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Signalized Corridor Timing Plan Change Assessment Using Connected Vehicle Data

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Abstract

Updates to traffic signal timing plans are expected to either improve operations or mitigate the effects of increased volumes. Longitudinal before-after studies are important when validating changes to traffic signal systems, but they have historically required field data collection as well as deployment of extensive detection and communication equipment. These infrastructure-based techniques are costly and hard to scale. This study utilizes commercially available connected vehicle (CV) trajectory data to assess the change in performance between August 2020 and August 2021 on a 22-intersection corridor associated with the implementation of a semi-automated adaptive control system. Approximately 1 million trajectories and 13.5 million GPS points are analyzed for weekdays in August 2020 and August 2021. The vehicle trajectory data is used to compute corridor travel times and linear referenced relative to the far side of each intersection to generate Purdue Probe Diagrams (PPD). Using the PPDs, operational measurements such as arrivals on green (AOG), split failures (SF), and downstream blockage (DSB) are calculated. Additionally, traditional Highway Capacity Manual (HCM) level of service (LOS) is estimated. Even though there was a 35% increase in annual average daily traffic (AADT), the weighted average vehicle delay only increased by two seconds, LOS did not change, AOG improved by 1%, and SF and DSB remained the same. Based on the small changes in operational performance and considering the increase in traffic volume it is concluded that the implementation of the semi-automated adaptive control system had a significant positive impact in the corridor. The presented framework can be utilized by agencies to use CV data to perform before-after studies to evaluate the impact of signal timing plan changes. The presented methodology can be applied to any location where CV trajectory data is available.

Keywords

Adaptive Control, Traffic Signals, Connected Vehicle, Trajectories, Performance

Measures, Before-After

1. Introduction

Traditionally, signal timing adjustments have been implemented periodically, usually every three to five years [1], or after receiving calls from unsatisfied motorists [2]. The latter approach is reactive since it allows for the operational state at the intersection to degrade until a public complaint is triggered.

Alternatively, state-of-the-practice Automated Traffic Signal Performance Measures (ATSPMs) have allowed agencies to continuously monitor their signal systems [1] [3]. ATSPMs are based on high-resolution traffic signal controller event data, which requires the presence of vehicle detection technology and communication systems [4]. The cost of these infrastructure investments often limits the scalability of ATSPMs and forces agencies to prioritize which intersections to equip with the technology.

In contrast, over 500 billion connected vehicle (CV) records are generated each month in the United States that are commercially available to any agency. This paper describes how CV data can be used to generate before-after studies for any traffic signal system. These techniques are applied to a 22-intersection corridor of US-27, located north of Cincinnati, between August 2020 and August 2021 that implemented a semi-automated adaptive control system in early 2021.

1.1. Literature Review

Various studies have utilized CV event data to analyze infrastructure safety. Hard-braking and hard-acceleration events have been found to have a positive significant correlation with crashes [5] [6] [7], making them valid surrogate safety measures. Saldivar-Carranza *et al.* estimated a 14% decrease in hard-accelerations after the stop-bar of a signalized intersection following a change of left-turn phasing from protected-permitted to protected-only [8]. Li *et al.* analyzed approximately 1.5 million hard-braking events to identify locations that warrant further engineering assessment [9].

CV trajectories can also provide scalable performance measures for a variety of intersection configurations [10] [11] [12]. Some of the developed trajectory-based performance measures include queue-lengths [13] [14], travel times [15] [16], delay [10] [17] [18] [19], arrivals on green (AOG) [10] [17] [19] [20], split failures (SF) [10] [19], and downstream blockage (DSB) [10]. Further, studies have presented agencies with frameworks on how to utilize CV data to assess their traffic signal systems when impacted by diversions caused by interstate work zones [21] and long-term closures [22]. However, few studies have been done on how to utilize real-world CV trajectories for system level before-after performance analysis of traffic signal systems that are retimed [15] or have implemented new control systems.

1.2. Objective

The objective of this study is to propose a methodology based on CV trajectory data that practitioners can follow to conduct before-after evaluations of corridor-wide traffic signal timing and system upgrades. A 22-intersection corridor with a recent implementation of a semi-automated adaptive system to update timing plans was used to demonstrate these techniques.

1.3. Connected Vehicle Data Description and Sample Penetration

The third-party crowdsourced CV trajectory data used in this study has been estimated to have a state-wide 4.2% penetration rate for August 2020 and 4.5% for August 2021 [23]. The data consists of individual vehicle trajectory waypoints with a 3-second reporting interval and 1.5 meters of spatial accuracy. Each waypoint has the following information: latitude, longitude, vehicle speed, vehicle heading, and an anonymous vehicle identifier.

In this study, approximately 1 million trajectories and 13.5 million waypoints were analyzed during the months of August 2020 and August 2021 to estimate the operational performance change at traffic signals that underwent retiming between these periods. The presented results provide practitioners with a quantitative assessment of the implemented control system that can be used for validation purposes.

2. Study Location and Analysis Period

The operation of a 22-intersection segment of US-27, located north of Cincinnati, Ohio (Figure 1), was upgraded in 2021 from a coordinated-actuated control to a semi-automated adaptive implementation of the Purdue Link Pivot Algorithm [24]. The new system suggests timing changes based on traffic conditions and an operator approves or rejects the recommendations. To validate the

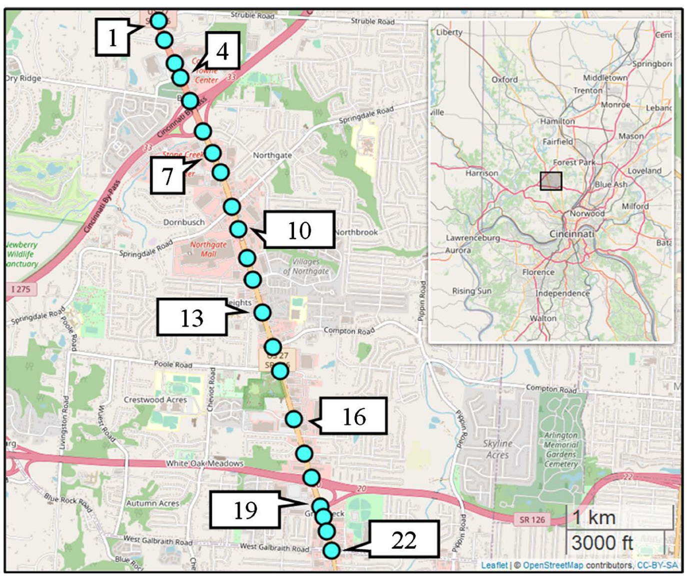

Figure 1. Study location.

efficiency of the implemented system, a before-after analysis based on August 2020 and August 2021 CV trajectory data is provided.

The intersections studied in this paper are listed on **Table 1**. It is important to note that Intersection ID 2, US-27 at Generation Dr., was installed between the two analysis periods. Therefore, movement performance measures at this location were only computed for the after analysis based on August 2021 data. However, corridor travel times implicitly capture the operational performance of the entire corridor.

Data Used for Analysis and Results

To have a consistent before-after comparison of performance measures, CV trajectory data for the same time interval was used to carry out the analysis:

- For the before period, trajectory data from August 3rd 2020 to August 28th 2020 weekdays (20 days) was used. This period will be referenced as August

Table 1. Studied intersection.

Intersection ID	Intersection Name
1	US-27 at Struble Rd.
2	US-27 at Generation Dr.
3	US-27 at Dry Ridge C Rd.
4	US-27 at Dry Ridge Rd.
5	US-27 at IR 275 WB
6	US-27 at IR 275 EB
7	US-27 at Stone Creek
8	US-27 at Redskin Dr.
9	US-27 at Springdale Rd.
10	US-27 at Marshall Square
11	US-27 at Mall Dr.
12	US-27 at Commons Circle
13	US-27 at Round Top
14	US-27 at Compton Rd.
15	US-27 at Poole Rd.
16	US-27 at Joseph Rd.
17	US-27 at Sovereign Dr.
18	US-27 at Cross Cty. WB
19	US-27 at Cross Cty EB
20	US-27 at Colerain
21	US-27 at Salvage Auto
22	US-27 at Galbraith Rd.

2020 (weekdays), where 152 intersection movements were analyzed.

- For the after period, trajectory data from August 2nd 2021 to August 27th 2021 weekdays (20 days) was used. This period will be referenced as August 2021 (weekdays), where 160 intersection movements were analyzed (eight more since the implementation of Intersection 2).

3. Traffic Volume Change

Annual average daily traffic (AADT) values for road segments in 2020 and 2021 on the studied corridor were obtained from the Ohio Department of Transportation (ODOT) Traffic Monitoring Management System (TMMS) [25] and are shown in **Table 2**. For the four segments for which data is available, there was a significant increase of 35% on traffic volume between 2020 and 2021, which can be attributed to post COVID-19 rebound of travel.

4. CV Computed Performance Measures

The following CV trajectory-based performance measures were calculated to provide insight on the effects that the implemented timing plans had on traffic operations [10] [26]:

- Arrivals on green (AOG): measurement based on vehicles experiencing stops while crossing intersections. AOG is used to assess the level of progression on a corridor.
- Split failures (SF): indication of the level of saturation at a specific approach. High ratios of SF suggest the need to rebalance split time.
- Downstream blockage (DSB): measurement of the level of obstruction by adjacent intersections. This is a useful tool to identify the source of congestion.
- Level of service (LOS): traditional Highway Capacity Manual (HCM) assessment based on control delay [27].
- Travel time: time taken by vehicles to traverse the entire corridor.

Figure 2 and **Figure 3** show the estimated performance measures by time-of-day (TOD) of vehicles traveling southbound through at the same 11-intersection segment of the studied corridor. Results are based in August 2020 weekday trajectories (before retiming) for **Figure 2** and in August 2021 weekday trajectories (after retiming) for **Figure 3**.

Qualitatively, it can be observed that AOG improved for most locations, which

Table 2. Volume change from count stations [25].

North Intersection ID	South Intersection ID	2020 AADT	2021 AADT	Difference
2	3	29,837	47,535	59%
4	5	30,092	41,405	38%
6	7	34,436	38,969	13%
13	14	29,852	39,504	32%
Total		124,217	167,413	35%

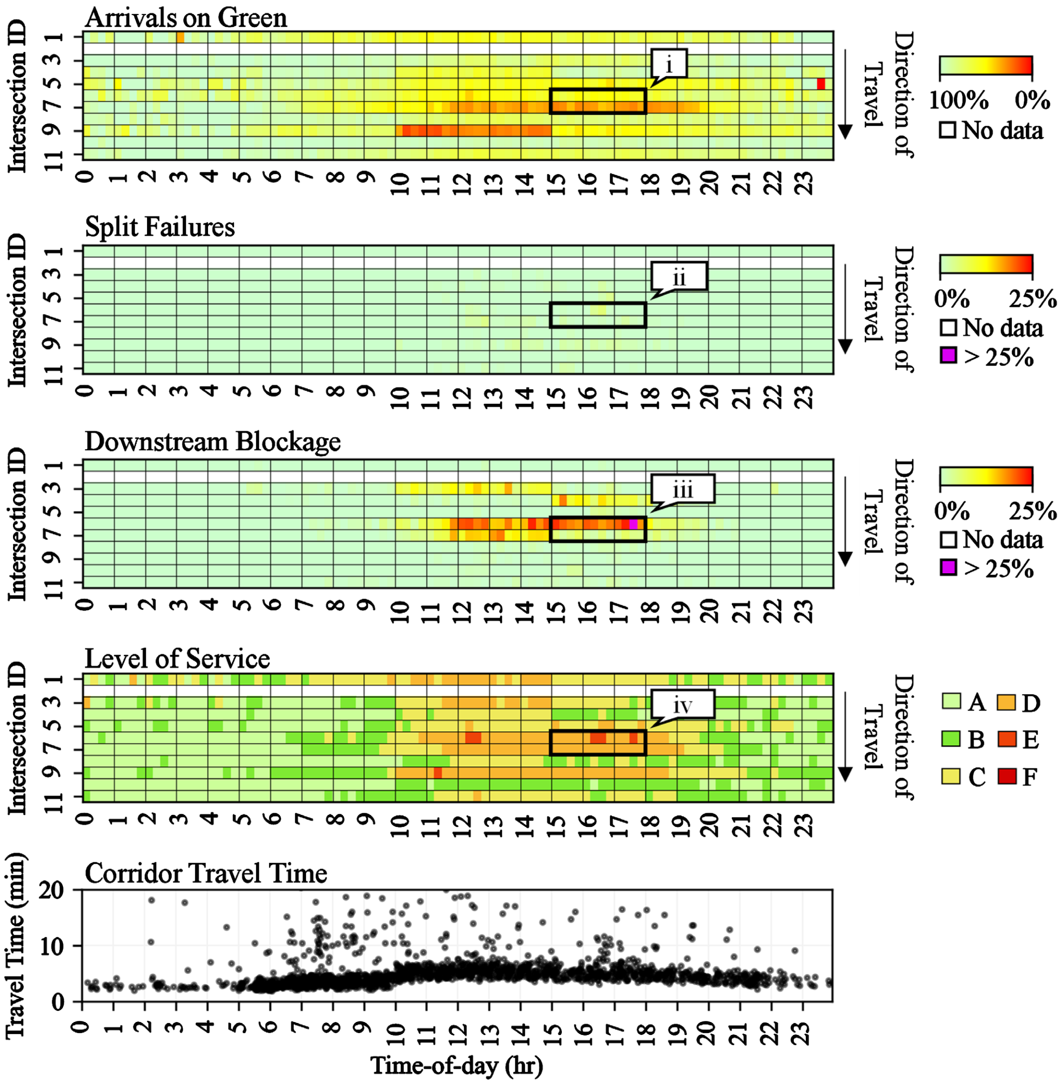

Figure 2. Signal performance measures during August 2020 weekdays (before semi-automated adaptive implementation) for vehicle trajectories traveling southbound through.

indicates a more efficient progression through the corridor. SF and travel time had no significant change. Regarding DSB and LOS, some locations had improvements in their operational performance and others saw slightly degraded conditions.

Considering that traffic volumes increased approximately by 35%, a significant deterioration of performance would have been expected. The fact that there was only a modest change in performance suggests that the signal timing plan updates and adaptive link pivot implementation effectively diminished the impact of increased demand and even improved operations in specific cases.

Intersection Operational Improvements and Influence on Adjacent Locations

By closely analyzing the graphics presented on Figure 2 and Figure 3, it is possible to identify insights not only on the operational changes, but also on the

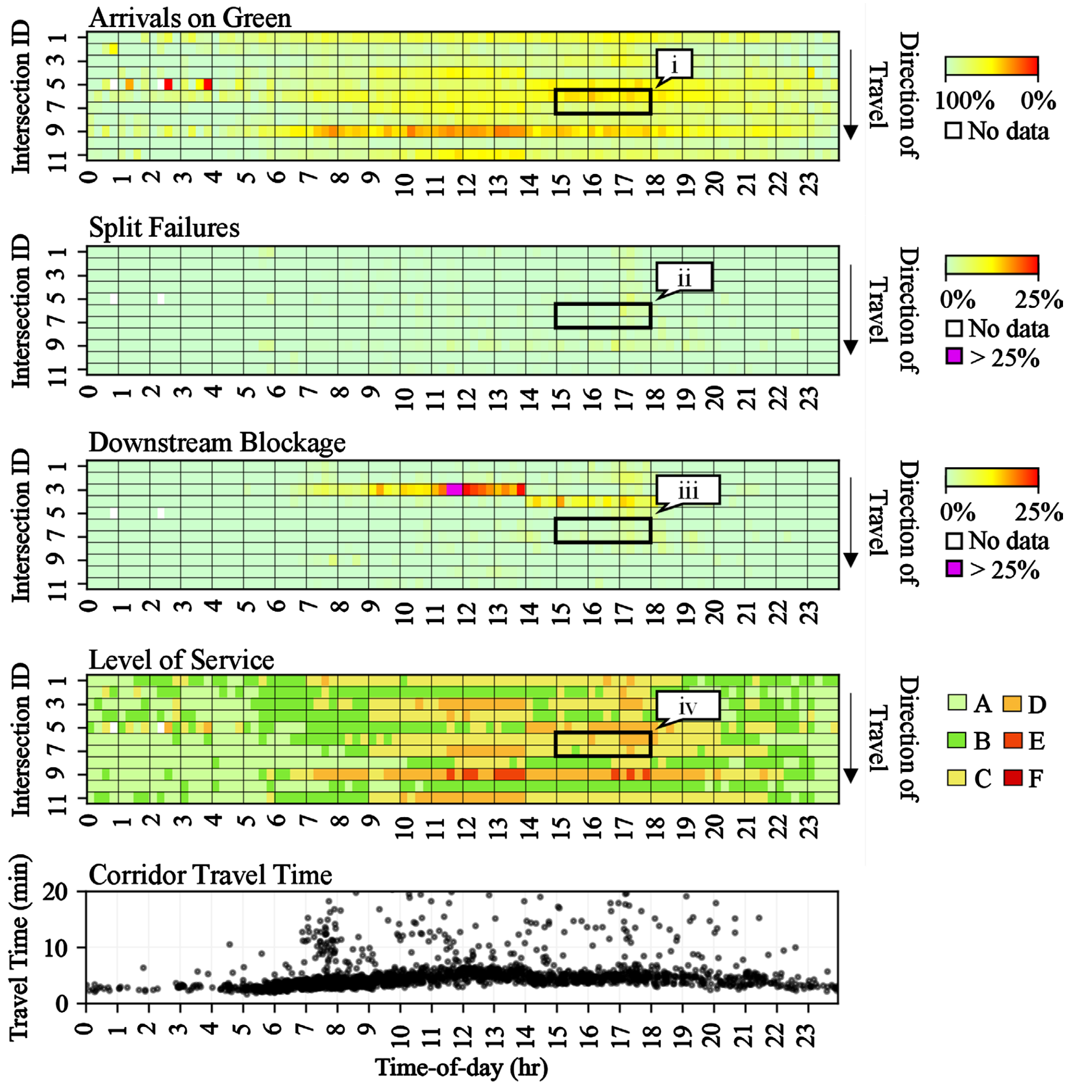

Figure 3. Signal performance measures during August 2021 weekdays (after semi-automated adaptive implementation) for vehicle trajectories traveling southbound through.

influence between adjacent intersections.

For example, Intersection ID 6 and 7 are closely spaced with a separation of 630 ft (192 m) as shown in Figure 4; hence, their operation is highly dependent on each other, particularly with regards to queue storage. Callouts i-iv on Figure 2 and Figure 3 highlight the performance of these two intersections during the PM peak period (15:00-18:00 hrs.). As seen, there are substantial improvements in AOG, DSB, and LOS in the after period.

The Purdue Probe Diagrams (PPD) [10] from which the performance measures are estimated for Intersections 6 and 7 are shown in Figure 5. Before the new semi-automated adaptive system was implemented, Intersection 7 had a 31% rate of AOG, which is noticeable by a lack of non-stopping (green) trajectories at its approach (Figure 5(c), callout iii). This low level of progression had negative effects on the upstream Intersection 6, since vehicles at this location experienced queued traffic soon after crossing the intersection, which is reflected

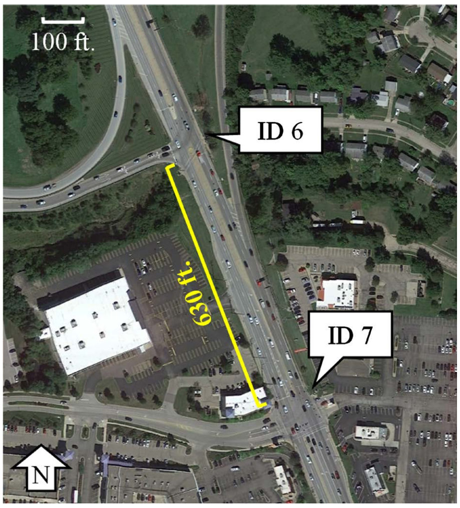

Figure 4. Aerial view of intersections 6 and 7.

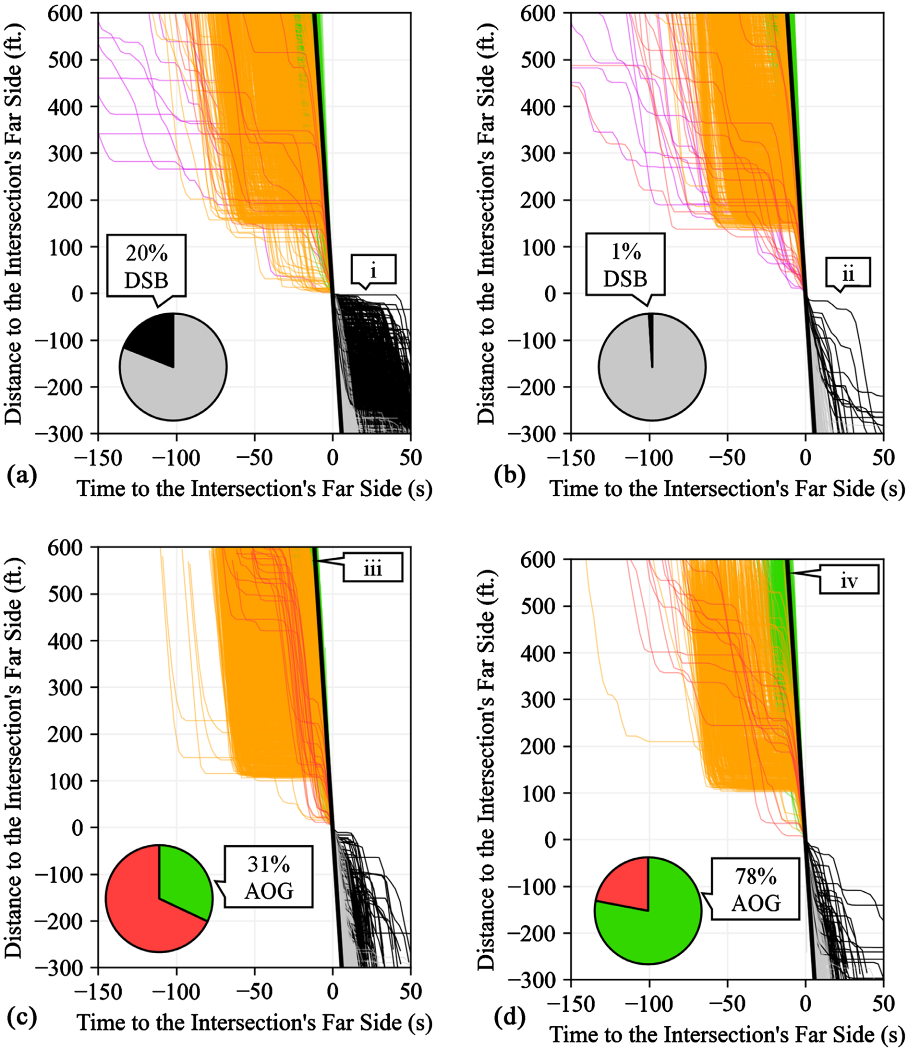

Figure 5. Purdue Probe Diagrams of vehicles traveling southbound through. (a) August 2020 weekdays (15:00-18:00) at ID 6; (b) August 2021 weekdays (15:00-18:00) at ID 6; (c) August 2020 weekdays (15:00-18:00) at ID 7; (d) August 2021 weekdays (15:00-18:00) at ID 7.

by a high percentage of vehicles experiencing DSB (**Figure 5(a)**, callout i). On the other hand, after the semi-automated adaptive system was implemented, Intersection 7 had an improved AOG rate of 78% (**Figure 5(d)**, callout iv). This enhanced progression had positive effects on Intersection 6, since the percentage of vehicles experiencing DSB was significantly reduced (**Figure 5(b)**, callout ii).

This analysis can also be performed solely from **Figure 2** and **Figure 3** by understanding the location of the intersections on the corridor and the correlation between the presented performance measures.

5. Results

August 2020 and August 2021 corridor-wide AOG, SF, DSB, and weighted average control delay, by movement, are shown on **Figure 6**. No significant changes were observed for AOG. SF increased for eastbound (EB) and westbound (WB) through (T) movements and decreased for EB left (L). DSB improved for EB-T movements but worsened for northbound (NB) through and EB-L. Weighted average control delay increased for the WB-T movement and the NB, EB, and WB left movements.

Table 3 shows the change in aggregated performance measure results for all

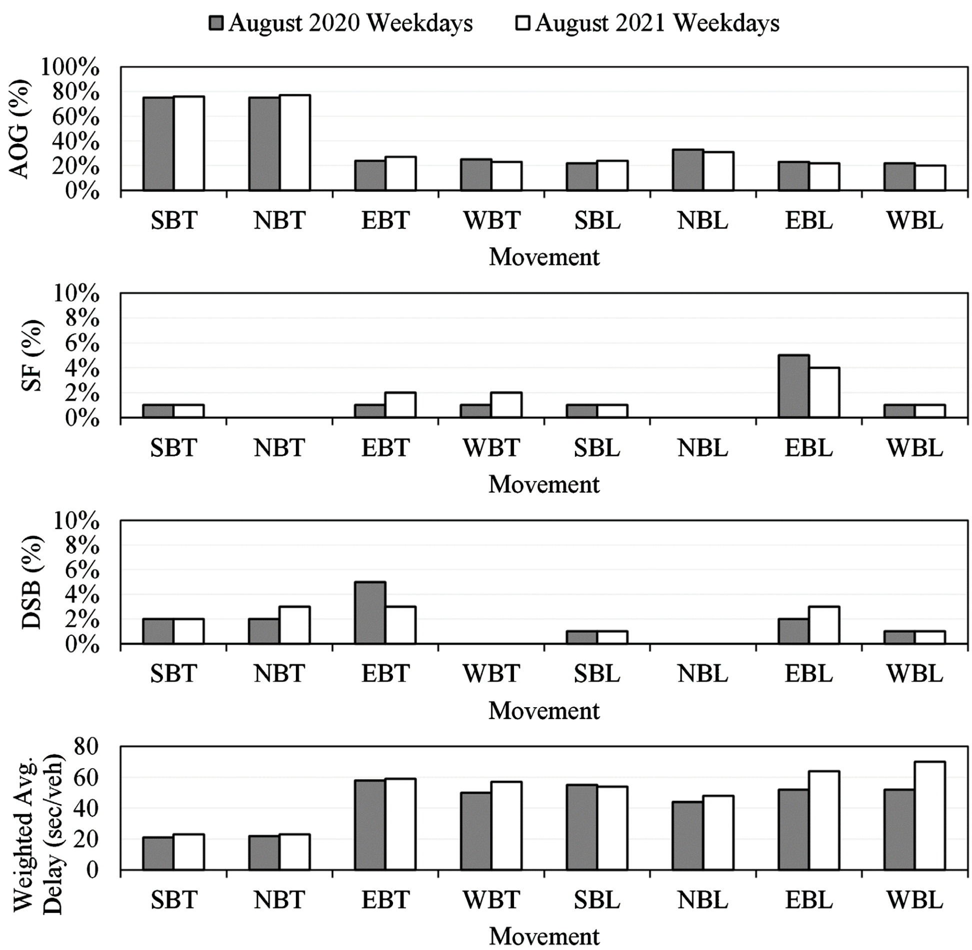

Figure 6. Change in performance by movement.

Table 3. Performance overview.

Measurement	Analysis Period	
	August 2020	August 2021
Count station traffic volume	124,217	167,413
Arrivals on green	70%	71%
Split failures	1%	1%
Downstream blockage	2%	2%
Weighted average control delay (sec/veh)	25	27
Level of service	C	C

the intersections and movements on the studied corridor. There was a 1% AOG improvement and a 2 second increase of weighted average control delay. SF, DSB, and LOS did not see any changes.

Based on the small changes in operational performance and considering the significant increase in traffic volume of 35%, it is clear that the semi-automated adaptive signal system was effective on diminishing the effects of an increased demand on the entire corridor.

6. Conclusions

This study presented a before-after assessment, based on connected vehicle trajectory data, of a 22-intersection corridor of US-27, located north of Cincinnati, to understand how the performance was affected by the implementation of a new semi-automated adaptive signal control system. The paper examined the variation in arrivals on green, split failure, downstream blockage, and delay derived from linear-referenced trajectories. Approximately 1 million trajectories and 13.5 million GPS points were analyzed from August 2020 (before retiming) and August 2021 (after retiming) connected vehicle data to generate corridor-wide (**Figure 2** and **Figure 3**) and approach level (**Figure 5**) visualizations. Further, the presented technique was shown to be capable of providing insight into the influence between adjacent intersections.

Figure 6 and **Table 3** illustrate only very minor changes in system performance after a 35% traffic volume increase. The weighted average control delay increased by only 2 seconds and the overall system level of service remained as "C".

The techniques presented are effective not only to validate the implementation of new traffic signal timing plans, but also to identify and warrant locations where timing or system upgrades are needed. The methodology presented in this paper can be applied to any location in the nation without the need of any sensing or communication equipment.

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Conflicts of Interest

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

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