Journal of Transportation Technologies, 2022, 12, 833-860
https://www.scirp.org/journal/jtts
ISSN Online: 2160-0481
ISSN Print: 2160-0473

Integrated Performance Measures for Bus Rapid Transit System and Traffic Signal Systems Using Trajectory Data

Jijo Kulathintekizhakethil Mathew[1], Howell Li[1], Enrique Saldivar-Carrranza[1], Matthew Duffy[2], Darcy Michael Bullock[1]

[1]Purdue University, West Lafayette, USA
[2]Indygo, Indianapolis, USA
Email: kjijo@purdue.edu, howell-li@purdue.edu, esaldiva@purdue.edu, matthew.duffy@indygo.net, darcy@purdue.edu

How to cite this paper: Mathew, J.K., Li, H., Saldivar-Carrranza, E., Duffy, M. and Bullock, D.M. (2022) Integrated Performance Measures for Bus Rapid Transit System and Traffic Signal Systems Using Trajectory Data. *Journal of Transportation Technologies*, **12**, 833-860.
https://doi.org/10.4236/jtts.2022.124046

Received: September 24, 2022
Accepted: October 18, 2022
Published: October 21, 2022

Abstract

Bus rapid transit (BRT) systems have been implemented in many cities over the past two decades. Widespread adoption of General Transit Feed Specification (GTFS), the deployment of high-fidelity bus GPS data tracking, and anonymized high-fidelity connected vehicle data from private vehicles have provided new opportunities for performance measures that can be used by both transit agencies and traffic signal system operators. This paper describes the use of trajectory-based data to develop performance measures for a BRT system in Indianapolis, Indiana. Over 3 million data records during the 3-month period between March and May 2022 are analyzed to develop visualizations and performance metrics. A methodology to estimate the average delay and schedule adherence is presented along a route comprised of 74 signals and 28 bus stations. Additionally, this research demonstrates how these performance measures can be used to evaluate dedicated and non-dedicated bus lanes with general traffic. Travel times and reliability of buses are compared with nearly 30 million private vehicle trips. Results show that median travel time for buses on dedicated bi-directional lanes is within one minute of general traffic and during peak periods the buses are often faster. Schedule adherence was observed to be more challenging, with approximately 3% of buses arriving within 1 minute on average during the 5AM hour and 5% of buses arriving 6 - 9 minutes late during the 5PM hour. The framework and performance measures presented in this research provide agencies and transportation professionals with tools to identify opportunities for adjustments and to justify investment decisions.

Keywords

Connected Vehicle Trajectory, Bus Rapid Transit, Performance, Traffic Signal

Retiming, Schedules

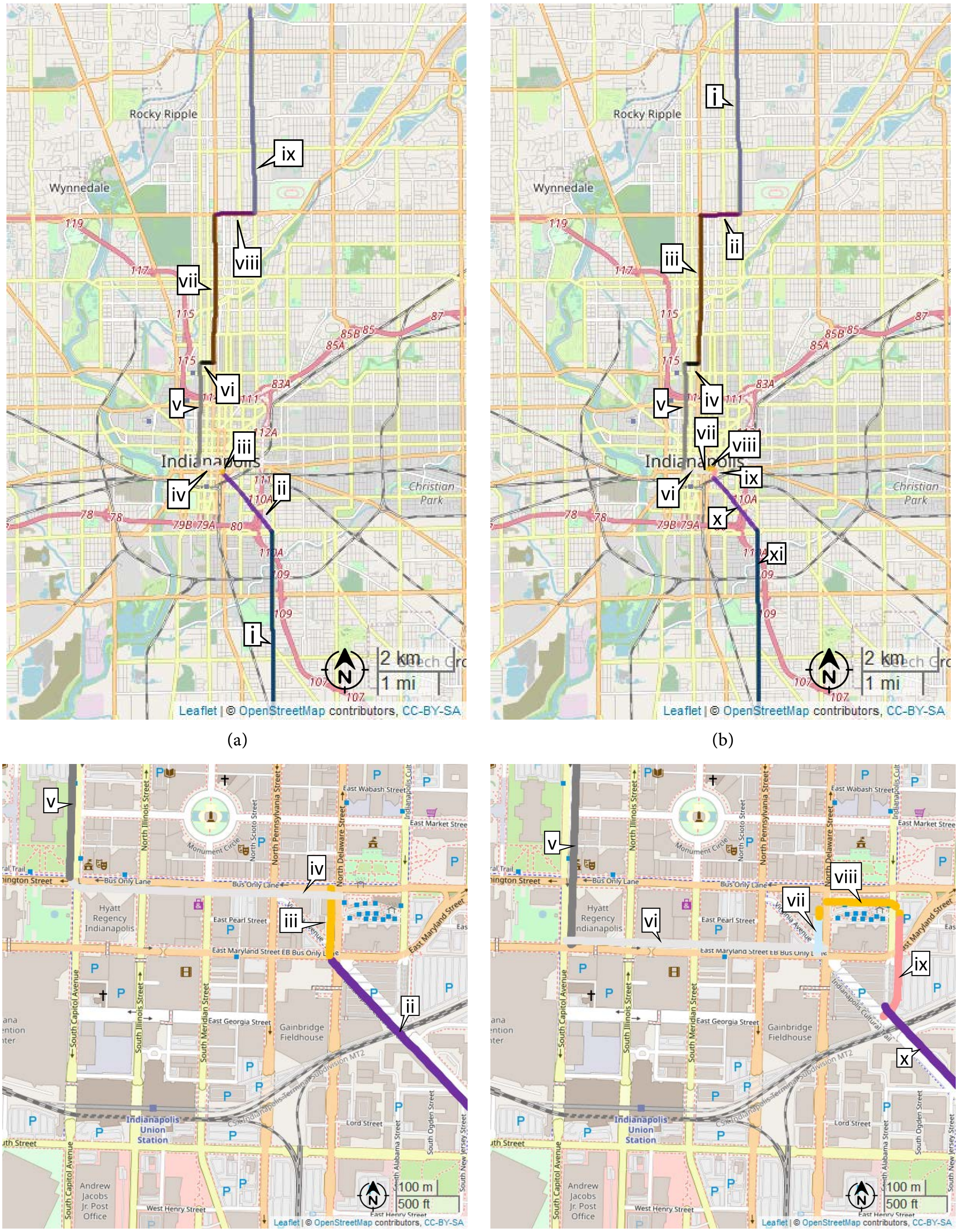
1. Introduction

In September 2019, the Indianapolis Public Transportation Corporation (dba IndyGo) started operating a 13.1-mile all-electric bus rapid transit (BRT) route [1]. The Red line runs from the north side neighborhood of Broad Ripple to the University of Indianapolis, through downtown. The types of running ways implemented on the route are dedicated bus lanes, contraflow dedicated bus lanes, business access and transit lanes (BAT lanes) and a bi-directional shared dedicated bus lane. Some sections of the route operate in mixed traffic conditions. **Figure 1** shows the route in both directions with **Table 1** detailing the running way type of each section. During the study period on weekdays between March and May 2022, a 0.59-mile detour was in place at the north section of the Capitol Avenue corridor and a bridge at the northern section of the College Avenue corridor had intermittent closures, both due to construction.

As part of the Red line, 74 traffic signals were upgraded, and all signals have implemented active GPS geofence-based transit signal priority (TSP) with red truncation and green extension. The requests are made unconditionally when the buses are detected within an approach's geofence. The route has 28 stations

Table 1. Corridor and lane type for BRT.

Northbound			Southbound		
Callout	*Corridor*	*Lane Type*	*Callout*	*Corridor*	*Lane Type*
i	Shelby St	Mixed traffic	i	College Ave	Dedicated (bi-directional)
ii	Virginia Ave	Mixed traffic	ii	E 38th St	Mixed traffic
iii	S Delaware St	Dedicated	iii	Meridian St	Dedicated
iv	E Washington St	Dedicated	iv	W 18th St	Mixed traffic
v	Capitol Ave	Dedicated (contraflow)	v	Capitol Ave	Dedicated (with general traffic left turns)
vi	W 18th St	Mixed traffic	vi	Maryland St	Mixed traffic
vii	Meridian St	Dedicated	vii	S Delaware St	Dedicated
viii	E 38th St	Mixed traffic	viii	CTC	Mixed traffic
ix	College Ave	Dedicated (bi-directional)	ix	Alabama St	Mixed traffic
			x	Virginia Ave	Mixed traffic
			xii	Shelby St	Mixed traffic



(a) (b) (c) (d)

Figure 1. Map of BRT Red line route in Indianapolis, IN. (a) Northbound; (b) Southbound; (c) Northbound zoomed in near downtown; (d) Southbound zoomed in near downtown.

and buses have a no-stopping policy when there are no passengers boarding or alighting the bus.

The route consists of a unique bi-directional dedicated running lane along College Avenue. Figure 2 shows a location where the lane (callout i) was implemented. The lane is shared by the north and southbound buses. Traffic signals have a bus signal head (callout ii) indicating when the bus may proceed through the intersection. The bus stations (callout iii) are located in the center of the roadway where the shared running way diverges and are elevated to allow for level boarding. A concrete curb was constructed along the center of the running way to prevent general traffic from crossing College Avenue. A few exceptions are at select intersections where dedicated left-and-U-turn lanes and protected phases allow for vehicles to turn in front of the bus lane.

Bus data is structured using the General Transit Feed Specification (GTFS). Real-time data is requested through a web-based application programming interface (API) to retrieve bus, route, and schedule information. The 2020 Federal Transit Administration "Mobility Performance Metrics (MPM) for Integrated Mobility and Beyond" report outlines performance strategies for achieving USDOT goals and objectives using data-driven metrics [2]. Three of the objectives to be achieved are system operations, performance, and the development of innovation. Measuring system reliability and performance through data collection and sharing, and the development of public and private sector partnerships to encourage technology innovation are some of the strategies defined to achieve those goals.

2. Literature Review

More recent implementations of BRT in the United States since the mid-2000s have included Boston [3], Orlando [4], Miami [5], San Pablo [6], Honolulu [7], Las Vegas [8], Los Angeles [9], Eugene [10], New York [11], Chicago [12], Roaring Fork [13], Houston [14], Cleveland [15], Columbus [16], Alexandria [17] and Minneapolis [18].

Figure 2. Dedicated bus lane and station.

According to a Federal Transit Administration report in 2020, two strategies for achieving system operations objectives are measuring system reliability and performance [2]. Twenty-five metrics were defined measuring the traveler-centric experience to improve efficiency, effectiveness, and customer experience. Wait time, total journey time, and option availability were among the metrics categorized with a score of "1" (aligned with goals and widely measured), while travel time, travel time reliability, and travel time prediction accuracy were categorized with a score of "3" (aligned with goals but not widely measured).

Bus dispatch data was used to assess bus running times and on-time performance in the early 2000s [19] [20]. With the development of GTFS in 2005 [21], near-real-time bus data have been made available by hundreds of agencies to practitioners through APIs and file archives.

Field studies have been performed evaluating bus performance using bus position data. Bertini and Tantiyanugulchai used GPS-instrumented automatic vehicle location (AVL) data to measure bus travel times along a corridor in Portland, Oregon in 2003 [22]. Uno *et al.* used GPS-instrumented bus probes at one-second fidelity to study level-of-service (LOS) and travel time reliability by map matching sampled data points to routes [23]. Mazloumi *et al.* assessed day-to-day travel time variability using one year of GPS data for a route in Melbourne [24]. In 2012, a study in New York City using data from GPS probes found TSP implementation reduced bus route travel times between 1% and 21% on average [11]. In a study by Farid *et al.*, even with low fidelity 60-second GPS data, a vector regression method was able to deduce running time, dwell time, and delay at signalized intersections [25]. Khadhir *et al.*, used GPS data from public transport buses in Chennai, India to study the variation of travel time over space and time. The results from the study were also used to develop an accurate bus travel time prediction model to improve the efficiency of public transportation systems [26]. Bus GPS data have also been used for time-of-day partitioning in a study in Suzhou, China using dwell time and inter-stop travel time [27].

Additionally, various connected vehicle (CV) implementations using dedicated short range communications (DSRC) technology have been tested for enabling transit priority in the mid-2010s [28] [29]. A study in 2017 conducted by the Utah Department of Transportation found that buses equipped with CV technology improved schedule adherence by only having 35% of the TSP requests being served [30], and improved reliability by 2.65% and 1.21% after signal retiming has been performed [31].

A study by Furth and Muller in the Netherlands showed that conditional priority reduced delays, improved service reliability, and increased schedule adherence [20]. Schramm *et al.* assessed the impacts of running way, passing capability, station spacing, use of transit signal priority, frequency of buses, use of level boarding, and the fare collection process on bus reliability during peak and off-peak periods, and have found that running way and passing capability were significant in reducing the travel time variability of buses because those features directly removed buses from general traffic [32]. However, in the study TSP was not found to be significant as a standalone feature to reduce travel time variability. Arias, *et al.* used GTFS and MARTA ridership data to evaluate proposed bus-only and preferential treatments of travel lanes in the Atlanta metro area to quantitatively justify investments using a passenger-weighted time savings metric [33].

Few studies have compared travel time and reliability of buses and general traffic using instrumented or connected vehicles. An early study has attempted to estimate speeds of general traffic vehicles using bus probes over short evaluation periods [22]. An evaluation comparing BRT and general traffic travel times in Karnataka, India showed that for a route with separate running way for BRT, bus speeds were generally faster than general traffic. However, overall travel times on the route were slower than the sampled floating cars because 80% of the delays were attributed to station dwelling [34]. Another study used simulation to study the impact of bus signal priority and dedicated bus lanes on reducing bus delay at signalized intersections. Results showed that while bus signal priority had considerable impact on reducing total travel time, dedicated bus lanes also improved bus travel time, but with increased travel time for other modes [35].

Recent advancements in third-party commercially-available connected vehicle trajectory data have enabled practitioners to measure travel time, reliability, and delay performance for general traffic vehicles at high spatial and temporal fidelity [36] [37]. It is now possible to quantitatively compare mode performance with bus AVL data to assess intersection approaches with high delay, schedule adherence/on-time performance, travel time and reliability along a route by time-of-day.

3. Study Scope and Objectives

There are now rich feeds of trajectory data from both buses and passenger cars available. However, there are no widely accepted performance measures that provide a framework for traffic engineers and transit agencies to use and to develop a mutual understanding of each other's systems. The current study focuses on developing travel time, reliability, and schedule adherence performance measures and visualizations for identifying locations where there may be signal retiming and TSP adjustment opportunities along the Red Line route. Reliability and performance of different sections of the route with dedicated, bi-directional, and mixed traffic lanes are also compared to evaluate the benefit of different running way implementations.

4. Data

The data used is between March and May 2022 weekdays and includes both GTFS and general traffic connected vehicle (GTCV) trajectory data.

4.1. General Traffic Connected Vehicle (GTCV) Trajectory Data

CV trajectory data consists of location, speed, heading, and unique trip identifier information of anonymized private passenger vehicles sourced from third-party traffic service providers [37]. The data is provided at a 3-second frequency with a spatial accuracy of 3 meters. In the state of Indiana, the penetration of this data is between 3% - 4% evaluated from a 2021 study [38]. **Figure 3** shows the traces of GTCVs over a day of collected samples in the Indianapolis metro area. During the study period, there were nearly 30 million GTCV records on the Red line with an average of roughly 318,000 records per day and approximately 7000 trips per day.

4.2. Bus Trajectory Data

Bus trajectory data consisted of attributes including timestamped speed, location, heading, and direction with a reporting frequency ranging from 5 to 30 seconds. Additional attributes such as occupancy status, headway and schedule adherence (number of seconds ahead of or behind schedule at each sample) are also available. **Figure 4** shows a snippet of the bus data on College Ave. During the three months between March and May 2022, trajectory data from the buses on the Red line generated a total of approximately 3 million records, with an average of roughly 40,000 records per day and 150 unique bus trips per day. Roughly 64% of the trips had an average reporting frequency of 5 seconds or less.

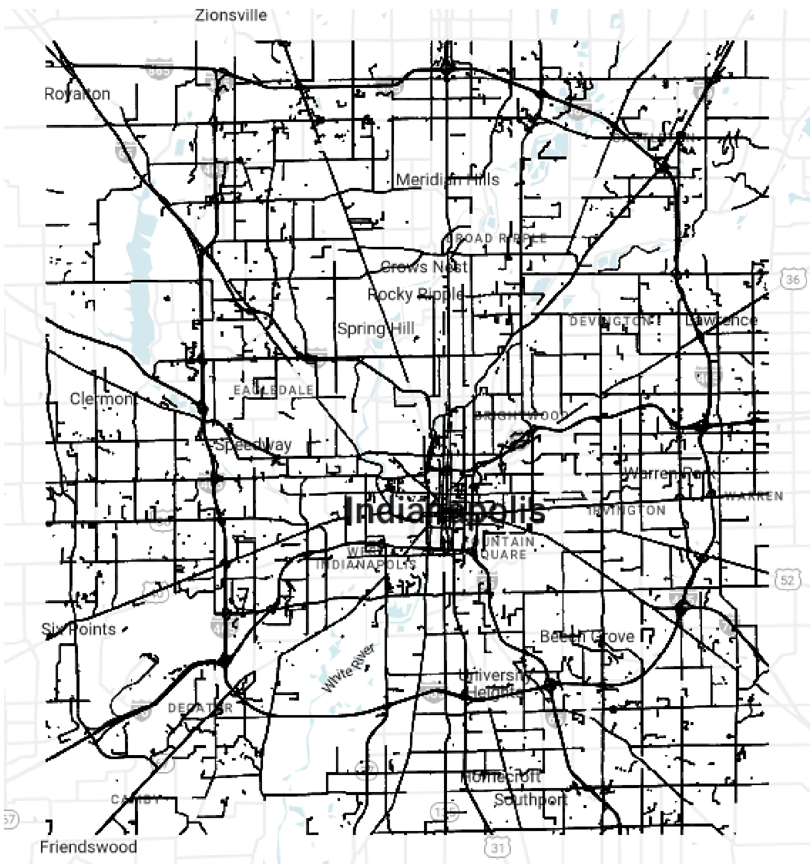


Figure 3. GTCV trajectory data around Indianapolis Metro.

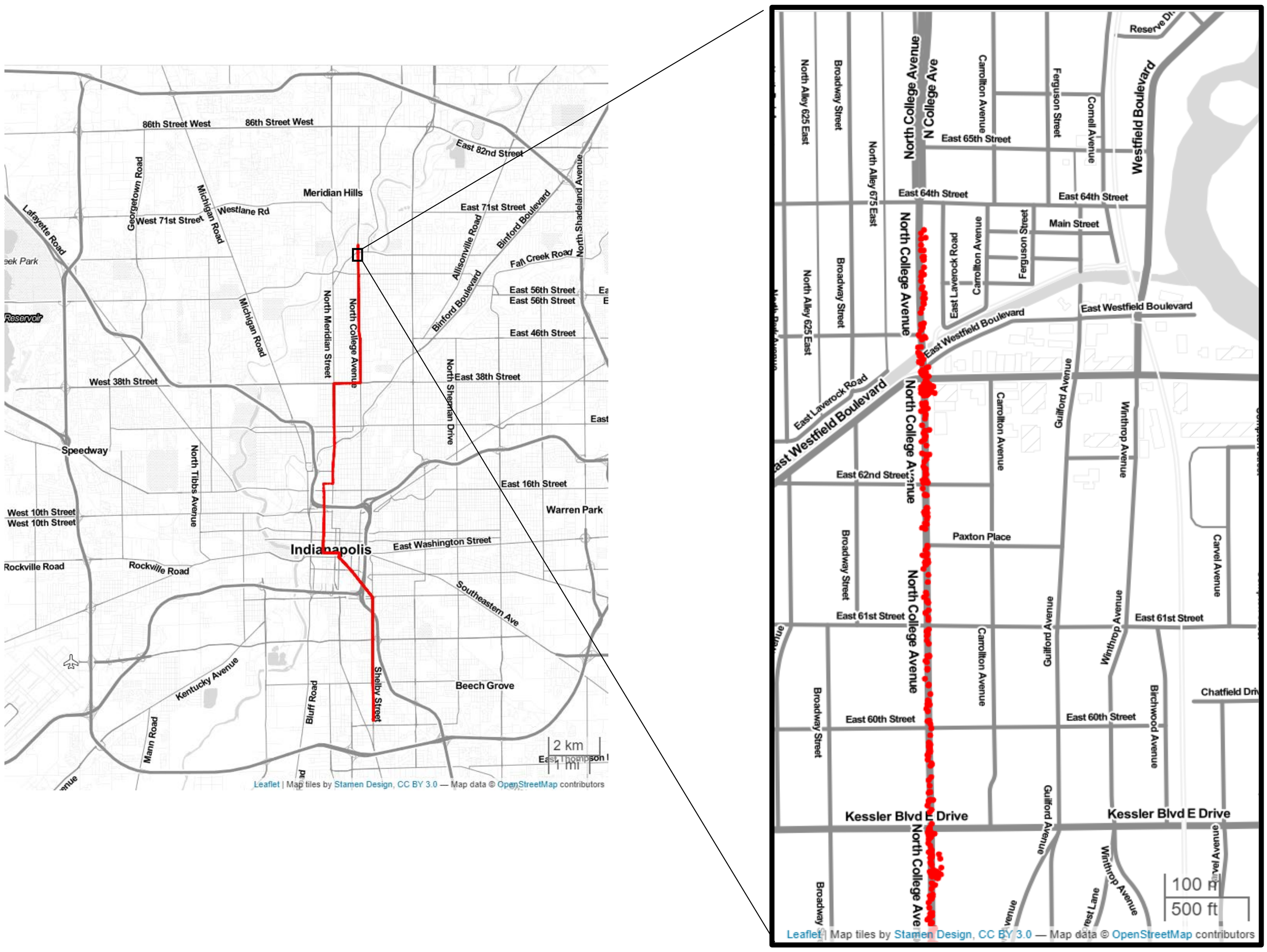


Figure 4. Bus trajectory data points on entire Red Line (left) and College Ave (right).

5. Methodology

This section describes methodology behind the visualization of trajectory plots, estimation of delay and schedule adherence at intersections.

5.1. Trajectory Plots

To perform spatial analysis and to visualize the trajectories on a distance-time plot, it is necessary to snap the bus and CV data points to their nearest roadway route in the direction of their heading. Linear referencing is carried out using spatial polygons generated every 50 feet from the origin for both northbound and southbound route [39]. The polygons are extended over the width of the roadway to include datapoints with low GPS accuracy. The datapoints are then spatially joined to these polygons to obtain their linear reference with respect to the route origin. Finally, a heading filter of ±10˚ with respect to the route heading is applied to remove directional outliers.

5.2. Average Bus Delay at Intersections

There are several well-documented methodologies in the literature that discuss the estimation of total delay from vehicle trajectories [36] [37] [40] [41]. Control delay for buses can also be computed in a similar way, however there are additional factors that need to be considered:

1) Dedicated bus lanes—With dedicated lanes, buses do not experience any queuing compared to other vehicles in the traffic stream.

2) Near-side intersections—At some intersections, the bus stations are present on the near-side, mostly within 50 - 100 ft of the stop bar (**Figure 5**). In these cases, the bus dwell times also need to be accounted for while estimating the control delay. For example, in **Figure 5**, the bus is experiencing delay in the form of dwelling even though the traffic signal indication is green (callout i).

3) Reporting frequency—For accurate estimates, it is preferable to have higher sampling intervals, ideally within 1 to 3 seconds.

To address the above factors, the following methodology is adopted:

1) Discard bus trips with an average reporting frequency greater than 5 seconds (highest frequency available).

2) Develop custom dimensional polygons (wide enough to cover all lanes but with different lengths) for every intersection in their direction of travel. All polygons begin from the center of the intersection.

a) For intersections with dedicated bus lanes, ~100 ft long (**Figure 6(a)**).

Figure 5. Intersection with near-side bus station.

(a) (b) (c)

Figure 6. Custom polygon geofences for delay and schedule adherence estimation at intersections. (a) Dedicated bus lane; (b) dedicated bus lane with near-side station; (c) mixed traffic lane.

b) For intersections with near-side bus stations, ~50 ft long polygons that excludes the bus station (**Figure 6(b)**).

c) For intersections having mixed traffic lane, ~200 ft long polygons to account for the queue upstream of the stop bar (**Figure 6(c)**).

3) Perform spatial join of bus trajectory points with the intersection polygons.

4) For each trip i at intersection j, estimate delay as:

$$D_{i,j} = t_{l,i,j} - t_{f,i,j} \tag{1}$$

where $D_{i,j}$ = delay for trip i at intersection j;

$t_{l,i,j}$ = timestamp of last point of trip i exiting the intersection polygon j;

$t_{f,i,j}$ = timestamp of first point of trip i entering the intersection polygon j.

5) Due to the 5 seconds reporting frequency, it is likely that some trips passing through the intersections without any delay may not report a point inside the polygon. In such cases, $D_{i,j}$ is set to zero and the timestamp of the nearest point ($t_{n,i,j}$) is approximated as the time of entering the intersection $t_{f,i,j}$.

6) For each trip i having delay $D_{i,j}$ at timestamp $t_{f,i,j}$, the timestamps are then floored to the nearest 15 minutes. Then, all dates in the study period are aggregated to the time bin.

7) Average delay $\overline{D_{j,b}}$, for intersection i at bin b is then estimated as

$$\overline{D_{j,b}} = \frac{\sum_{i=1}^{n} D_{i,j,b}}{n} \tag{2}$$

where $D_{i,j,b}$ is the delay estimated for trip i at intersection j in bin b;

n is the total number of sample trips in bin b.

8) The average delay for the bin is discarded if n is less than 5 samples.

5.3. Average Bus Schedule Adherence

For every bus data record, the schedule adherence is reported as an attribute. The methodology to estimate average schedule adherence at intersections is the same as the above methodology to estimate average intersection delay, except that the schedule adherence of the first point entering the intersection polygon is extracted as the schedule adherence of the trip at that intersection at that instant of time. For trips without a datapoint inside the polygon, the schedule adherence of the nearest data point and timestamp are extracted.

5.4. Average CV Delay at Intersection

Control delay from connected passenger vehicle trajectory data is estimated by comparing the travel time of a vehicle traversing an intersection to the travel time of a hypothetical trajectory of an unimpeded vehicle traversing the same intersection under free-flow conditions. This technique takes into consideration deceleration, stopped, and acceleration delays [40]. Further, since passenger CV data has a 3-second reporting interval, no additional filtering is required. Detailed methodology behind the estimation of delay can be found in [37].

As passenger vehicles are affected by queues, each vehicle is analyzed up to 1320 ft. (1/4 mi.) upstream of the intersection or until another control flow device is encountered. Moreover, turning movements are identified from the trajectory data itself without any geofencing by using a center point of an intersection and estimating the approach ingress and egress directions of the trajectories [42].

6. Impact of Dedicated Bus Lane

6.1. Weekday Travel Time

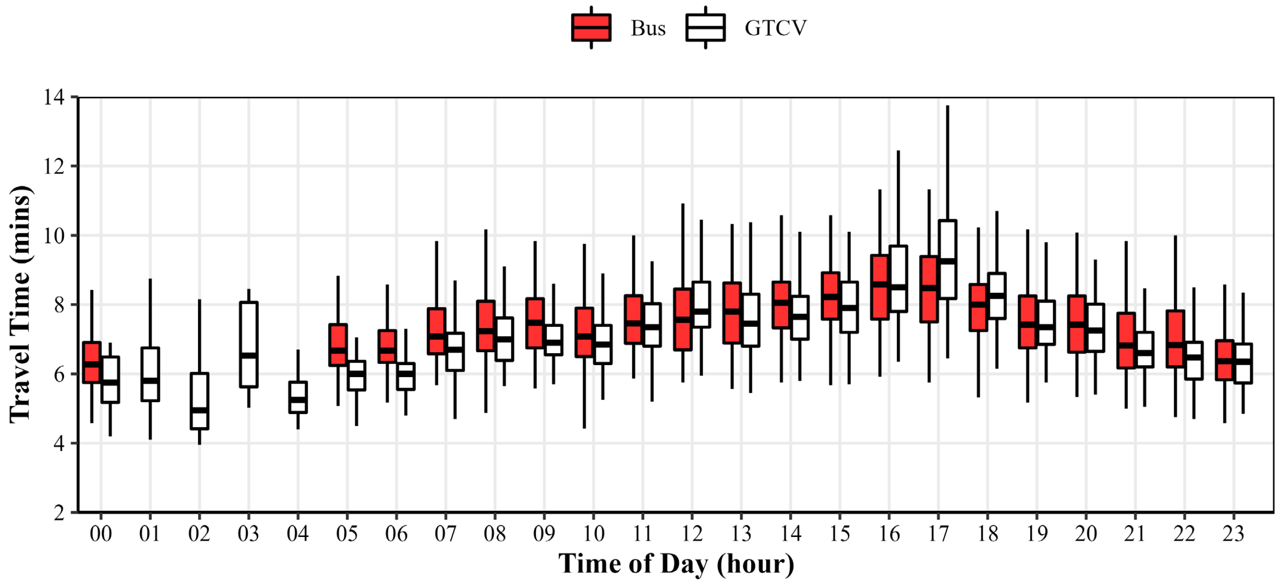
Figure 7(a) and **Figure 7(b)** show boxplots comparing weekday travel times between buses and GTCV by every hour in the northbound direction on College Ave and Shelby St, respectively. Travel times computed for every weekday trip during the analysis period is aggregated by the start time of the trip when the buses or GTCVs enter the corridor. On College Ave (callout v on **Figure 1**), northbound and southbound buses share a dedicated bus lane, whereas on Shelby St (callout i on **Figure 1**), the buses run mixed with general traffic. Both these corridors of College Ave and Shelby St are approximately 3 miles in length.

On College Ave (**Figure 7(a)**), the median travel times for buses and GTCVs are comparable (around 7.5 minutes), with GTCVs taking slightly less time than buses. However, during the 17:00 hour peak period buses are found to be quicker than GTCVs, with a median travel time savings of roughly 1 minute. On Shelby St (**Figure 7(b)**), buses take slightly more time than GTCVs, with an overall median travel time of 8.5 minutes for buses compared to 8 minutes for GTCVs. Buses are also less reliable on Shelby St (interquartile range of 1.9 minutes) compared to College Ave (interquartile range of 1.6 minutes).

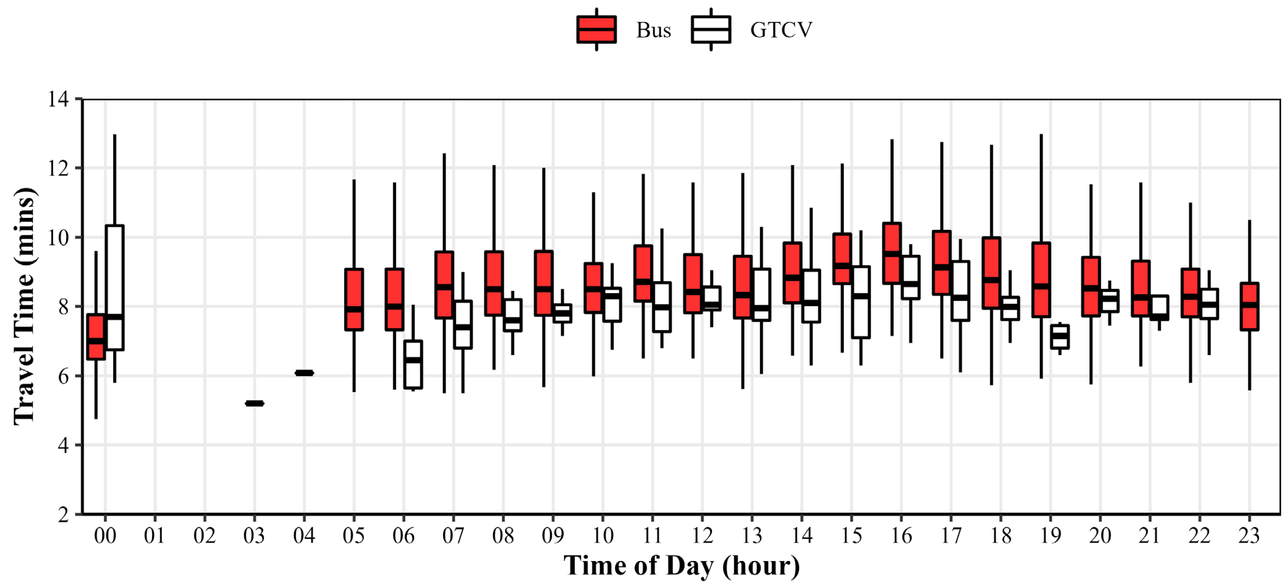
The maximum difference in median travel times between buses and GTCVs on College Ave is around 0.9 minutes (buses quicker at 17:00 hours) whereas on Shelby St is 1.4 minutes (vehicles quicker at 19:00 hours). Moreover, the buses are also more reliable with the dedicated bi-directional lanes with a travel time range of about 4 minutes compared to 6 minutes with mixed traffic. This highlights the impact of dedicated bus lanes in saving travel time and improving reliability. It should also be noted that the bus travel time estimated in this analysis are inclusive of the dwell time lost at bus stations.

6.2. Delay Comparison

Figure 8(a) and **Figure 8(b)** compare heatmaps color coded by the average delay experienced by GTCV and buses, respectively on intersections in the northbound direction of College Avenue. Each cell represents a 15-min period, and the intersections are shown on the y-axis with the time of day on the x-axis. Near-side intersections with possible capture of dwell times are highlighted in blue. In addition to the delay, the corresponding HCM level of service (LOS) [43] is also shown in the legend. Blank cells represent periods where there are insufficient samples (less than 5 samples). Broad Ripple intersection did not



(a)

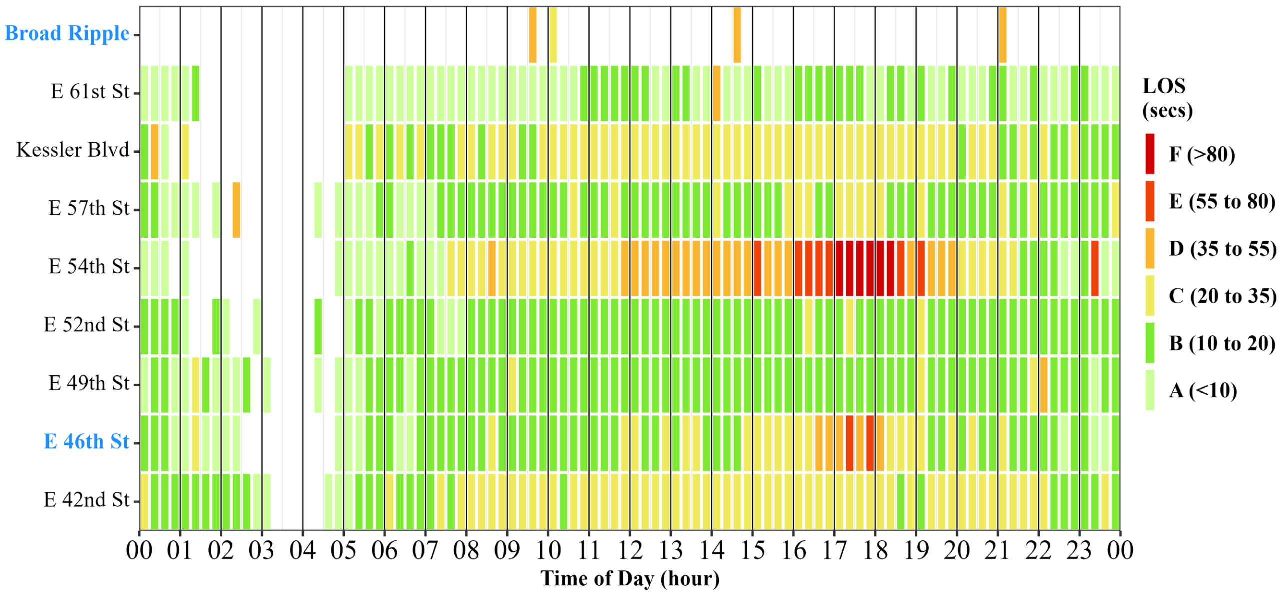


(b)

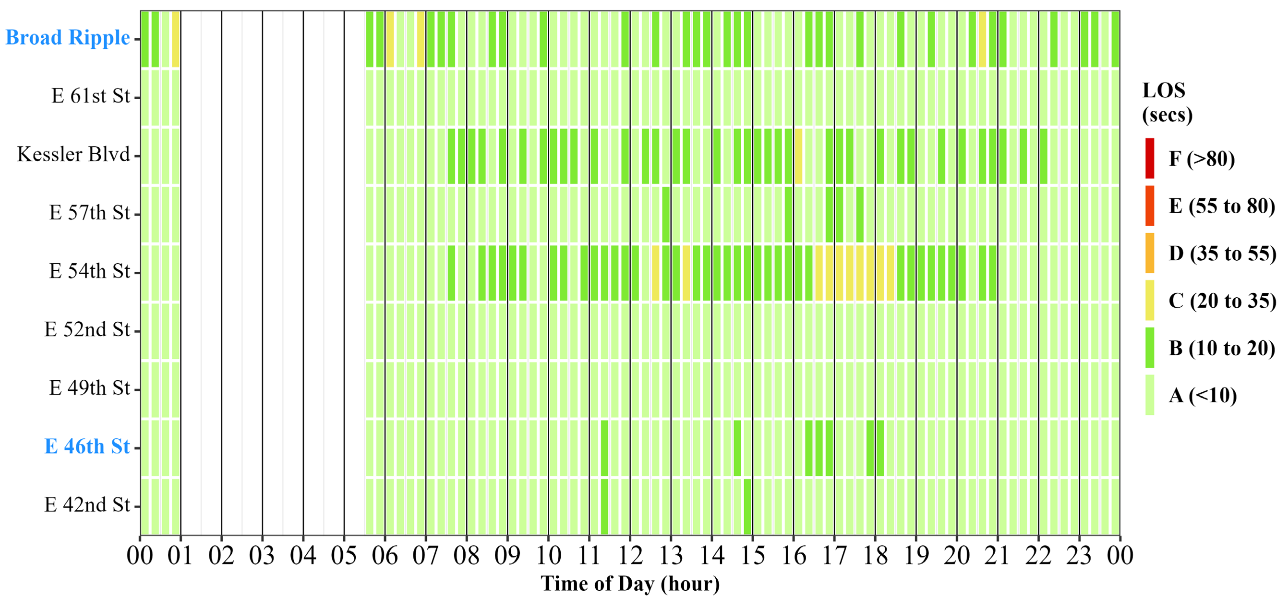
Figure 7. Weekday travel time comparison between GTCVs and buses segmented by sections with and without dedicated bus lanes. (a) Northbound between E 38th St/college ave and college ave/broad Ripple, section has dedicated bi-directional bus lanes; (b) Northbound between Virginia Ave/Shelby St and Shelby St/Campus Dr, section has no dedicated bus lanes.

have enough CVs as this section was only open to limited traffic due to construction activities during the analysis period.

Figure 8(a) and Figure 8(b) show similar patterns of delay for buses and GTCVs, with GTCVs experiencing more severe delays. For example, at E 54th St, where CVs experience more than 55s of delay during the PM peak between 16:00 and 19:00 hours, buses are found to have delays of 35s or less. At E 46th St and E 42nd St, buses are mostly travelling at free flow speed when GTCVs face a delay of 20s or more. During peak periods and saturated conditions, buses take



(a)

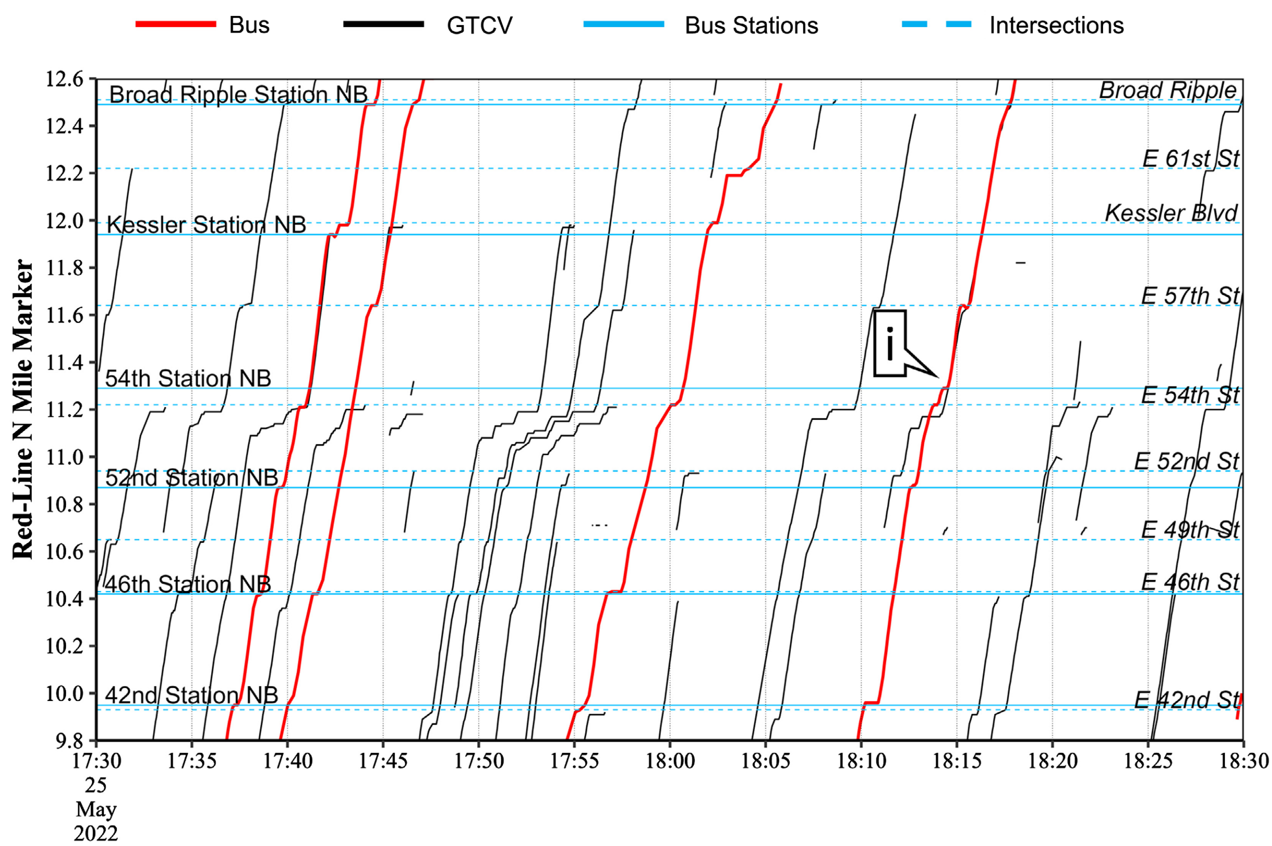


(b)

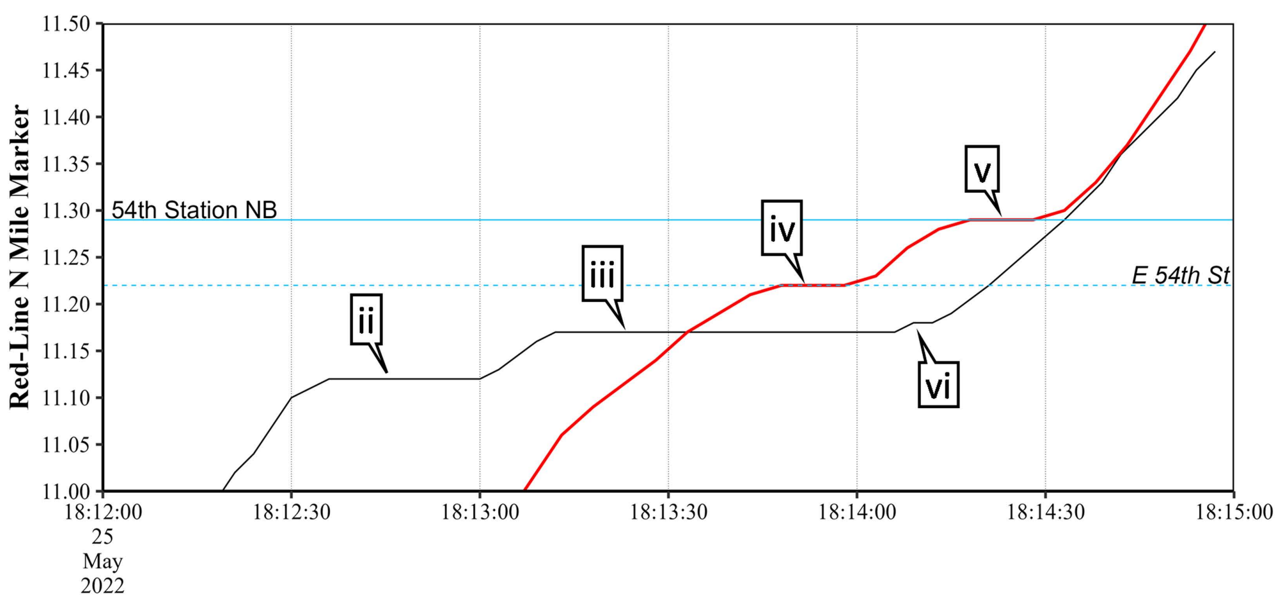
Figure 8. Average intersection delay on northbound College Ave. (a) GTCV; (b) Bus.

advantage of the dedicated lanes and TSP to flow through traffic without any significant impedance. However, general traffic experiences congestion and control delays at signalized intersections.

Figure 9(a) shows a distance-time plot of buses (red) and GTCVs (black) on College Ave traveling northbound between the period 17:30 and 18:30 hours on Wednesday May 25, 2022. The bus stations are shown on the left as solid blue lines and intersections are shown on the right as dotted blue lines. While GTCVs encounter split failures [44] over a number of times, the buses ever only experience arrivals on red. Figure 9(b) shows a zoomed in view of callout i between



(a)



(b)

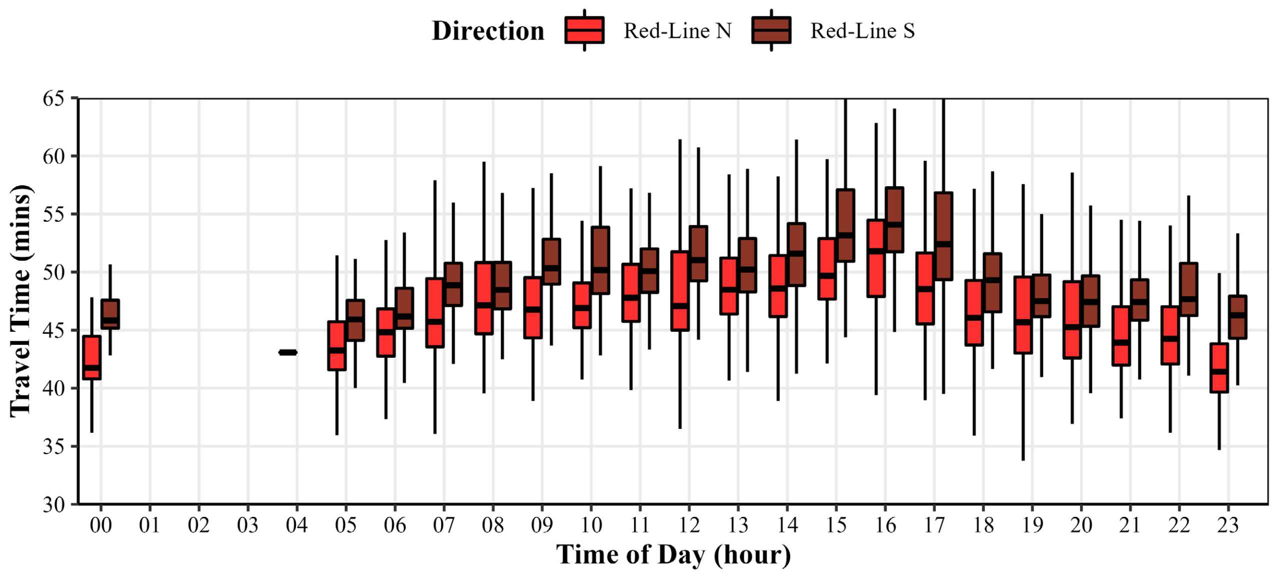
Figure 9. Bus and GTCV trajectory on northbound. (a) College Ave; (b) GTCV experiencing split failure at E 54th St.

18:12 and 18:15 hours at the E 54th St intersection. The GTCV experiences a split failure [37] denoted by the two stops upstream of the intersection (callout ii and iii) but the bus arrives on red (callout iv) and proceeds through the intersection instantly at the onset of green before stopping at the bus station (callout v). The general traffic vehicle, however, again undergoes additional delay waiting for the queue to clear (callout vi) before passing the intersection. In this instance, the bus only faces a delay of roughly 10s at the intersection, compared to the GTCV's overall delay of about 90s.

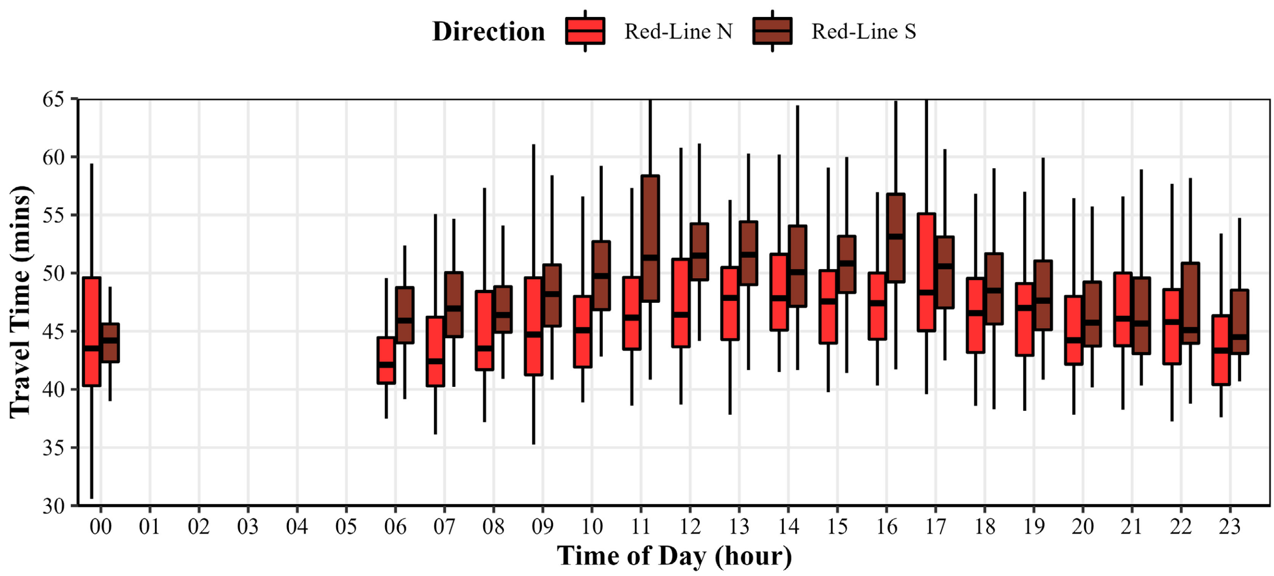
7. Identifying Challenges at the Intersection Level

7.1. Bus Route Travel Time

Figure 10(a) and Figure 10(b) show boxplots comparing the directional bus route travel time by hour of the day for weekdays and weekends, respectively.



(a)



(b)

Figure 10. Bus corridor travel time. (a) Weekdays; (b) Weekends.

Travel times computed for every trip during the three-month analysis period is aggregated by the start time of the trip. In general, it takes less than an hour to complete a trip, with northbound trips found to be quicker than southbound trips during both weekdays and weekends. The southbound trip travels an extra 1000 ft and two additional signalized intersections than the northbound trip, thus resulting in additional travel time.

Overall, on weekdays (**Figure 10(a)**), the median travel times for northbound and southbound trips are around 46 and 49 minutes, respectively. Median travel time patterns are also similar between the directions, with a slight increase during morning peak (45 - 50 minutes) and continuing throughout the day before hitting the maximum during the evening peak (50 - 55 minutes). After 8PM, median travel times are between 40 - 45 minutes and just above 50 minutes for northbound and southbound respectively. During weekends (**Figure 10(b)**), the peaking in travel time occurs around 11AM, with median travel time around 45 minutes on northbound and 50 - 55 minutes on southbound. This continues until 5PM before reducing to around 45 minutes for both directions.

7.2. Intersection Delay

There are several factors that contribute towards the fluctuations in bus travel time; two primary factors are control delay and bus station dwellings. **Figure 11**

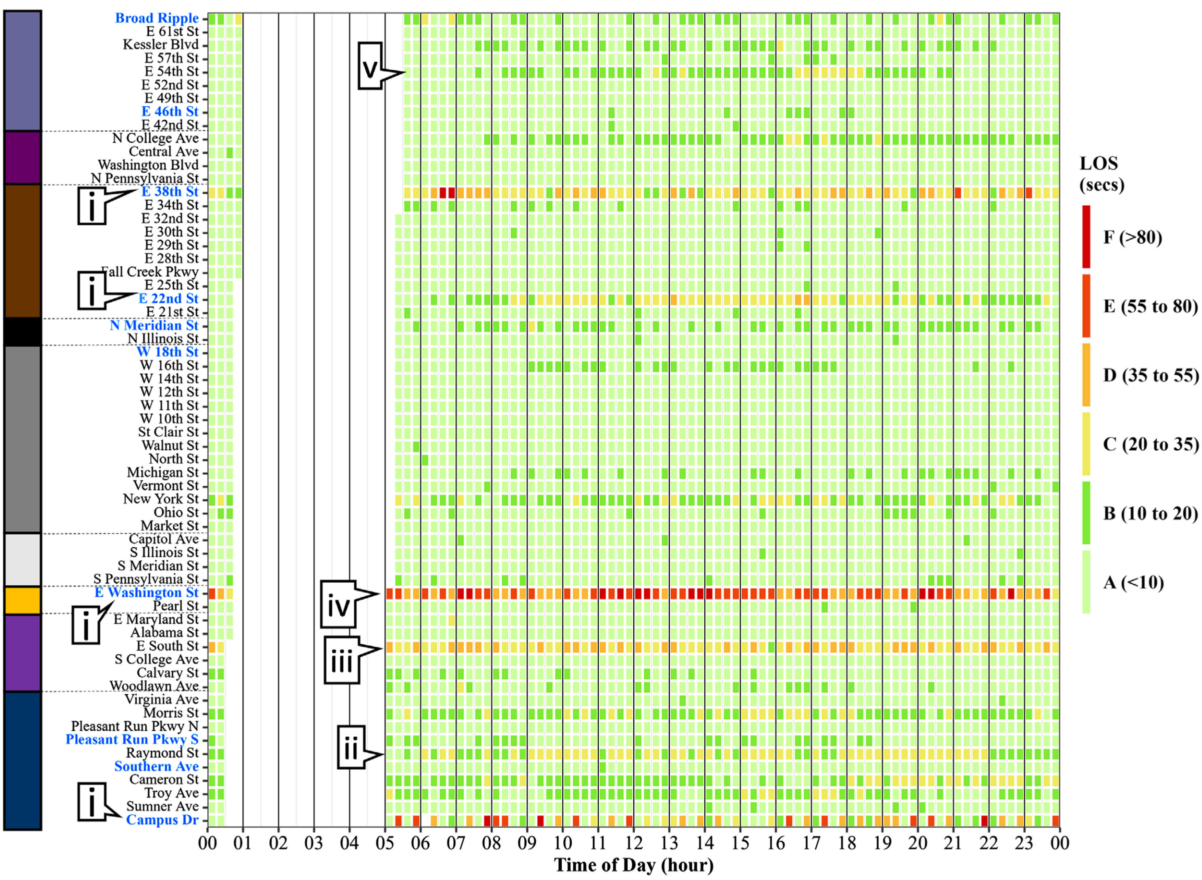


Figure 11. Average bus delay at northbound intersections.

show a heatmap (similar to **Figure 9(b)**) color-coded by the LOS experienced by buses across all signalized intersections in the northbound route. Each color on the left of the Y-axis represents a corridor as shown in **Figure 1**.

In general, buses are progressing at free flow conditions or LOS B during most of the time, highlighting the impact of the dedicated bus lane and TSP. The route south of E Washington St (callout iv) runs mixed with general traffic. E 38th St, E 22nd St, E Washington St and Campus Dr are few intersections (callout i) with some of the longest delays, however since these are near-side intersections, it is possible that some of the delay could be influenced by the dwell time. Apart from the near-side intersections, Raymond St (callout ii), E South St (callout iii) and E 54th St (callout v) are some intersections that warrant retiming operations.

7.3. Schedule Adherence

On-time arrival of buses or schedule adherence is also an important performance measure for assessing system performance and reliability. **Figure 12(a)** contrasts the actual bus trajectories (solid red line) along the entire 13-mile northbound route with the ones that would have been expected had they arrived on time (dashed red lines). **Figure 12(b)** shows a zoomed-in version of **Figure 12(a)** on College Ave between the intersections E 42nd St and E 57th St on 25 May 2022 between 15:30 and 19:00 hours. Callout i shows a trip that is perfectly on schedule whereas callout ii shows two trips that are off schedule. On average, in both directions, more than 3% of buses arrive within 1 minute during 05:00-06:00 hours. The worst adherence is during the 17:00-18:00 hours with approximately 5% of buses arriving within 9 minutes (northbound) and 6 minutes (southbound). Although agencies strive towards maintaining a regular on-schedule performance, sometimes non-recurring factors such as interim construction, operator unfamiliarity due to route scheduling, and consistent feedback loops between operators and route managers could lead to trips being off-schedule.

For the on-schedule trip in **Figure 12(b)** (callout i), the schedule adherence at E 54th St or any intersection is zero. However, for the off-schedule trip (callout ii), the schedule adherence at E 54th St is approximately +19.5 minutes (19.5 minutes late, callout iii).

Figure 13 illustrates a heatmap color coded by the average schedule adherence experienced by buses across all signalized intersections in the northbound direction during the three-month study period. Each cell represents a 15-min period, and the intersections are shown on the y-axis (in route order) with the time of day on the x-axis.

Buses operate mostly within schedule from origin (Campus Dr, callout i), but start going off-schedule as they enter E Washington St (callout ii). This intersection is near the transit center where the operators take a short break. Heading further on Washington St (light gray highlight on left of y-axis) and Capitol Ave (dark gray highlight), the buses deviate further from schedule as they navigate

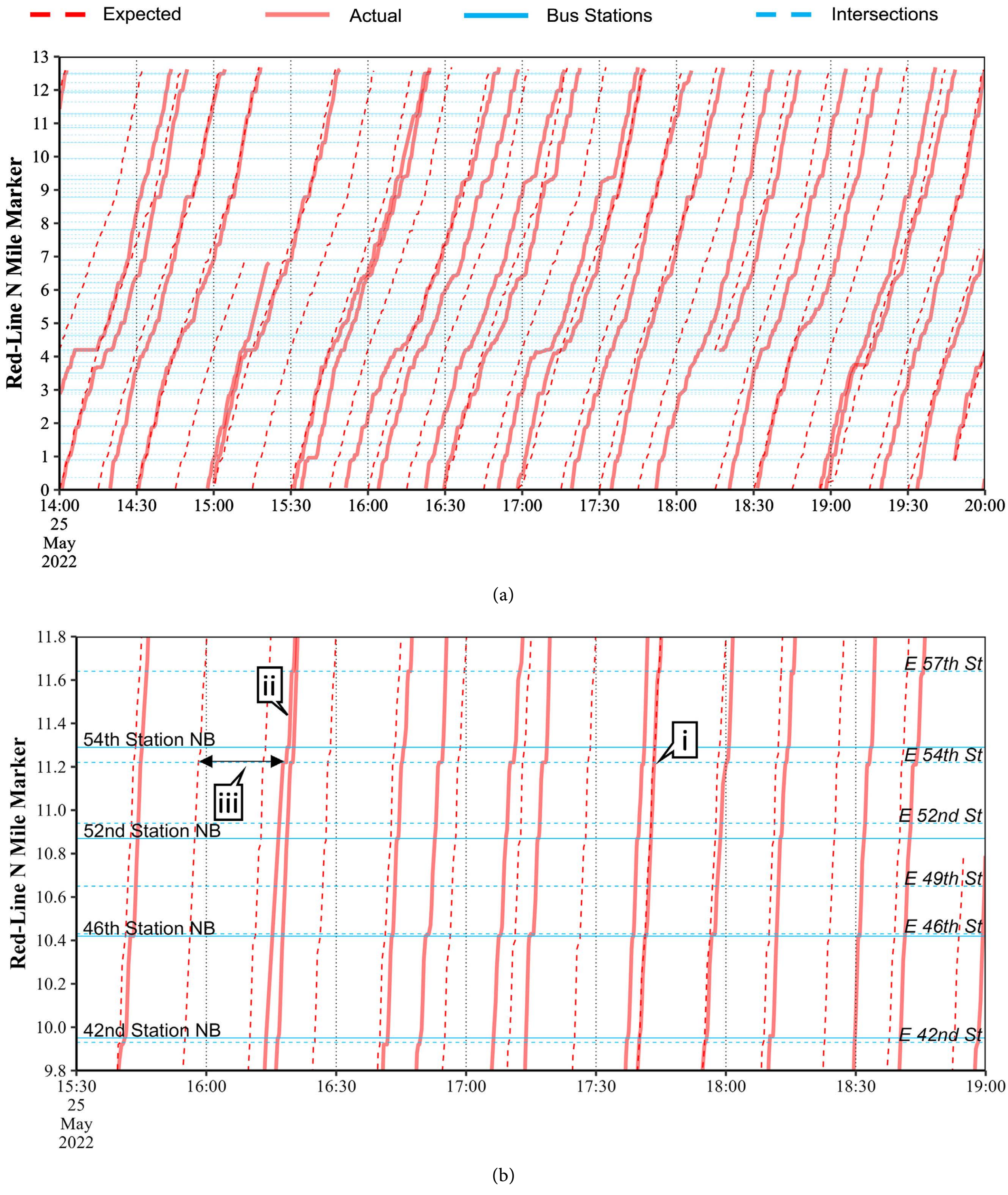


Figure 12. Expected and actual bus trajectories in northbound direction. (a) Entire NB route; (b) College Ave Corridor.

through downtown Indianapolis. On Meridian St (brown highlight), the buses seem to catch up on schedule. The highest deviation from schedule is seen during the evening peak between 16:00 and 19:00 hours, where the buses are late on average by 15 - 20 minutes.

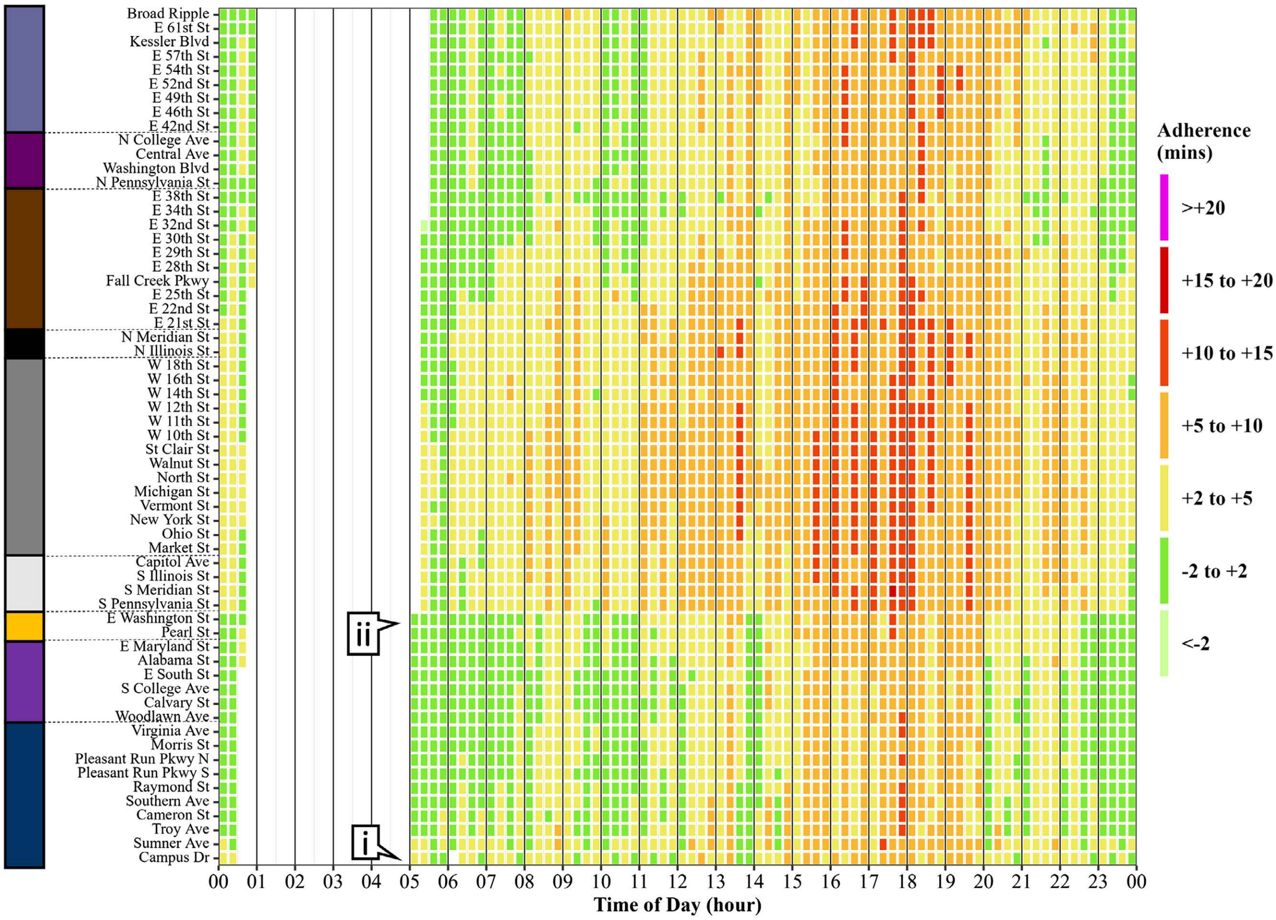


Figure 13. Average bus schedule adherence at northbound inter sections.

7.4. Candidate Intersections to Visit

The average intersection delay (**Figure 11**) and average schedule adherence (**Figure 13**) are two key performance measures that can help identify which intersections may have opportunities for signal timing adjustments. **Figure 14(a)** shows a scatter plot for every 15-min of average schedule adherence (x-axis) against the average intersection delay (y-axis) in the northbound direction. **Figure 14(b)** illustrates a cumulative frequency diagram of the above delays and schedule adherence. In general, across all signalized intersections in the northbound direction and their 15-min periods, the median schedule adherence in approximately +4 minutes (callout i) and the median delay is roughly 4s (callout ii). Buses experience an intersection delay of 20s or less (LOS B or better) during 90% of all the displayed 15-min periods (callout iii). This indicates that a small fraction of the signalized intersections would benefit from signal timing adjustments.

Figure 14(c) shows the same scatter plot as **Figure 14(a)** but excludes the near-side intersections. The LOS values and their thresholds are also color-coded in this plot. Intersections and periods to the left bottom of the plot (callout iv) are doing exceptionally well in terms of delay and schedule adherence. Points to

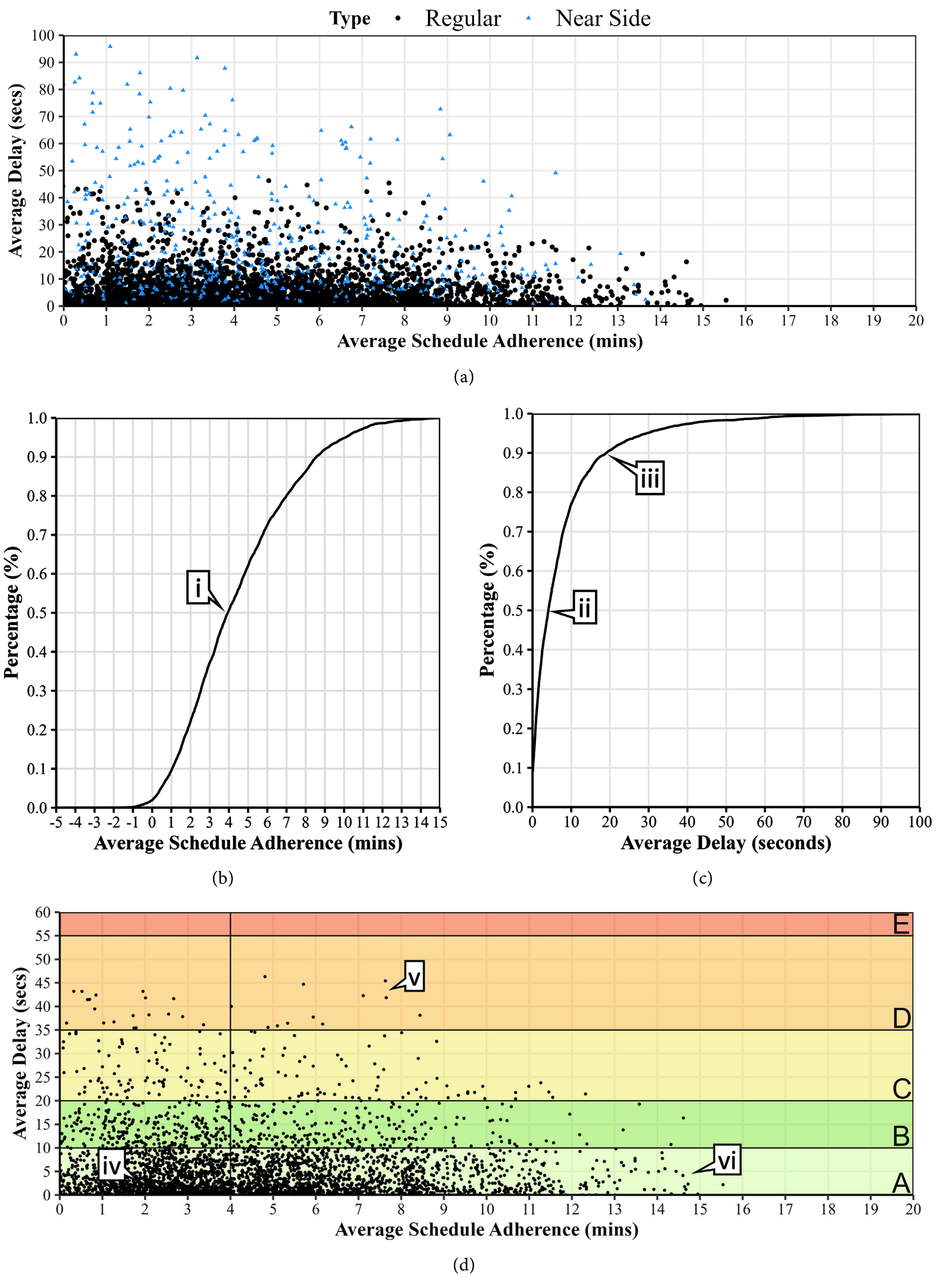


Figure 14. Performance evaluation of current traffic signals. (a) All intersections; (b) Avg. schedule adherence CFD; (c) Avg. delay CFD; (d) Intersections without near-side bus stations.

top right with high delay and extreme schedule adherence values (callout v) are candidates for schedule adjustments and signal retiming. Points to the bottom right show cases where the buses are off schedule but do not face any significant delays at the intersections (callout vi).

Figure 15 overlays a dot on the average schedule adherence heatmap from Figure 13 when the buses experience an average delay of 20s or more (LOS C or worse). Excluding the near-side intersections, three intersections that stand out are E South St (callout i), New York St (callout ii) and Raymond St (callout iii). Figure 16 illustrates the same visualization for the southbound route. In the southbound direction, E South St (callout i), New York St (callout ii) and E 38th St (callout iii) stand out. These comprehensive visualizations of the delay and schedule adherence by time of day helps practitioners prioritize intersections and time periods for evaluation, and potential adjustments to schedules and signal timing if they are found to be warranted.

8. Discussion

8.1. Signal Timing and Phase Adjustment Candidates

Considering delay, the top two intersections (callouts i and ii on Figure 15 and

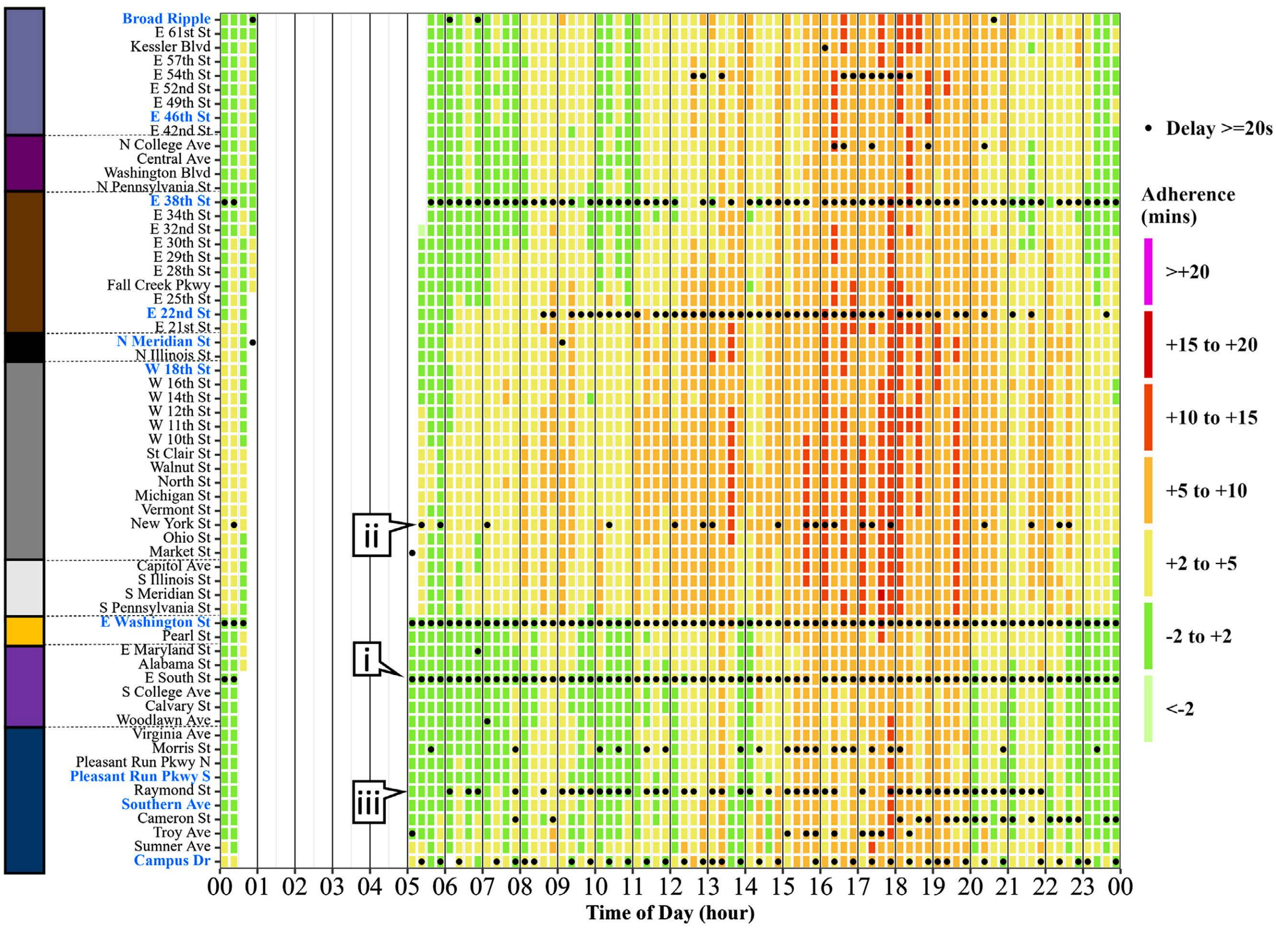


Figure 15. Candidate intersections for retiming in northbound direction.

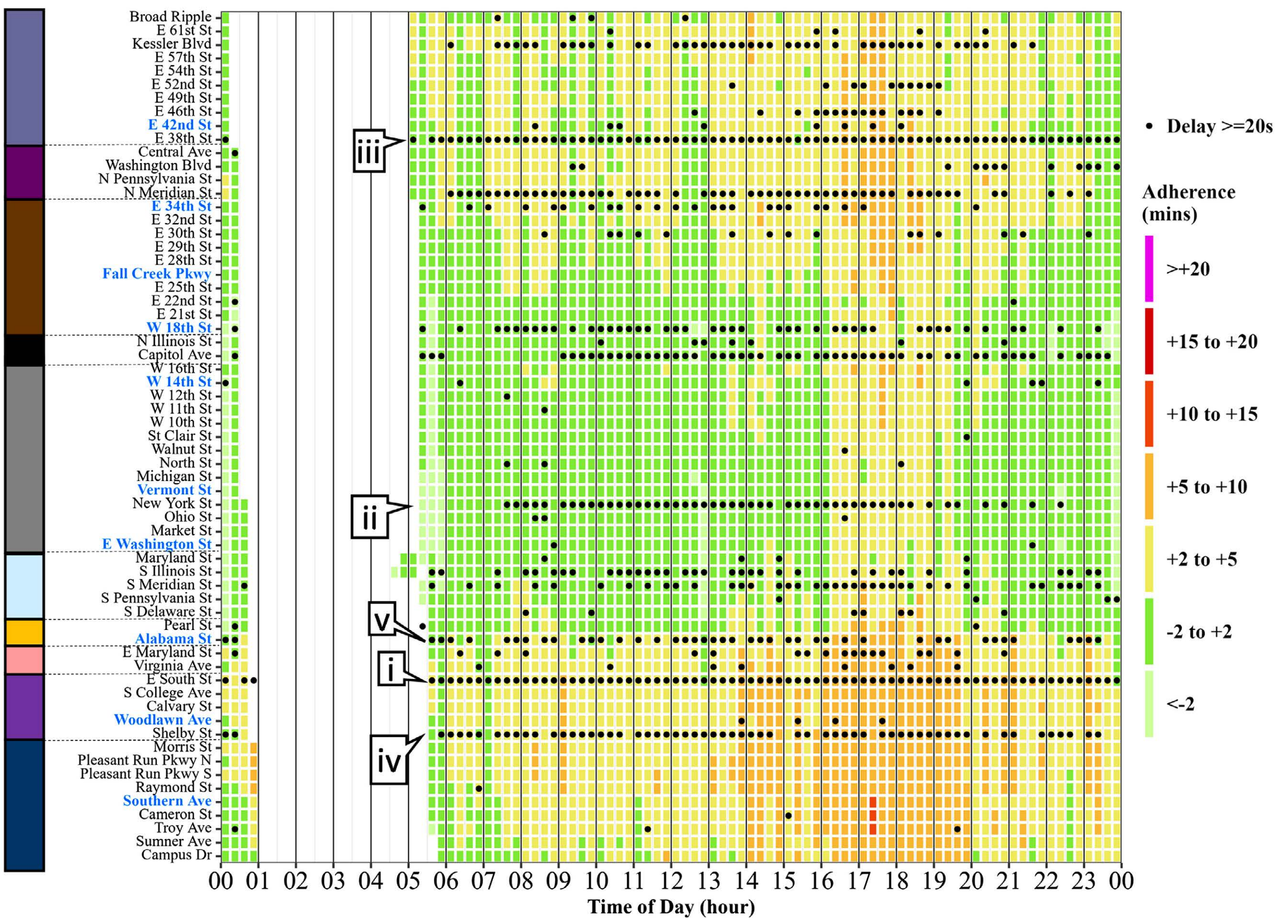
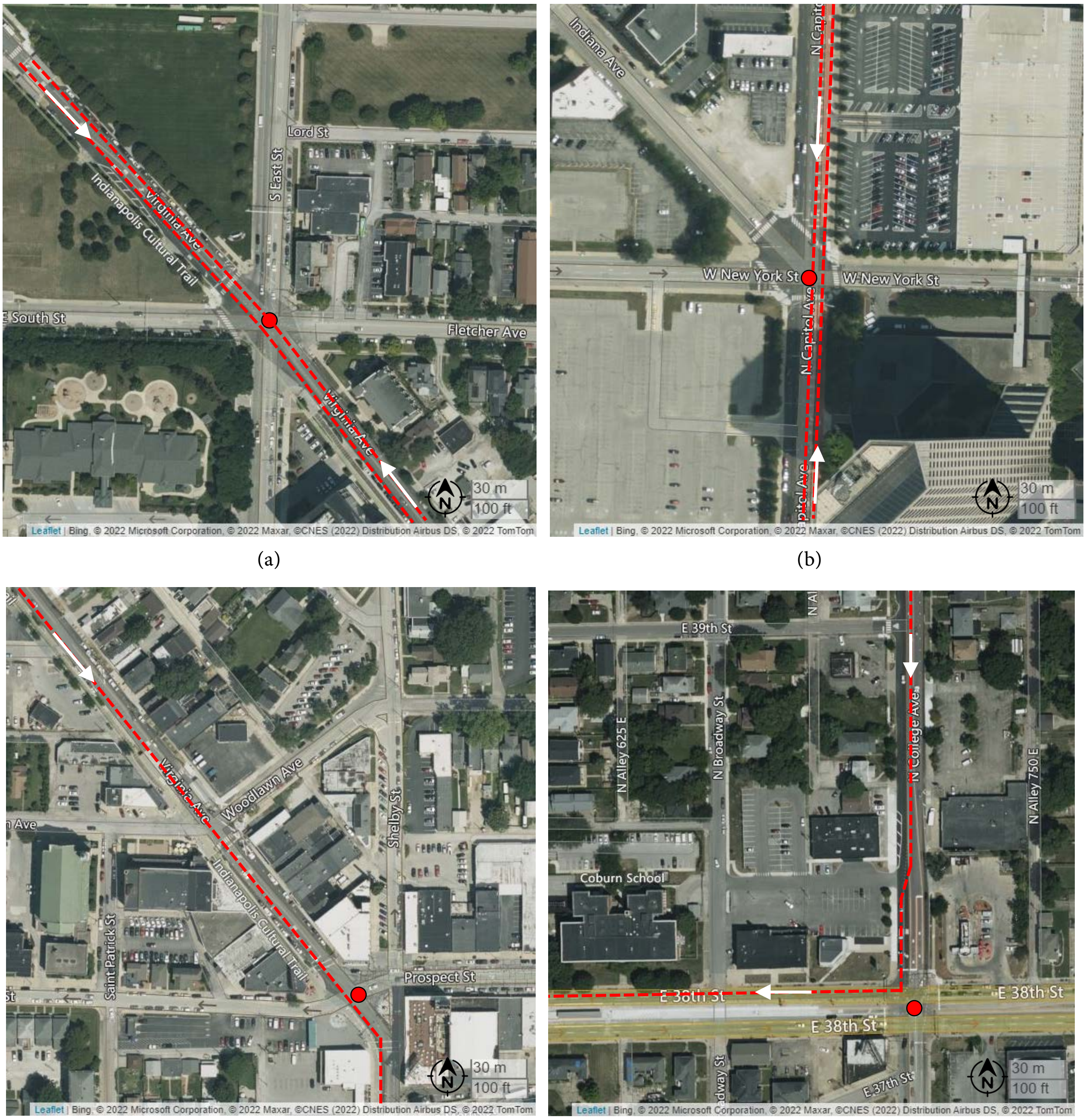


Figure 16. Candidate intersections for retiming in southbound direction.

Figure 16) that stand out in both the northbound and southbound directions throughout the day are E South St (at Virginia Ave with mixed traffic), and New York St (at Capitol Ave with dedicated running way). Further examination of the intersection geometry reveals that these two intersections have more than four legs (Figure 17(a) and Figure 17(b)) which explain the high delay faced by buses at these intersections since within one cycle length the signal has to serve more movements than a typical four-legged intersection. Signal timing changes that reduce bus control delay include running the intersection on free or allowing the signal controller to extend phase length past max green or exceed cycle length. In the southbound direction, E 38th St (at College Ave) and Shelby St (at Virginia Ave) also experiences high delay throughout the day (callouts iii and iv on Figure 16, respectively). Shelby St is also an intersection with more than four legs (Figure 17(c)). E 38th St is one of the intersections where the southbound bus needs to make a right turn from the dedicated bus lane on the center of College Ave across three through and right general traffic lanes (Figure 17(d)). Possible adjustments including decoupling the bus phase overlap from the eastbound and westbound left or westbound through could make the bus phase come up sooner.



(a) (b) (c) (d)

Figure 17. Top intersections for signal retiming assessment. (a) E South St at Virginia Ave in both directions; (b) New York St at Capitol Ave in both directions; (c) Shelby St at Virgina Ave in southbound; (d) E 38th St at College Ave in southbound.

8.2. Operational Adjustment Candidates

Looking at schedule adherence in northbound direction, the buses deviate from schedule after E Washington St (callout ii on Figure 13), accruing up to seven additional minutes of delay after the intersection. Similarly in the southbound direction, the buses seem to deviate from schedule after Alabama St (callout v on Figure 16), accruing additional delay of about seven minutes past the intersection. Evidently, these intersections are near the transit station in downtown where the operators take a short break. Operationally, this may present an opportunity for route managers and bus operators to communicate how schedules are calibrated during the dwell time and when the buses depart the transit station. Adjusting the schedules to accommodate anticipated short breaks could be one possible way to align on-time performance expectations for riders.

9. Summary and Future Research

This paper uses connected vehicle data and bus trajectory data to assess the performance of bus rapid transit system in Indianapolis, Indiana. Nearly 30 million private connected vehicle records and over 3 million bus records are analyzed during the three-month period between March and May 2022. Comparing travel times between general traffic using connected vehicle trajectory data and buses on dedicated bi-directional lanes, buses are found to match the travel times of general traffic, with maximum median travel time differences less than 1 minute during all times of the day. During peak periods, buses are even quicker and more reliable than the general traffic (**Figure 7(a)**). However, on shared roadways without any dedicated bus lanes, buses were less reliable and slower than the general traffic as expected (**Figure 7(b)**).

This research also presents a methodology to estimate bus delays and schedule adherence at intersections using bus trajectory data. Performance measures and visualizations using average intersection delay (**Figure 11**) and schedule adherence (**Figure 13**) are also developed to evaluate the performance of the BRT system and identify opportunities where signal retiming and schedule adjustments may prove beneficial (**Figure 15** and **Figure 16**).

The framework and performance measures presented in this study provide agencies and transportation professionals with tools to assess operational performance and reliability, especially for increasing on-time performance. Intersections and time periods where the buses experience high delays are candidates for potential signal retiming, offset adjustments and sequence variations if they are found warranted. The results would allow agencies to proactively identify locations where operational adjustments may be helpful using data-driven metrics. For example, intersections and time periods with low delay and good schedule adherence do not need any further enhancements, whereas those with high delay are likely to be revisited. Additionally, conditionally granting TSP for buses that are behind schedule could improve the reliability and schedule adherence. TSP requests for buses that are ahead of schedule may not need to be granted to benefit general traffic. Furthermore, adjusting the schedules or allocating additional time at major stations or transit centers could be one possible way to align with on-time performance expectations.

One limitation of this research is the inability to separate intersection delay from bus station dwelling at near-side intersections. Future research will target the incorporation of methodologies [25] and additional data elements from ATSPM data to separate the bus dwellings from delay. Furthermore, bus attributes indicating door open/closing and occupancy would be helpful in identifying exact time periods of bus dwellings. Future research will also evaluate before/after comparison of delay and schedule adherence after performing operational strategies on few of the intersections identified in this research.

Acknowledgements

Data between March and May 2022 used in this study was provided by Wejo Data Services Inc. and IndyGo. This work was supported in part by the Joint Transportation Research Program and Pooled Fund Study, TPF-5(377), led by the Indiana Department of Transportation (INDOT) and supported by the state transportation agencies of California, Connecticut, Georgia, Minnesota, North Carolina, Ohio, Pennsylvania, Texas, Utah, Wisconsin, plus the City of College Station, Texas, and FHWA Operations Technical Services Team. The contents of this paper reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein, and do not necessarily reflect the official views or policies of the sponsoring organizations. These contents do not constitute a standard, specification, or regulation.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] IndyGo (2019) Red Line—Detailed Information. IndyGo. https://www.indygo.net/red-line-detailed-information

[2] Federal Transit Administration (2020) Mobility Performance Metrics (MPM) for Integrated Mobility and Beyond. Federal Transit Administration, Washington DC. https://www.transit.dot.gov/sites/fta.dot.gov/files/docs/research-innovation/147791/mobility-performance-metrics-integrated-mobility-and-beyond-fta-report-no-0152.pdf

[3] Ivany, D. (2004) Bus Rapid Transit on the Streets of Boston, MA, USA—Making It Fit. *ITE Journal*, **74**, 42-45.

[4] CUTR (2003) Lynx LYMMO Bus Rapid Transit Evaluation. Technical Memorandums One through Three. CUTR-NCTR-RR-2003-17. https://digitalcommons.usf.edu/cutr_nctr/234

[5] Baltes, M., Perk, V., Perone, J. and Thole, C. (2003) South Miami-Dade Busway System Summary. National BRT Institute, Tampa.

[6] Thole, C. and Cain, A. (2006) The San Pablo Rapid BRT Project Evaluation. Federal Transit Administration, Washington DC, FTA-FL-26-7022-2006.1.

[7] Cham, L., *et al.* (2006) Honolulu Bus Rapid Transit Project Evaluation. Final Report, Federal Transit Administration, Washington DC, FTA-VA-26-7226-2006.1. https://nbrti.org/wp-content/uploads/2017/05/Honolulu_BRT_Final_Report.pdf

[8] Schimek, P., *et al.* (2006) 2006 Evaluation of the Las Vegas Metropolitan Area Express (MAX) Bus Rapid Transit Project. Federal Transit Administration, Washington DC, FTA-DC-26-7248-2006.1. https://rosap.ntl.bts.gov/view/dot/35232

[9] Stutsman, J.M. (2002) Bus Rapid Transit or Light Rail Transit—How to Decide? Los Angeles Case Study. *Transportation Research Record*, **1793**, 55-61. https://doi.org/10.3141/1793-08

[10] Carey, G. (2006) Bus Rapid Transit—The Eugene-Springfield, OR, USA, Experience. *ITE Journal*, **76**, 20-23. https://trid.trb.org/view/787508

[11] NYC DOT (2017) Green Means Go: Transit Signal Priority in NYC. Metropolitan Transit Authority, New York. http://www.nyc.gov/html/brt/downloads/pdf/brt-transit-signal-priority-july2017.pdf

[12] Phillips, D. and Vance, R. (2014) Implementation of Open Source TSP. 21*st World Congress on Intelligent Transport Systems ITSWC* 2014: *Reinventing Transportation in Our Connected World*, Detroit, 7-11 September 2014, 4564-4569. https://www.engineeringvillage.com/share/document.url?mid=cpx_M2e5a96d914d9c3f80a6M5fe110178163171&database=cpx&view=detailed

[13] Bazley, C., Vink, P. and Blankenship, D. (2014) Survey Results for Rural Bus Rapid Transit (BRT) VelociRFTA and Future Human Factor Considerations. 58*th International Annual Meeting of the Human Factors and Ergonomics Society*, Chicago, 27-31 October 2014, 1224-1228. https://doi.org/10.1177/1541931214581255

[14] Wanek-Libman, M. (2020, August 24) Houston's METRORapid Silver Line Opens for Service. Mass Transit. https://www.masstransitmag.com/bus/article/21151461/houstons-metrorapid-silver-line-opens-for-service

[15] Rta, G.C. (2014, December 7) Dec. 8: Clifton Project Ready, Cleveland State Line Opens. Greater Cleveland Regional Transit Authority. https://www.riderta.com/news/csu-line-opens

[16] Clark, J. (2018, January 1) COTA Offering Quicker Trip with New CMAX Route. NBC4i. https://www.nbc4i.com/news/local-news/cota-offering-quicker-trip-with-new-cmax-route

[17] Lazo, L. (2014, August 23) New Bus-Only Lanes in Alexandria Offer the Region's First Experience with Bus Rapid Transit. *Washington Post*. https://www.washingtonpost.com/local/trafficandcommuting/metroway-the-regions-first-bus-rapid-transit-debuts-sunday-in-northern-virginia/2014/08/22/17c63392-2920-11e4-958c-268a320a60ce_story.html

[18] Center for Transportation Studies (2019, March 10) METRO A Line Increases Transit Capacity and Ridership without Slowing Traffic. Center for Transportation Studies, University of Minnesota, Minneapolis. https://www.cts.umn.edu/publications/catalyst/2019/march/aline

[19] Kimpel, T.J., Strathman, J., Bertini, R.L. and Callas, S. (2005) Analysis of Transit Signal Priority Using Archived TriMet Bus Dispatch System Data. *Transportation Research Record*, **1925**, 156-166. https://doi.org/10.1177/0361198105192500116

[20] Furth, P.G. and Muller, T.H.J. (2000) Conditional Bus Priority at Signalized Intersections: Better Service with Less Traffic Disruption. *Transportation Research Record*, **1731**, 23-30. https://doi.org/10.3141/1731-04

[21] Wong, J. (2013) Leveraging the General Transit Feed Specification for Efficient Transit Analysis. *Transportation Research Record*, **2338**, 11-19. https://doi.org/10.3141/2338-02

[22] Bertini, R.L. and Tantiyanugulchai, S. (2004) Transit Buses as Traffic Probes: Use of Geolocation Data for Empirical Evaluation. *Transportation Research Record*, **1870**, 35-45. https://doi.org/10.3141/1870-05

[23] Uno, N., Kurauchi, F., Tamura, H. and Iida, Y. (2009) Using Bus Probe Data for Analysis of Travel Time Variability. *Journal of Intelligent Transportation Systems*, **13**, 2-15. https://doi.org/10.1080/15472450802644439

[24] Mazloumi, E., Currie, G. and Rose, G. (2010) Using GPS Data to Gain Insight into Public Transport Travel Time Variability. *Journal of Transportation Engineering*, **136**, 623-631. https://doi.org/10.1061/(ASCE)TE.1943-5436.0000126

[25] Farid, Y.Z., Christofa, E. and Paget-Seekins, L. (2016) Estimation of Short-Term Bus Travel Time by Using Low-Resolution Automated Vehicle Location Data. *Transportation Research Record*, **2539**, 113-118. https://doi.org/10.3141/2539-13

[26] Khadhir, A., Anil Kumar, B. and Vanajakshi, L.D. (2021) Analysis of Global Positioning System Based Bus Travel Time Data and Its Use for Advanced Public Transportation System Applications. *Journal of Intelligent Transportation Systems*, **25**, 58-76. https://doi.org/10.1080/15472450.2020.1754818

[27] Bie, Y., Gong, X. and Liu, Z. (2015) Time of Day Intervals Partition for Bus Schedule Using GPS Data. *Transportation Research Part C*: *Emerging Technologies*, **60**, 443-456. https://doi.org/10.1016/j.trc.2015.09.016

[28] Wang, Y., Ma, W., Yin, W. and Yang, X. (2014) Implementation and Testing of Cooperative Bus Priority System in Connected Vehicle Environment: Case Study in Taicang City, China. *Transportation Research Record*, **2424**, 48-57. https://doi.org/10.3141/2424-06

[29] Lee, Y.-J., Dadvar, S., Hu, J. and Park, B.B. (2017) Transit Signal Priority Experiment in a Connected Vehicle Technology Environment. *Journal of Transportation Engineering*, *Part A*: *Systems*, **143**, Article ID: 05017005. https://doi.org/10.1061/JTEPBS.0000062

[30] Leonard, B.D., Mackey, J., Sheffield, M., Bassett, D., Larson, S. and Hooper, I. (2019) Demonstrating Transit Schedule Benefits with a Dedicated Short-Range Communication-Based Connected Vehicle System. *Transportation Research Record*, **2673**, 215-224. https://doi.org/10.1177/0361198119859321

[31] Wang, Q., Yang, X., Leonard, B.D. and Mackey, J. (2020) Field Evaluation of Connected Vehicle-Based Transit Signal Priority Control under Two Different Signal Plans. *Transportation Research Record*, **2674**, 172-180. https://doi.org/10.1177/0361198120921161

[32] Schramm, L., Watkins, K. and Rutherford, S. (2010) Features That Affect Variability of Travel Time on Bus Rapid Transit Systems. *Transportation Research Record*, **2143**, 77-84. https://doi.org/10.3141/2143-10

[33] Arias, D., *et al.* (2021) Using GTFS to Calculate Travel Time Savings Potential of Bus Preferential Treatments. *Transportation Research Record*, **2675**, 1643-1654. https://doi.org/10.1177/03611981211009226

[34] Halyal, S., Mulangi, R.H., Harsha, M.M. and Laddha, H. (2022) Study on Travel Time Characteristics of Hubli-Dharwad Bus Rapid Transit System in Comparison with Heterogeneous Traffic Lane. In: Kumar, P.G., *et al.*, Eds., *Recent Advancements in Civil Engineering*, Springer, Singapore, 701-712. https://doi.org/10.1007/978-981-16-4396-5_61

[35] Baalaganapathy, V.L., Girijan, A., Vanajakshi, L.D. and Chilukuri, B.R. (2021) Evaluation of Bus Signal Priority and Dedicated Bus Lane for Efficiency Improvement. *Proceedings of the Sixth International Conference of Transportation Research Group of India*, Volume 1, 293-309. https://doi.org/10.1007/978-981-19-3505-3_20

[36] Waddell, J.M., Remias, S.M., Kirsch, J.N. and Trepanier, T. (2020) Utilizing Low-Ping Frequency Vehicle Trajectory Data to Characterize Delay at Traffic Signals. *Journal*

of Transportation Engineering, Part A: Systems, **146**, Article ID: 04020069. https://doi.org/10.1061/JTEPBS.0000382

[37] Saldivar-Carranza, E., Li, H., Mathew, J., Hunter, M., Sturdevant, J. and Bullock, D.M. (2021) Deriving Operational Traffic Signal Performance Measures from Vehicle Trajectory Data. *Transportation Research Record*, **2675**, 1250-1264. https://doi.org/10.1177/03611981211006725

[38] Hunter, M., Mathew, J., Cox, E., Blackwell, M. and Bullock, D. (2021) Estimation of Connected Vehicle Penetration Rate on Indiana Roadways. JTRP Affiliated Reports. https://doi.org/10.5703/1288284317343

[39] Mathew, J.K., Li, H., Landvater, H. and Bullock, D.M. (2022) Using Connected Vehicle Trajectory Data to Evaluate the Impact of Automated Work Zone Speed Enforcement. *Sensors*, **22**, Article No. 2885. https://doi.org/10.3390/s22082885

[40] Quiroga, C.A. and Bullock, D. (1999) Measuring Control Delay at Signalized Intersections. *Journal of Transportation Engineering*, **125**, 271-280. https://doi.org/10.1061/(ASCE)0733-947X(1999)125:4(271)

[41] Ko, J., Hunter, M. and Guensler, R. (2008) Measuring Control Delay Components Using Second-by-Second GPS Speed Data. *Journal of Transportation Engineering*, **134**, 338-346. https://doi.org/10.1061/(ASCE)0733-947X(2008)134:8(338)

[42] Saldivar-Carranza, E.D., Li, H. and Bullock, D.M. (2021) Identifying Vehicle Turning Movements at Intersections from Trajectory Data. 2021 *IEEE International Intelligent Transportation Systems Conference* (*ITSC*), Indianapolis, September 2021, 4043-4050. https://doi.org/10.1109/ITSC48978.2021.9564781

[43] Transportation Research Board (2010) Highway Capacity Manual. Fifth Edition, Transportation Research Board of the National Academies, Washington DC.

[44] Freije, R., *et al.* (2014) Graphical Performance Measures for Practitioners to Triage Split Failure Trouble Calls. *Transportation Research Record*, **2439**, 27-40. https://doi.org/10.3141/2439-03