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Continuous Flow Intersection Performance Measures Using Connected Vehicle Data

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Abstract

Continuous flow intersections (CFIs), also known as displaced left turns (DLTs), are a type of alternative intersection designed to improve operations at locations with heavy left-turn movements by reallocating these vehicles to the left side of opposing traffic. Currently, simulation is commonly used to evaluate operational performance of CFIs. However, this approach requires significant on-site data collection and is highly dependent on the analyst's ability to correctly model the intersection and driver behavior. Recently, connected vehicle (CV) trajectory data has become widely available and presents opportunities for the direct measurement of traffic signal performance measures. This study utilizes CV trajectory data to analyze the performance of a CFI located in West Valley City, UT. Over 4500 trajectories and 105,000 GPS points are analyzed from August 2021 weekday data. Trajectories are linear-referenced to generate Purdue Probe Diagrams (PPDs) and extended PPDs to estimate split failures (SF), arrivals on green (AOG), traditional Highway Capacity Manual (HCM) level of service (LOS), and the distribution of stops. The estimated operational performance showed effective progression during the PM peak period at all the critical internal storage areas with AOG levels at exit traffic signals between 83% and 100%. In contrast, all external approaches with longer queue storage areas had AOG values ranging from 2% to 81% during the same time period. The presented analytical techniques and summary graphics provide practitioners with tools to evaluate the performance of any CFI where CV trajectories are available without the need for on-site data collection.

Keywords

Performance Measures, Connected Vehicles, Trajectories, Continuous Flow Intersection, Displaced Left Turn

1. Introduction

Heavy left-turn movements can cause significant operational challenges at conventional signalized intersections. Some typical solutions are the improvement of alternative routes, widening the right-of-way, lane channelization, and the implementation of special signal phasing. If these techniques cannot be employed or are insufficient, grade separation solutions might be considered. Nevertheless, the cost and construction time required for grade separated intersections represent major constraints [1].

Continuous flow intersections (CFIs), also known as displaced left turns (DLTs), provide an alternative at-grade intersection design that can improve operations at locations with significant left-turning movements [1] [2]. At a CFI, one or more left-turn movements are displaced to the left of oncoming traffic upstream from the main intersection. Once left-turning vehicles reach the main intersection they can cross at the same time as opposing through traffic. This approach allows for the reduction of traffic signal phases and conflict points at the main intersection which can improve operations [2] [3].

Traditional infrastructure-based performance measurement typically monitors intersections independently and requires the practitioner to conceptually piece together tightly-coupled systems using local knowledge and field experience, such as upstream platooning, intersection spacing, storage, and downstream blockage [4]. As CFIs function as systems of closely-spaced intersections, it is important to monitor the performance of both the main intersection and left-turn crossovers to holistically evaluate the performance of the CFI.

1.1. Literature Review

Most of the CFI performance studies have been based on microsimulation [1] [2] [3] [5]-[11]. Jagannathan and Bared used VISSIM software to identify improvements on average control delay, average queue length, and intersection capacity by using CFIs compared to conventional intersection designs [5]. Park and Rakha concluded from video and simulation analysis that drivers are initially unfamiliar with the operations of CFIs, but as they become used to the geometry, operations improve [8]. Yang *et al.* verified with simulation that a proposed signal optimization model can provide enough green time to through and heavy turning movements while preventing queues from spilling over on the left-turning bays [10]. Alternatively, few studies have used infrastructure-based Automated Traffic Signal Performance Measures (ATSPMs) [4] [12] to assess performance at CFIs [13].

Recently, high-fidelity connected vehicle (CV) trajectory data has become commercially available. This new CV data provides opportunities to develop scalable traffic signal performance measures for conventional intersections [14] [15] [16] [17] [18], roundabouts [19], diamond interchanges [20], and diverging diamond interchanges (DDIs) [21]. However, no study has used CV trajectory data to evaluate the operational performance of CFIs.

1.2. Objective

Trajectory data allows practitioners to holistically evaluate the experience of traversing vehicles that travel through intersection systems that are comprised of more than one traffic signal, such as CFIs. The objective of this study is to utilize scalable CV-based methodologies to evaluate progression, delay, and split failures at a CFI. Additionally, the distribution of stops along relevant approaches is analyzed to characterize the length and location of queues to identify areas of opportunity.

2. Study Location

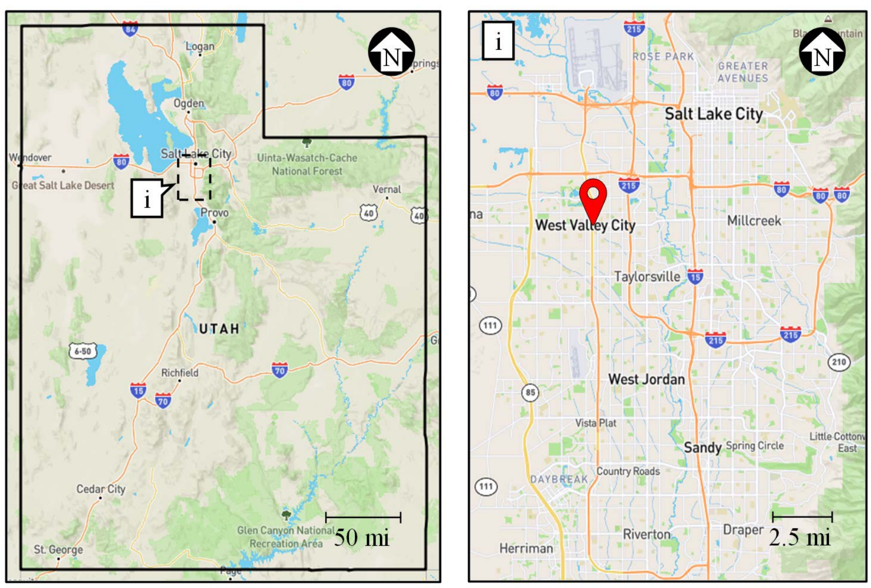
To demonstrate the trajectory-based techniques to calculate operational performance measures, Bangerter Highway at 3500 S, a CFI in West Valley City, UT (Figure 1), was analyzed with August 2021 weekday data. This CFI is located in a suburban area and usually serves over 30,000 vehicles approaching the intersection from the north and south, and 14,000 vehicles approaching from the east and west, daily [22].

3. Continuous Flow Intersection

In this section, the operation of the CFI at Bangerter Highway and 3500 S, as well as the conventional signal timing for this type of intersection is explained.

3.1. Operation

Figure 2 shows an aerial view of the studied intersection. This partial CFI [2] has displaced left turns only at the major street (Bangerter Hwy, N-S). The system is comprised of three signalized intersections:



(a) (b)

Figure 1. Study location. (a) Utah; (b) Salt Lake City metropolitan area.

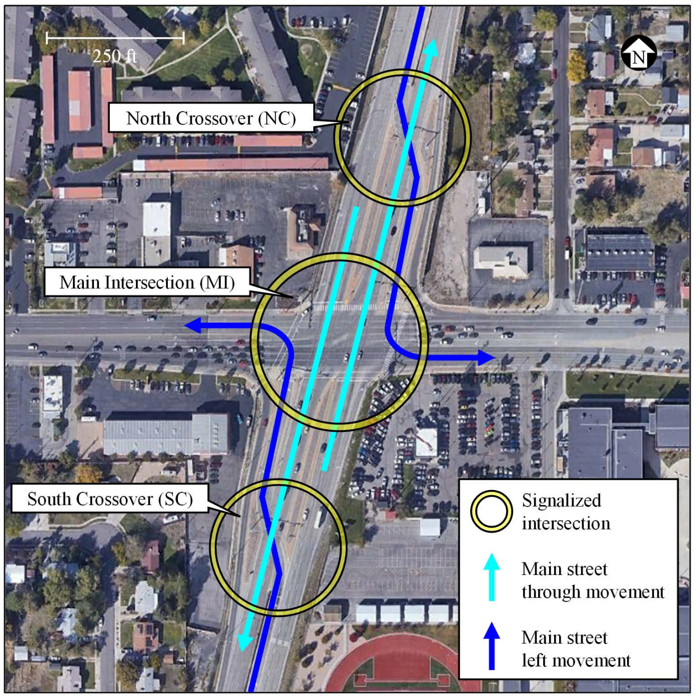


Figure 2. Bangerter Highway at 3500 S, West Valley City, UT.

- North Crossover (NC): this signal controls the flow of vehicles traveling northbound (NB) through (light blue) and vehicles traveling southbound (SB) crossing over (dark blue) that will then turn left at the main intersection. Vehicles traveling SB that will continue through at the main intersection are not affected by this signal.
- Main Intersection (MI): this signal controls all the movements that cross through this intersection. Since the major street left-turning vehicles have been crossed to the left of opposing traffic upstream from the MI, all through and left movements on the major street can occur simultaneously unless the adjacent pedestrian walk phases are called.
- South Crossover (SC): this signal controls the flow of vehicles traveling SB through (light blue) and vehicles traveling NB crossing over (dark blue) that will then turn left at the MI. Vehicles traveling NB that will continue through at the MI are not affected by this signal.

By crossing over left-turning vehicles upstream of the MI, the phases required for left-turn movements are not needed; hence, signal efficiency is improved [1].

For movements that must traverse two signals, it is imperative to provide efficient progression on the exit (last) signal. This is because storage at the exit signal is limited and congestion could lead to queue spillback that would significantly affect operations.

3.2. Signal Timing

Figure 3 shows conventional signal phasing for partial CFIs [2] [3]. All the movements are served in four intervals. For every instance where vehicles flow

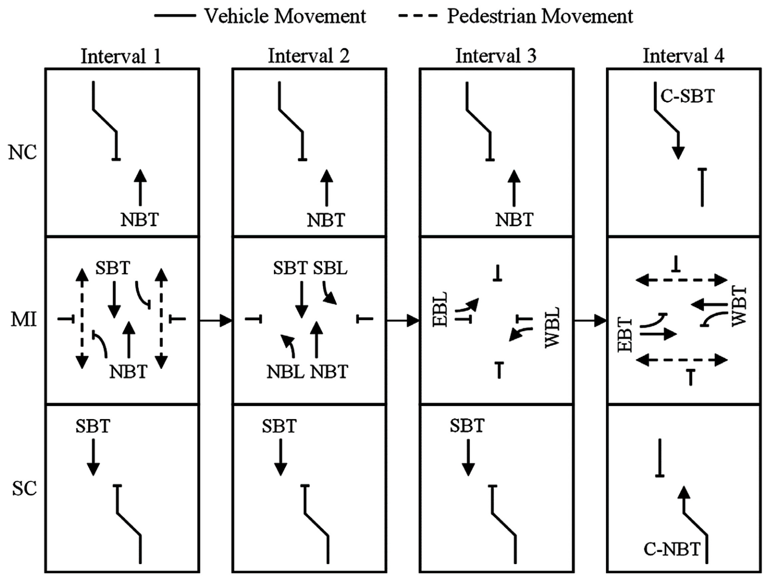


Figure 3. Conventional signal phasing for partial CFIs with major street displaced left turn [3].

from the MI towards a crossover (intervals 1 to 3), both the NC and SC intersections allow for vehicles to travel outbound from the CFI. Only when the minor street through movements are traversing the intersection (interval 4), vehicles cross over upstream of the MI to eventually turn left.

4. Methodology

In this section, the data and the proposed techniques used for CFI assessment are presented.

4.1. Connected Vehicle Trajectory Data

The state of Utah has modest, but sufficient CV data penetration to provide a robust analysis. A recent study indicated Utah CV trajectory data for August 2021 had a non-interstate estimated penetration rate of 2.8% [23]. The data consists of individual vehicle waypoints with latitude, longitude, the vehicle speed and heading, a timestamp, and an anonymized journey identifier. The data reports with a temporal frequency of three seconds and a spatial accuracy of 1.5 meters. For this study, over 4500 unique journeys and 105,000 waypoints are analyzed.

4.2. Continuous Flow Intersection Performance Measures

In this subsection, CV-based techniques are used to evaluate CFI performance. The following analyses are presented:

1) *Conventional and extended Purdue Probe Diagrams* (*PPDs*) for evaluating the experience of traversing vehicles while crossing through the entire system, by movement;

2) *Performance summaries* by intersection movement and time-of-day;

3) *First stop distribution* of sampled vehicles along each relevant approach.

4.2.1. Purdue Probe Diagram

PPDs are a CV-based tool designed to provide insights on the experience of vehicles traversing an intersection [14] by movement [24].

On a PPD for a conventional intersection, vehicle trajectories are linear-referenced to the far-side (FS) of a single intersection and plotted by the distance and time remaining to exit. A thick black line representing the hypothetical free-flow trajectory (FFT) of a vehicle traveling at the posted speed limit is shown for reference. Additionally, each trajectory is color-coded based on the number of stops it had upstream of the FS. From a PPD, the following traffic signal performance measures can be calculated [14]:

- Arrivals on green (AOG): evaluation of the quality of progression calculated as the ratio of non-stopping vehicles (green trajectories).
- Split failures (SF): assessment of the level of saturation estimated as the ratio of vehicles that stop more than once (red and purple trajectories).
- Level of service (LOS): Highway Capacity Manual (HCM) LOS [25] can be calculated by comparing the time it takes each traversing vehicle to cross the intersection with the FFT and estimating control delay [26].
- Downstream blockage (DSB): evaluation of the level of obstruction produced by downstream intersections.

Conventional PPDs are effective when evaluating vehicle movements on an intersection-by-intersection basis [17] [18]; however, when analyzing the performance of a system comprised of more than one signalized intersection, such as a CFI, the Extended Purdue Probe Diagram (EPPD) is preferred [20] [21]. An EPPD stacks all relevant individual PPDs of vehicles following a specific movement on a system of intersections where the trajectories reference the distance and time remaining to cross the final intersection's FS. As color-coding is done by intersection, performance evaluation for each segment in the system is possible.

Figure 4 shows EPPDs from August 2021 weekdays for the CFI's major street through and displaced-left movements during the PM peak period between the 16:00 and 18:00 hrs. In all four movements some vehicles stop before entering the CFI (above the upmost horizontal blue line), but once in the system (between horizonal blue lines) they effectively progress through the second intersection (callout i) as indicated by high AOG values ranging from 83% to 100%. This is important to avoid queue spillback from the limited storage areas inside the CFI. Further, it can be stated that these movements operate on under-saturated conditions as no significant levels of split failures occur.

Figure 5 shows PPDs and EPPDs from August 2021 weekdays for the CFI's minor street through and left movements during the PM peak period. The through westbound (WB) and eastbound (EB) movements (**Figure 5(a)** and **Figure 5(c)**, respectively) only have to cross one signalized intersection while the left-turning WB and EB movements (**Figure 5(b)** and **Figure 5(d)**, respectively) must traverse

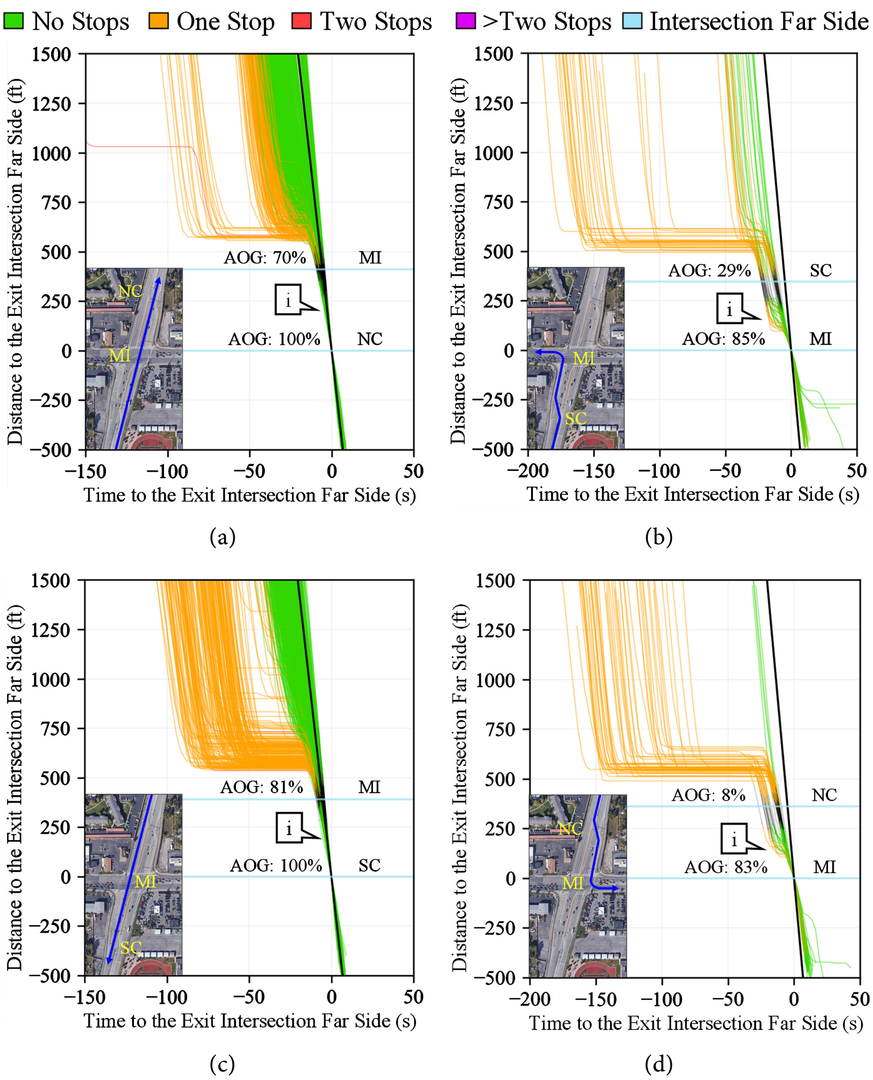


Figure 4. Extended Purdue Probe Diagram of major street movements on August 2021 weekdays between 16:00 and 18:00 hrs. (a) Northbound through; (b) Northbound displaced-left;(c) Southbound through; (d) Southbound displaced-left.

two. Similar to the major street movements, the minor street left movements have very efficient progression when exiting the CFI (callout i), with AOG values of 100%. However, all minor street movements show significant number of vehicles experiencing split failures before entering the intersection, indicating oversaturated conditions.

4.2.2. Performance Summaries

PPDs provide traffic signal performance measures at the movement-level for a defined time period. To assess all movements at various intersections simultaneously by time-of-day (TOD), a series of heatmaps summarizing performance by movement at 15-minute intervals are proposed. This approach permits the prompt identification of operational challenges and potential improvement opportunities.

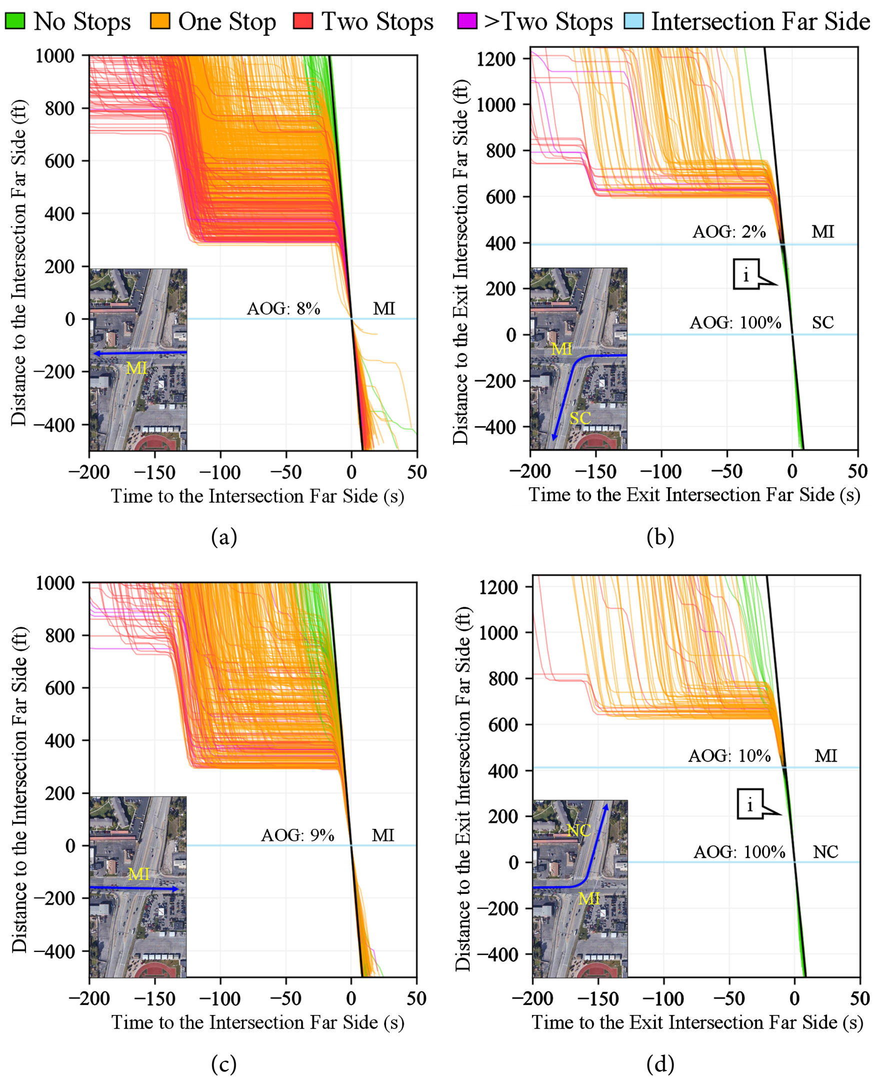


Figure 5. Minor street movements on August 2021 weekdays between 16:00 and 18:00 hrs. (a) Westbound through PPD; (b) Westbound left EPPD; (c) Eastbound through PPD; (d) Eastbound left EPPD.

Figure 6 shows heatmaps indicating the percentage of vehicles experiencing split failures at the three signalized intersections that comprise the analyzed CFI. No significant challenges are observed at the crossovers (**Figure 6(b)** and **Figure 6(d)**). However, at the MI (**Figure 6(c)**), side street movements show high SF ratios during the 14:15 to 18:30 period. Since the movements on the major street do not present any congestion challenges, split rebalance that could potentially benefit the minor street left-turn movements (interval 3 on **Figure 3**) may be possible. Significant operational improvements of the westbound-through (WBT) and eastbound-through (EBT) movements is difficult as the maximum green time they can received as capped by the travel time from the crossovers to the MI by the southbound-left (SBL) and northbound-left (NBL) movements.

Figure 7 shows the percentage of sampled vehicles that arrive on green at each intersection. Some vehicles entering the CFI system (callout i) have to stop and

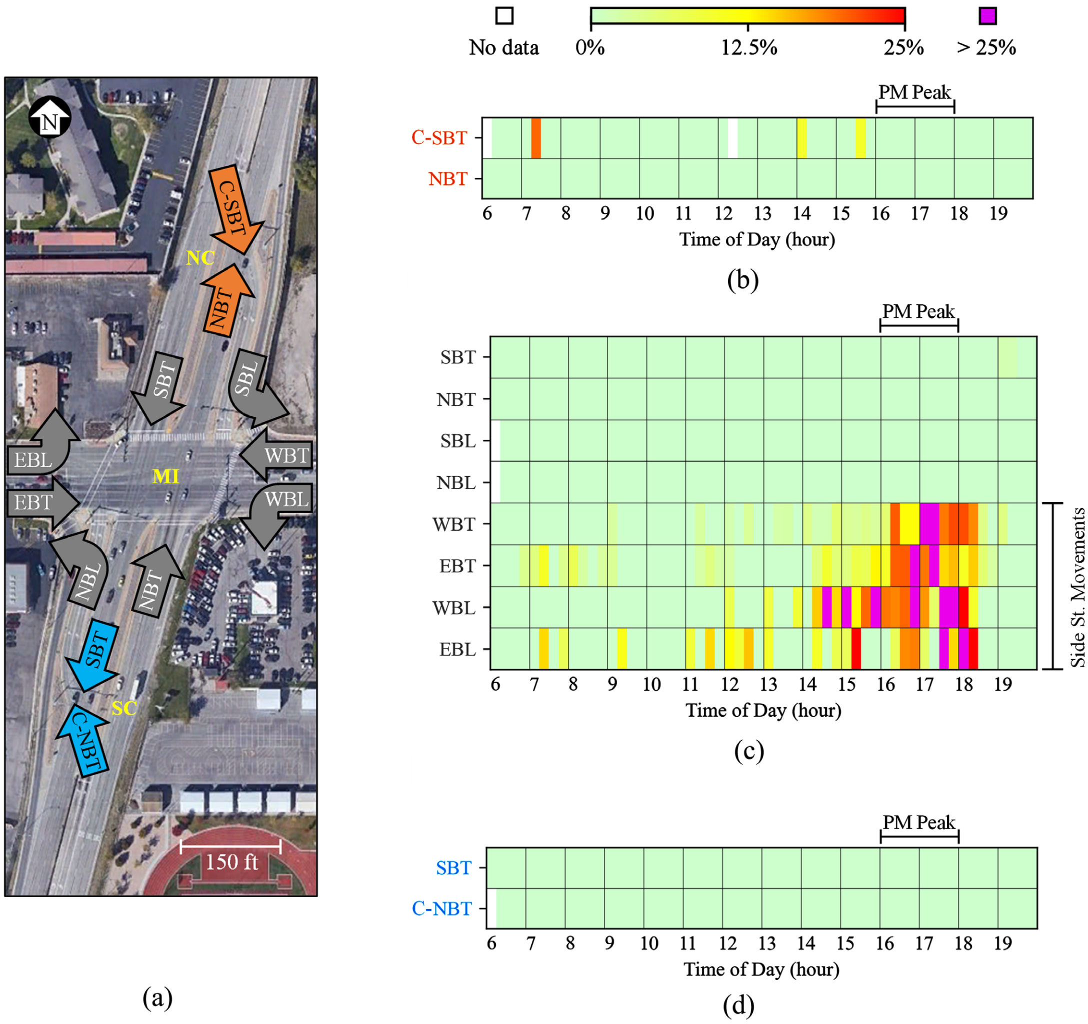


Figure 6. Split failure summary results by movement at all signals on the CFI for August 2021 weekdays. (a) Movements analyzed; (b) North crossover; (c) Main intersection; (d) South crossover.

hence present low AOG levels. However, once the entry intersection is crossed, progression at the exit intersection (callout ii) is efficient and AOG is high. This helps maintain minimal queues on the inner storage areas.

Figure 8 shows heatmaps indicating the LOS experienced at each movement. To facilitate the evaluation of the graphic, vehicle movements that enter the system on the major street are indicated with callout i, and vehicle movements that exit with callout ii. The effects of saturation and progression on control delay become evident.

4.2.3. First Stop Distribution

Figure 9 shows linear-referenced histograms of the location relative to the exit intersections' far-side where vehicles first stop while approaching each intersection for movements that cross two signals at the studied CFI. The distributions are calculated by identifying the location where vehicles come to a full stop for the first time upstream of each signalized intersection in the system. Then, the

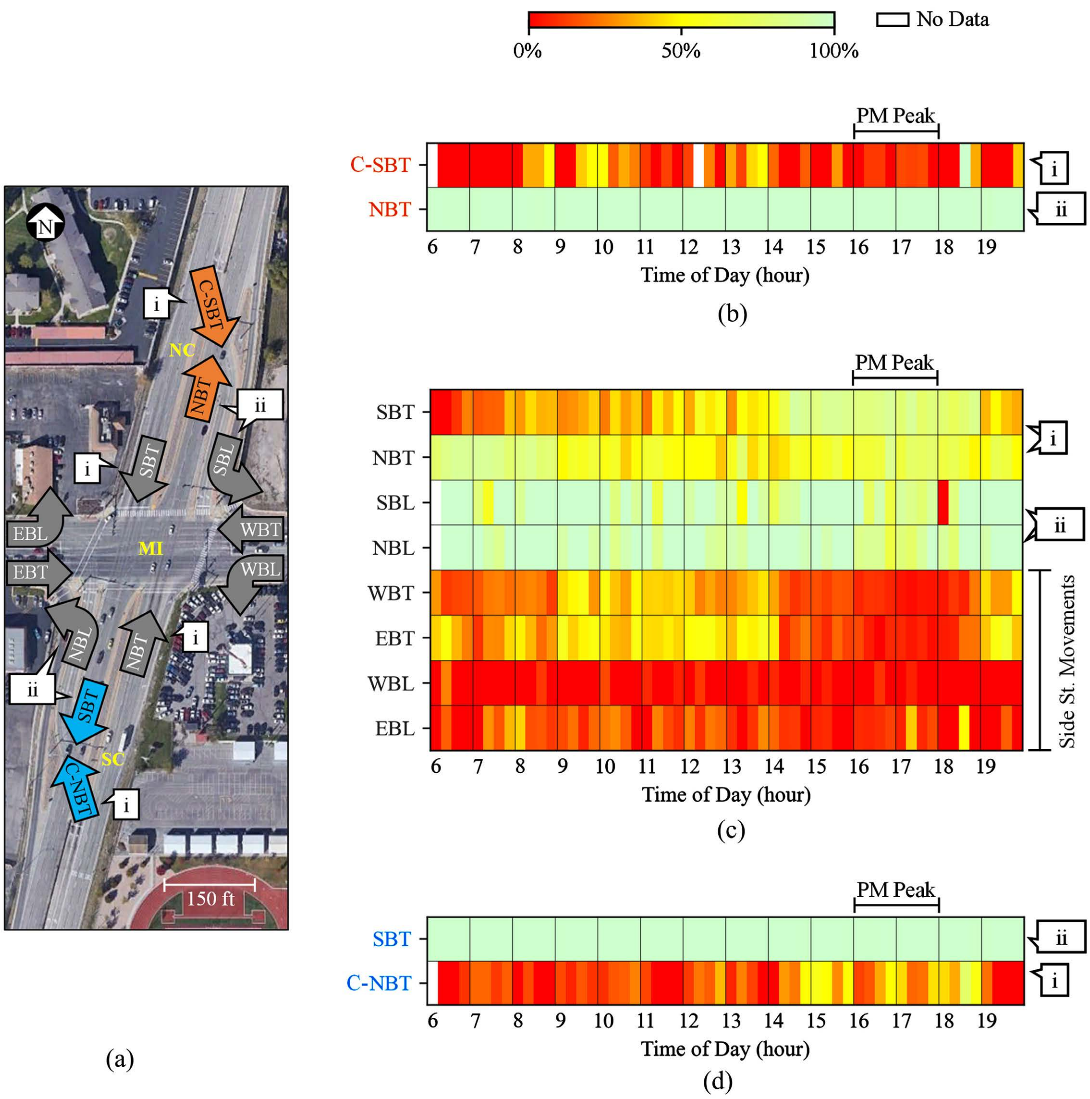


Figure 7. Arrivals on green summary results by movement at all signals on the CFI for August 2021 weekdays. (a) Movements analyzed; (b) North crossover; (c) Main intersection; (d) South crossover.

recorded values are normalized as a percentage of the total number of sampled vehicles for the evaluated movement.

This analysis can help identify approaches where stops or inefficiencies occur. For example, **Figure 9** shows how few vehicles stop at the through movements that traverse the crossover intersections (NBT and SBT). In contrast, significant number of left-turning vehicles stop before entering the CFI. More importantly, for the internal approaches with limited storage, 15% of vehicles traveling NBL stop between MI and SC (callout i), and 17% of vehicles traveling SBL stop between MI and NC (callout ii). Given the distance of the first stops between the MI and the crossovers, it is unlikely that there are any capacity issues as the queues do not extend to the crossovers. However, it might be of interest to investigate further the cause of the stops and whether offset adjustments can be made to prevent NBL and SBL vehicles from stopping at the MI.

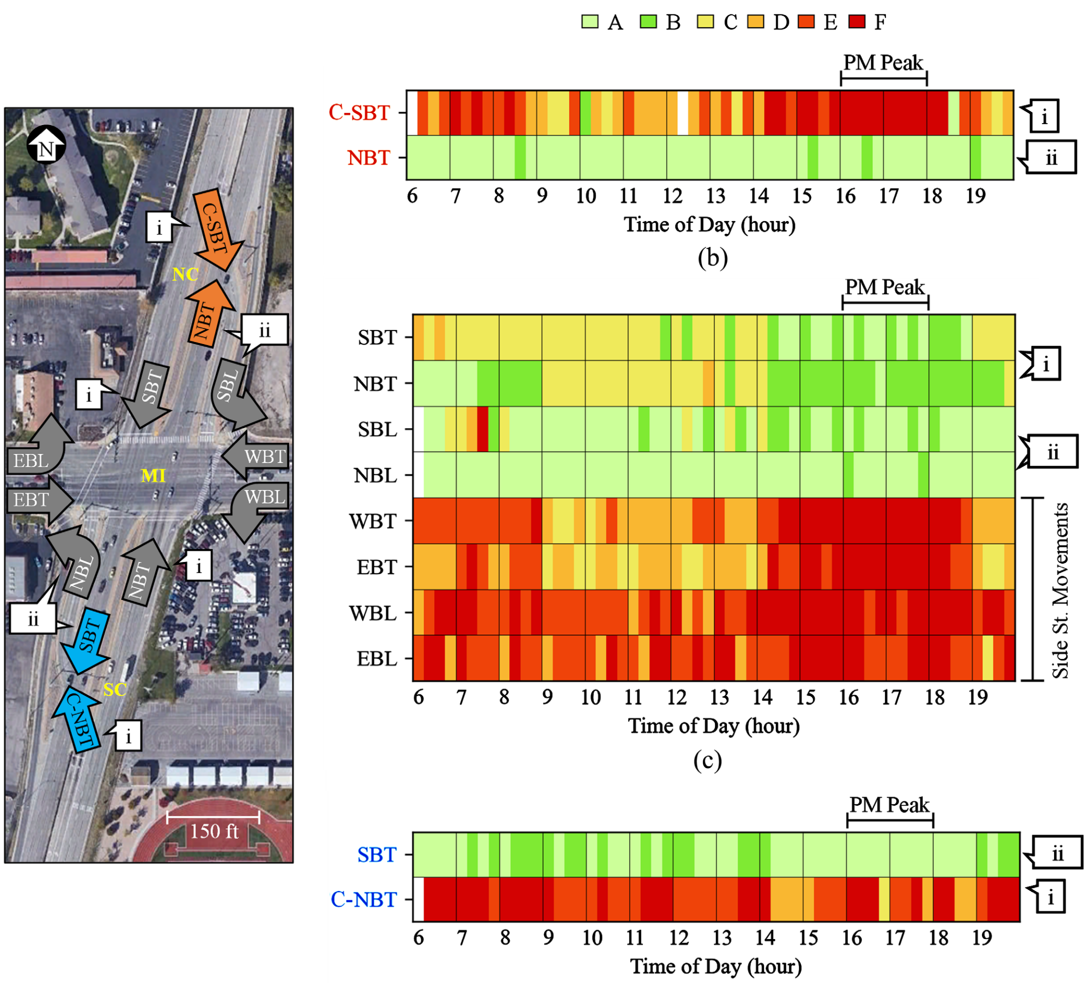


Figure 8. Level of service summary results by movement at all signals on the CFI for August 2021 weekdays. (a) Movements analyzed; (b) North crossover; (c) Main intersection; (d) South crossover.

5. Conclusions

Continuous flow intersections are alternative intersections that aim at improving operations where left-turning movements are heavy. As CFIs are deployed, it is important to holistically measure performance across the multiple signals that compose a CFI. This study utilized commercially available, high-fidelity, CV trajectory data to evaluate operations of a CFI located in West Valley City, UT. The following graphics were generated to assess performance:

- Extended Purdue Probe Diagrams: movement-level diagrams that show the progression of traversing vehicles through the entire CFI system. These diagrams provide practitioners with a holistic view of vehicles' experience while crossing the CFI.
- Performance summary by time-of-day: intersection-level graphics that simultaneously show the performance of all movements at the CFI by TOD. These visualizations allow for a quick identification of potential improvement opportunities by comparing movement performance.

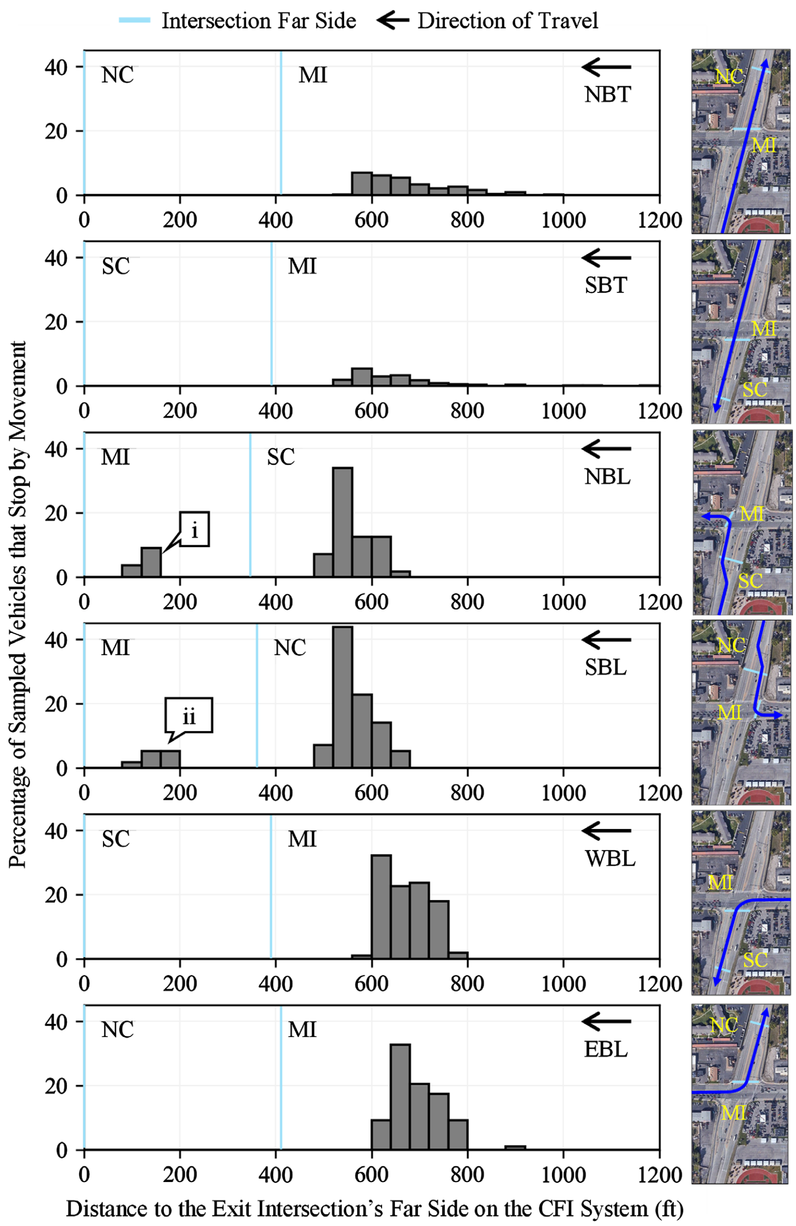


Figure 9. Distance to the exit intersection's far side (ft) of vehicles' initial stops as a percentage of the total sampled trajectories by movement during August 2021 weekdays between 16:00 and 18:00 hrs.

- Distribution of stops: evaluation of the location of stops of vehicles traversing two signalized intersections in the system. This visualization allows the identification of significant progression challenges and internal storage areas that might spillback.

The techniques used to evaluate the studied CFI can be implemented anywhere CV data is available without the need for simulations, site-visits, or sensing equipment. However, it is important to mention that the techniques rely on CV-trajectory data that is reported frequently (every 3 seconds) and with high accuracy (1.5 meters). Any significant deviation on these data characteristics could affect results' reliability.

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Conflicts of Interest

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

References

[1] Reuben Goldblatt, B., Mier, F. and Friedman, J. (1994) Continuous Flow Intersections. *Institute of Transportation Engineers*, **64**, 35-42.

[2] Hughes, W., Jagannathan, R., Sengupta, D. and Hummer, J. (2010) Alternative Intersections/Interchanges: Informational Report (AIIR). https://www.fhwa.dot.gov/publications/research/safety/09060/09060.pdf

[3] Steyn, H., Bugg, Z., Ray, B., Daleiden, A., Jenior, P. and Knudsen, J. (2014) Displaced Left Turn Intersection: Informational Guide. https://safety.fhwa.dot.gov/intersection/crossover/fhwasa14068.pdf

[4] Day, C., *et al.* (2014) Performance Measures for Traffic Signal Systems: An Outcome-Oriented Approach. Purdue University, West Lafayette. https://doi.org/10.5703/1288284315333

[5] Jagannathan, R. and Bared, J.G. (2004) Design and Operational Performance of Crossover Displaced Left-Turn Intersections. *Transportation Research Record: Journal of the Transportation Research Board*, **1881**, 1-10. https://doi.org/10.3141/1881-01

[6] el Esawey, M. and Sayed, T. (2007) Comparison of Two Unconventional Intersection Schemes: Crossover Displaced Left-Turn and Upstream Signalized Crossover Intersections. *Transportation Research Record: Journal of the Transportation Research Board*, **2023**, 10-19. https://doi.org/10.3141/2023-02

[7] Dhatrak, A., Edara, P. and Bared, J.G. (2010) Performance Analysis of Parallel Flow Intersection and Displaced Left-Turn Intersection Designs. *Transportation Research Record: Journal of the Transportation Research Board*, **2171**, 33-43. https://doi.org/10.3141/2171-04

[8] Park, S. and Rakha, H. (2010) Continuous Flow Intersections: A Safety and Environmental Perspective. 13*th International IEEE Conference on Intelligent Transportation Systems*, Funchal, 19-22 September 2010, 85-90. https://doi.org/10.1109/ITSC.2010.5625038

[9] Vedagiri, P. and Daydar, S. (2012) Performance Analysis of Continuous Flow Intersection in Mixed Traffic Condition. *International Journal on Transportation and Urban Development*, **2**, 20-25.

[10] Yang, X., Cheng, Y. and Chang, G.-L. (2016) Operational Analysis and Signal Design for Asymmetric Two-Leg Continuous-Flow Intersection. *Transportation Research Record*: *Journal of the Transportation Research Board*, **2553**, 72-81. https://doi.org/10.3141/2553-08

[11] Alzoubaidi, M. (2022) Operational and Safety Performance Assessment of Innovative Intersection and Interchange Designs in a Connected Vehicle Environment. University of Wyoming, Laramie.

[12] Day, C., Bullock, D., Li, H., Lavrenz, S., Smith, W.B.B. and Sturdevant, J. (2015) Integrating Traffic Signal Performance Measures into Agency Business Processes. Purdue University, West Lafayette. https://doi.org/10.5703/1288284316063

[13] Abdelrahman, A., Abdel-Aty, M., Lee, J., Yue, L. and Al-Omari, M.M.A. (2020) Evaluation of Displaced Left-Turn Intersections. *Transportation Engineering*, **1**, Article ID: 100006. https://doi.org/10.1016/j.treng.2020.100006

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

[15] Wolf, J.C., Ma, J., Cisco, B., Neill, J., Moen, B. and Jarecki, C. (2019) Deriving Signal Performance Metrics from Large-Scale Connected Vehicle System Deployment. *Transportation Research Record*: *Journal of the Transportation Research Board*, **2673**, 36-46. https://doi.org/10.1177/0361198119838520

[16] Waddell, J.M., Remias, S.M. and Kirsch, J.N. (2020) Characterizing Traffic-Signal Performance and Corridor Reliability Using Crowd-Sourced Probe Vehicle Trajectories. *Journal of Transportation Engineering*, *Part A*: *Systems*, **146**, Article ID: 04020053. https://doi.org/10.1061/JTEPBS.0000378

[17] Saldivar-Carranza, E.D., Hunter, M., Li, H., Mathew, J. and Bullock, D.M. (2021) Longitudinal Performance Assessment of Traffic Signal System Impacted by Long-Term Interstate Construction Diversion Using Connected Vehicle Data. *Journal of Transportation Technologies*, **11**, 644-659. https://doi.org/10.4236/jtts.2021.114040

[18] Saldivar-Carranza, E., Li, H., Mathew, J., Fisher, C. and Bullock, D.M. (2022) Signalized Corridor Timing Plan Change Assessment Using Connected Vehicle Data. *Journal of Transportation Technologies*, **12**, 310-322. https://doi.org/10.4236/jtts.2022.123019

[19] Saldivar-Carranza, E., Mathew, J.K., Li, H. and Bullock, D.M. (2022) Roundabout Performance Analysis Using Connected Vehicle Data. *Journal of Transportation Technologies*, **12**, 42-58. https://doi.org/10.4236/jtts.2022.121003

[20] Saldivar-Carranza, E., Rogers, S., Li, H. and Bullock, D.M. (2022) Diamond Interchange Performance Measures Using Connected Vehicle Data. *Journal of Transportation Technologies*, **12**, 475-497. https://doi.org/10.4236/jtts.2022.123029

[21] Saldivar-Carranza, E.D., Li, H. and Bullock, D.M. (2021) Diverging Diamond Interchange Performance Measures Using Connected Vehicle Data. *Journal of Transportation Technologies*, **11**, 628-643. https://doi.org/10.4236/jtts.2021.114039

[22] Utah Department of Transportation (2022) Automated Traffic Signal Performance Measures. https://udottraffic.utah.gov/ATSPM

[23] Sakhare, R.S., Hunter, M., Mukai, J., Li, H. and Bullock, D.M. (2022) Truck and Pas-

senger Car Connected Vehicle Penetration on Indiana Roadways. *Journal of Transportation Technologies*, **12**, 578-599. https://doi.org/10.4236/jtts.2022.124034

[24] 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*, Indianapolis, 19-22 September 2021, 4043-4050. https://doi.org/10.1109/ITSC48978.2021.9564781

[25] Transportation Research Board (TRB) (2010) Highway Capacity Manual 2010. National Research Council (NRC), Washington DC.

[26] Quiroga, C. 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)