the selected routes have similarity in terms of corridor land use and right-of-way. The unsegregated bus service of Ahmedabad is known as Ahmedabad Municipal Transport Service (AMTS). The AMTS route selected for comparison runs partly in inner and partly in outer city, similar to that of route 1 in the present study. This route starts from GST crossing stop and ends at Nigam society stop. The 15-day GPS data received from AMTS buses were first organized into point geometry features using position information. These point features were matched with the digital road network and then reduced to travel time and further into travel speed. The entire process was divided into three parts, i.e. data conversion and pre-processing, map matching, and data reduction and data aggregation. Table 7 presents a travel-time reliability comparison between BRTS and AMTS routes. On comparing the first index, i.e. average travel time per kilometre, it can be observed that non-BRTS route takes 0.7 min/km more and hence is a low performer based on the above index. The poor performance of AMTS route is also confirmed by a higher value of T10, T50 and T95/km. Higher values of COV and standard deviation of travel time for AMTS route indicate higher travel-time variability and less reliability of AMTS buses. Higher percentage of (T90 – T10)/T10/km for AMTS route indicates unstable travel time during morning peak. Hence,

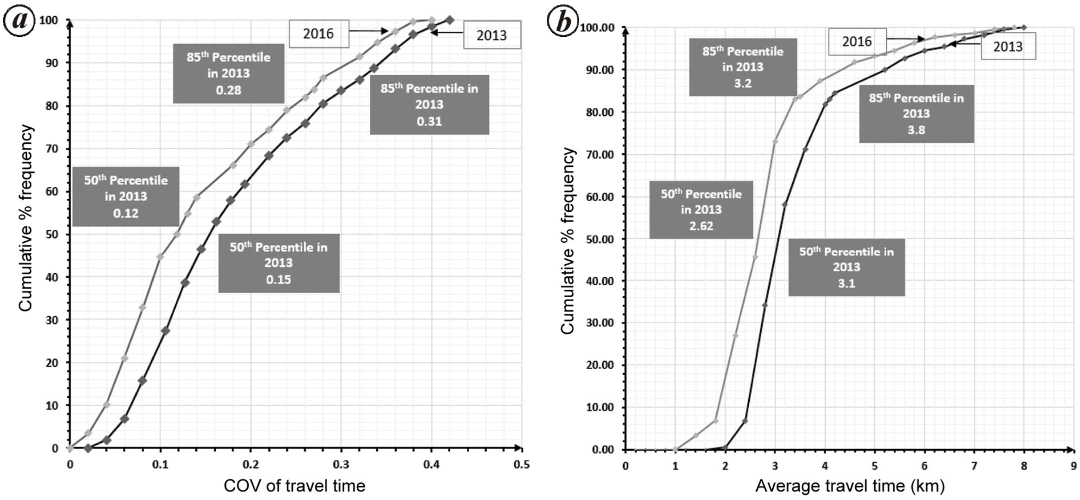


**Figure 8.** Cumulative frequency plots of (***a***) COV of travel-time and (***b***) average travel time/km.

**Table 7.** Travel-time reliability comparison between buses operating in bus rapid transit systems (BRTS) and Ahmedabad municipal transport service (AMTS)

| Indices | Morning peak (BRTS route-2) | Morning peak (AMTS route) |
|---|---|---|
| Average travel time/km (min) | 3.0 | 3.7 |
| Standard deviation/km (min) | 0.3 | 0.6 |
| COV (%) | 13.0 | 33.0 |
| T10/km (min) | 2.6 | 2.9 |
| T50/km (min) | 2.8 | 3.4 |
| T90/km (min) | 3.5 | 3.8 |
| T95/km (min) | 3.6 | 3.9 |
| (T90 – T10/T50)/km (%) | 30.8 | 37.4 |

based on the difference in the values of indices, it can be comprehended that the BRT route is more reliable in terms of route efficiency and travel-time reliability than a non-BRT route.

## Evaluating shift in network level of service

The network-based evaluation was done using two indices, i.e. average travel time per kilometre and COV. The former index is associated with network efficiency, and the latter with stability of the network. Among the various factors that affect LOS, this article focuses on those related to efficiency and stability of public transit network. GPS data were collected during the entire month in January 2013 and January 2016. The data were used to observe changes in the LOS of the network. There was a substantial change in total network length during these years as it increased from 61 km in 2013 to 89 km in 2016; also the number of routes increased from 7 to 12.

Figure 8 shows cumulative distribution plots of both the average travel time per kilometre and COV of travel time/km for 2013 and 2016. The 2016 plot for both the indices appears to the left of 2013; this indicates that the efficiency and stability of the BRTS network have increased in 2016. Hence, it would be appropriate to mention that the LOS of the network is better in 2016 than 2013.

## Conclusion

Travel-time reliability or variability analysis is future of measuring performance of transit system and its components. The focus of this study is to evaluate the performance of the BRTS routes using GPS data. The study reports performance evaluation by considering parameters that are of concern to users and operators. Within-a-day and day-to-day travel-time reliability analyses were done keeping in mind the operator's perspective, whereas schedule adherence and headway regularity analyses were done keeping in mind the user's perspective. Monochromatic maps (Figure 5 *a* and *b*) have been introduced in this study to visually understand the travel-time variability of the routes within a day. These maps are useful to planners and operators for analysing the entire year's big data. These visual maps can also be useful in clubbing the entire year's data in different colour bars showing average values of travel-time reliability parameters with different darkness for each departure time-window bar.

The segment-level analysis presented in this study is of practical importance because BRTS routes at various places in India and abroad follow a hybrid structure, which indicates that they are partly segregated and partly unsegregated. Dividing these routes into segments will help in suggesting specific improvements for both segregated and unsegregated parts.

Further in the study, reliability of BRT route was compared with a non-BRT route to observe advantages of the former route in terms of travel-time reliability over the conventional bus routes. The comparison was done based on various travel-time reliability and efficiency indices.

The study proposes an approach to evaluate the BRTS network from the viewpoint of travel-time stability and reliability using GPS data. The change in network LOS from 2013 to 2016 was observed based average travel time per kilometre and COV of travel time. This was done to observe how the change in total corridor length and fleet size during these years affected the performance of the network. A left shift in the cumulative plot suggests an improvement in overall network performance for year 2016 compared to 2013.

This study also proposes a procedure for performance analysis using GPS data, which can be applied to any other route or network of any length, either for a short period, entire day or for an entire year. It clearly shows how to handle these data to extract valuable information to avoid problems in BRTS operations.

This study can be extended by analysing factors which influence either the route performance or network LOS. The effect of factors like weather condition, land-use and design of roads can be tested. Further, the simulation models can be used for replicating existing conditions and then carrying out sensitivity analysis of improvements to increase the performance of a system as a whole.

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