EVALUATING ASCT OPERATIONS FOR DODGE STREET CORRIDOR

FINAL REPORT

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16. Abstract As Adaptive Traffic Control (ATC) is increasingly being implemented by various traffic agencies, careful evaluation is needed of the degree to which a given ATC implementation improves traffic signal performance. The present study details the evaluation of ATC for two arterial corridors in the City of Omaha, Nebraska. Several performance measures were used across two stages of ATC implementation as well as during the unanticipated COVID-19 lockdown stage. The average travel time and variability in travel time showed that Stage 1 of ATC implementation in Omaha did not improve traffic signal performance for the study's main corridor, Dodge Street. This led to Stage 2 ATC implementation, in which there were slight improvements compared to Stage 1. However, travel time was still found to be higher as compared to the base scenario, though this increase was in most cases within 10%. The city shut down ATC operation during the PM peak period on the Dodge Street Corridor because of its poor performance. ATC was also found to negatively impact side-street delay in most scenarios. However, Omaha's ATC implementation successfully reduced and adjusted signal cycle length in response to COVID-related demand changes thus showing some responsiveness to changing demand. In essence, the ACT system does provide adjustments during atypical conditions but cannot outperform static timing patterns during recurring traffic demand.			
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EXECUTIVE SUMMARY

One of the possible ways to improve traffic signal performance in terms of operational behavior and safety is by implementing Adaptive Traffic Control (ATC). ATC has been in existence for the last few decades but has grown almost 600% since 2008. The primary reasons behind this growth have been both promotion and the positive outcomes of ATC reported for several agencies. However, some agencies have also faced difficulties in the implementation of ATC. Thus, a thorough evaluation on a small scale in any given locale is deemed a necessity before implementing ATC on a wider scale. The present study involved the evaluation of adaptive signals using several performance measures to determine their impact on two of the major arterial corridors of Omaha, Nebraska.

The first part of the evaluation on Dodge Street used infrastructure-independent sources to calculate the variation in travel time across the different stages of the study. This study’s evaluation was carried out in four stages—before ATC implementation, Stage 1 of ATC implementation, Stage 2 of ATC implementation, and the COVID-19 lockdown stage. On comparing the before stage with this study’s other stages, it was found that travel time did not change significantly during Stage 1, slightly increased for the eastbound direction of travel for Stage 2, and unsurprisingly reduced during the various stages of the COVID-19 lockdown. This study’s high-resolution data were also used to evaluate side-street delay, which reduced for most intersections during peak periods for the Stage 2 ATC implementation, driven by shorter cycle lengths. Unfortunately, COVID cut short Stage 2 of this study, making it impossible to evaluate the ATC implementations’ safety impacts as planned. The evaluation of 84th Street showed conditions to have worsened compared to before ATC implementation for most of its intersections.

In conclusion, this report presents an evaluation of corridor that underwent adaptive control implementation, it can be stated performance under adaptive control was found to be worse than a well-timed corridor in terms of both main-street and side-street delay for most time periods during normal volume conditions. The performance deteriorated significantly during oversaturated conditions, and the ATC was shut down during the PM peak period on the Doge Street corridor. The ATC was responsive to the COVID-related change in demand and did reduce cycle lengths with reduction in traffic volumes.

In essence, the ACT system does provide adjustments during atypical conditions but cannot outperform static timing patterns during recurring traffic demand.

CHAPTER 1 INTRODUCTION

1.1 Background

The installation of traffic signals at intersections is aimed at providing optimum flow to the traffic while reducing the number of crashes and their severity as well as prioritizing a particular roadway user type or movement (Chandler et al. 2013). According to a site's temporal and spatial demand, traffic signals are installed to help road users traverse the roadways.

Over the last few decades, traffic signals have undergone tremendous changes in terms of technological advancement. Traffic signals are designed and maintained by traffic signal engineers based on observation from time to time of signals' usual demand level, subjected to constraints such as the minimum safe crossing time for pedestrians. With cities' evolution, these signal timing plans become obsolete due to changes in traffic demand and land use patterns. Some of these changes are gradual, while others can be relatively rapid. Some changes can be periodic and for a shorter duration (like during events near the downtown area), while others can be quite unpredictable (like the COVID-19 lockdown). Hence, updating traffic signal timing at frequent intervals is deemed a necessity for any traffic agency.

According to a report from the Federal Highway Administration (FHWA), modifications to the performance of the 330,000 traffic signals operating in the United States (US) are typically driven by citizen complaints due to the lack of an "ongoing performance measure capability" (Center for Accelerating Innovation 2019This leads to deterioration in traffic signal performance, safety, and efficiency over time and ultimately leads to traffic congestion. This norm of aperiodic evaluation of intersections' signal timing not only raises questions about systems' overall performance but also adds up to substantial signal retiming cost. Hence, an array of efficient and robust measures is needed by an agency to monitor traffic signal performance from time to time. The report here presents an evaluation using some of the state-of-the-art performance measures able to produce such an evaluation of signalized intersections.

Over the years, traffic congestion has consistently stood out to be amongst the top three largest single threats to the economic prosperity of the nation (Owens et al. 2010). The per capita cost of traffic congestion keeps on rising from $1,200 per year in 2016 to $1,400 in 2019 (INRIX 2020). On these grounds, the importance of traffic signals for road users lies in the fact that two-thirds of the total distance driven in the US is on roads controlled by traffic signals (Morales 1995). These are defined as some of the primary locations causing congestion and delay to traffic movement.

From the point of view of a road user, traffic congestion leads to unnecessary delay and associated frustrations. Some of the effects are late arrival to important office meetings or other events, which can lead to loss of business, disciplinary actions, and other personal loss. Poor signal timing can also lead to delay in emergency responses, increase in vehicular fuel consumption, threat to the climate in terms of increased vehicle emissions, and increased vehicle maintenance costs (Sharma et al. 2018).

Apart from traffic congestion and delay, poor management of traffic signals or improper retiming of traffic signals leads to crashes and fatalities. Forty percent of the crashes that occur are related to or nearby signalized intersections (Ascone and Lindsey 2009). Fatalities are also high near intersections. In fact, in one of the studies by the Insurance Institute for Highway Safety (IIHS), it was determined that 67% of traffic-crash-related fatalities are along arterial corridors, which often consist of a series of signalized intersections along a roadway (Sharma et al. 2018).Thus, there is a need to continuously improve traffic signals to minimize the user cost and delay as well as improve safety at intersections.

One of the ways to improve traffic signal performance in terms of operational behavior and safety evaluation is by implementing adaptive traffic control (ATC). ATC has been in existence over the last few decades but has grown almost 600% since 2008 (Dobrota et al. 2020). The primary reason behind this growth is both promotion and the positive outcomes of ATC for several agencies. The present study involves the evaluation of adaptive traffic signals using several performance measures to determine their outcome on two of the major arterial corridors of Omaha, Nebraska. The subsequent parts of this report elaborate on this assessment.

1.2 Traffic Signal Improvement Techniques

As traffic signals continue over time to provide service to the vehicles arriving at an intersection, their timing tends to become obsolete with the continuously changing nature of traffic. For this reason, some form of intervention is needed (Koonce et al. 2008). This is usually performed in one of two ways—signal retiming or adaptive signal control. The remaining part of this section describes these two procedures in detail.

1.2.1 Signal Retiming

The primitive method of improving traffic signal performance from time to time is known as traffic signal retiming. Signal retiming involves gathering field data in the form of turning movement counts, pedestrian traffic volume, and other parameters, which is followed by a detailed analysis using software packages like SiDRA and Synchro. This analysis usually involves solving some form of a complicated optimization problem where a delay-based objective function is minimized or progression is maximized (Gordon 2010). These procedures are carried out by a traffic signal engineer or a technician, who usually implements such a procedure every three to five years (Koonce et al. 2008). The primary reasons driving traffic signal retiming according to Gordon (2010) usually involve:

- Substantial changes to land-use patterns
- Public complaints
- Traffic conditions like spillback during peak periods

Though traffic signal retiming involves a few complicated computations, it has been seen to benefit some locations in terms of reduction in delay (13%–37%), decrease in the number of stops on red (10%– 49%), increase in the efficiency of fuel use (2%–9%), reduction in crashes

(31%), and improved travel time (8%–25%) (Tarnoff and Ordonez 2004). However, this signal retiming procedure needs periodic attention, which involves both funding that can go up to $4,500 per intersection (Tarnoff and Ordonez 2004) and human intervention.

1.2.2 Adaptive Traffic Control

As signal retiming causes a lot of trouble and expense to traffic agencies, they have tended to shift towards Adaptive Traffic Control (ATC). As pointed out in one study (Koonce et al. 2008), the application of ATC has been found to be highly beneficial to traffic agencies under the following conditions:

- Traffic demand is highly variable on a day-to-day basis.
- Traffic demand tends to change significantly whenever there is a change in land use in the vicinity.
- Traffic incidents like crashes or other events result in changes to traffic behavior.
- Unanticipated changes like traffic signal preemption warrant a response.

ATC technologies tend to work via either one of two mechanisms (Sharma et al. 2018). Firstly, they tend to gather information from field-based equipment like detectors and continuously update signal timings by optimization. Secondly, they may be programmed with a set of predefined scenarios and, based on the present traffic condition, they provide the signal timing corresponding to that scenario.

In other words, ATC tends to alter the existing signal timing as per the needs of the system. For instance, an adaptive system might completely eradicate one of the traffic signal phases for a particular cycle if there is no demand present for that movement. As pointed out in one study involving traffic operations, ATC can respond to unforeseen changes in traffic patterns due to an incident, preemption, or a sudden increase in traffic (Sharma et al. 2018).

1.3 Evolution of Adaptive Traffic Control

The use of ATC strategies began in the 1970s with the development of the Sydney Coordinated Adaptive Traffic System (SCATS) in Australia and the Split Cycle Offset Optimization Technique (SCOOT) in the United Kingdom. Among adaptive control strategies designed specifically for North America, Optimization Policies for Adaptive Control (OPAC) (Gartner et al. 2001) and the Real-Time Hierarchical Optimized Distributed and Effective System (RHODES) (Gartner et al. 2001) were among the first to be developed. Other examples include Adaptive Control Software Lite (ACS-Lite) and InSync. These systems each have their own method of evaluation including absorbing as input data from devices installed in the field such as detector data, analyzing the traffic flow, and finally allocating appropriate green time to each phase.

The first real study of ATC systems across the nation was carried out by the National Cooperative Highway Research Program (NCHRP) in 2008 (Stevanovic 2010) that reported on

ATC deployed across 40 agencies. Ever since that time, the number of ATC implementations has increased tremendously due to promotion and reports of ATC performance success (Dobrota et al. 2020). As of 2018, a biannual ATC database showed that there are at least 350 cases of adaptive control across the US and Canada (Stevanovic et al. 2019). With the growing popularity of “plug-and-play” ATC technologies with various agencies, the evaluation of ATC requires more elaborate analysis.

1.4 Pros and Cons of Adaptive Traffic Control

As ATC has been deployed, evaluation has revealed that some agencies tend to benefit from the system, while for others ATC seems to result in worse traffic signal performance. The primary methods for evaluation of performance are usually carried out to assess operational and safety performance (Dobrota et al. 2020).

The benefits of ATC have been found to be specific to particular sites. The following are some of the operational and safety benefits of ATC that have been seen by various researchers across different agencies as identified by surveys throughout the nation.

- The initial ATC implementations during the 1980s showed a reduction of travel time during peak hours by 35%–39% (Sims and Dobinson 1980).
- Before the 21st century, evaluations of delay following ATC implementation showed a reduction under normal circumstances by 6.6%–42% for various agencies and an average reduction of 19% during special events (Casey 2000). The reduction in travel time was around 13%–25% for agencies during the same time frame. The number of stops at ATC-signalized intersections had also reduced by 28%–41%, which had boosted the safety performance of these intersections.
- A later study during 2010 found that ATC-signalized intersections’ travel time reduction ranged from approximately 6%–26%, their reduction in the number of stops ranged from 15%–70%, and their reduction in delay ranged from 11%–60% during their peak hours of operation (Selinger and Schmidt 2010).
- In a rather recent (2020) and more elaborative survey of various agencies, ATC-related reduction in travel time ranged from 6.4%–14.5%, delay had reduced by 11.3%–17.5%, number of stops had reduced by 6.2%–19.4%, and side-street delay had reduced from -13.9%–3.4% for specific times of day (Dobrota et al. 2020).

It should be noted ATC comes with some drawbacks, the primary one being its high cost of deployment, as one survey has found (Stevanovic 2010). In fact, the cost of implementing ATC is drastically variable, ranging from $6,000 to $65,000 per intersection. One other difficulty which has been pointed out is the lack of traffic signal operations staff able to work with ATC technologies. Another crucial drawback which has been raised as a matter of concern for some agencies is the operational inefficiency of their ATC technology (Dobrota et al. 2020). Inability to obtain the primary goal defined by the agency for ATC has been another reason for discontinuity of ATC use (Dobrota et al. 2020).

Thus, agencies need to carefully set their goals and objectives for ATC implementation and evaluate their ATC technology according to their needs (Zhao and Tian 2012, Sprague and Archambeau 2012).

1.5 Conclusion

The present study evaluates the performance of an ATC technology through various stages of its deployment. The study evaluates the ATC's performance at two planned stages of implementation—Stage 1 and Stage 2—and also during the COVID-19 lockdown in comparison with the "before" condition for two arterial corridors in the City of Omaha, Nebraska. The following are the performance measures taken to study the behavior of these corridors:

- Average travel time and variability in travel time—The travel time at different stages of ATC implementation across each corridor was used to evaluate the performance of the ATC implemented in the City of Omaha. First, the dynamic nature of travel time compared for the "before" and "after" conditions was evaluated using probe-based data. This was followed by a study of travel time variability. Finally, different sorts of travel time runs were conducted across the different study periods to evaluate the ATC's overall performance.

- Cycle length study—Cycle length is a parameter that is controlled by a traffic agency when no adaptive system is functional, whereas it is controlled by the adaptive system when an adaptive system is functional. The cycle length study performed for this research determined how traffic signal cycles were adjusted by ATC and the frequency of cycle changes during various times of day in relation to the change in demand by the traffic.

- Platoon ratio profile—The platoon ratio was used to identify if vehicles were arriving by groups at an intersection, when these groups were arriving at the intersection, and how well they were managed by the adaptive system.

- Side-street delay—It often happens that when vehicles arrive at an intersection from side streets crossing an arterial corridor, they are made to wait longer than their competitors. This measure evaluates how the adaptive system was treating the side-street vehicles during the various stages of its implementation.

- Safety evaluation—This was intended to be a study of the various types of crashes occurring along the two corridors during the different phases of the study and the impact of ATC on mitigating crashes. Unfortunately, significant changes in traffic demand due to COVID affected the amount of time available for ATC data collection and ultimately made it impossible for this study's planned safety evaluation to be performed.

Based on each of these performance measures (except the safety evaluation, as described earlier), the City of Omaha's ATC implementation was evaluated.

The remainder of this report is divided into four chapters. The first part reviews past ATC studies conducted using various performance measures. The next part deals with this study's evaluation methodology in detail, which is followed by the results obtained. Finally, conclusions are drawn based on the results observed through this study's ATC evaluation.

CHAPTER 2 REVIEW OF STUDIES ON ADAPTIVE TRAFFIC CONTROL PERFORMANCE

2.1 Performance Evaluation at Signalized Intersections using Automated Traffic Signal Performance Measures

Performance measures for signalized intersections can help transportation agencies to implement and evaluate ATC. Such measures also provide a standard for periodic comparison of traffic networks, even after an ATC technology has been installed. Without a proper set of performance management tools and a set of screening and prioritizing mechanisms, ATC evaluation can be disrupted and can even lead to misguidance. Hence, the evaluation of ATC calls for a robust set of performance data.

The first real implementation resembling automated traffic signal performance measures (ATSPMs) happened in 2001 (Grenard et al. 2001). It was then demonstrated in one research study in 2006 that inductive loop detection is less prone to errors than video detection (Rhodes et al. 2006). Ever since then, ATSPMs have become popular all over the nation.

The ATSPMs developed by the Utah Department of Transportation and Purdue University are obtained by computing high-resolution data logs generated by certain models of advanced signal controllers (UDOT 2021). Although ATSPMs have been developed for corridors with modern traffic signal control equipment, the research conducted for this project adapted several ATSPM concepts to obtain performance measures using probe data—a process that is feasible even for corridors with “vintage” electromechanical controllers. Thus, it is useful to review some recent research to understand how agencies are applying ATSPM data to corridor-level performance evaluation. Some examples of the evaluation being carried out by ATSPMs include the following:

- The proportion of vehicles arriving solely during the red and green states has been used to extract and evaluate an intersection’s traffic signal performance (Olszewski 1990).

- An adaptive real-time split and offset programming algorithm has been developed to improve traffic progression through an arterial corridor (Bullock and Abbas 2001).

- Performance measures have also been evaluated on a cycle-to-cycle basis in some studies (Bullock and Abbas 2001, Day et al. 2008a, Luyanda et al. 2003, Balke et al. 2005).

- Volume-to-capacity ratio and arrival type at an intersection has been used by some researchers to evaluate traffic signal performance as well (Smaglik et al. 2007a, Day et al. 2009).

- High-resolution signal event data have been used by many researchers over the past decade (Richardson et al. 2017, Day et al. 2014, Day and Bullock 2015).

- Travel time and travel time reliability have also been used by researchers to evaluate the performance of arterial corridors and traffic networks (Day et al. 2015, Poddar et al. 2020).

- Measures related to cycle length, queue serving time, phase failure, and others have been developed separately by various institutions across the US (Day et al. 2010).

- Anomalous behavior at signalized intersections on out-of-the-ordinary days has been studied by researchers to predict the behavior of traffic during normal days (Huang et al. 2018).

Some of the popular methods of evaluating performance at signalized intersections are shown in Table 1.

Table 1. Performance measures and the corresponding methods used to evaluate them

Performance Measure	**Methods to Determine Measure**
Delay	Field detectors (Sharma and Bullock 2008, Sharma et al. 2007, Ban et al. 2009) Video recording (Sharma and Bullock 2008, Smaglik et al. 2007a) Probe data (Li et al. 2018) Simulation (Dogan et al. 2016, Kang 2000)
Number of stops	Video recording (Fernandes et al. 2015) Simulation (Kang 2000, Dogan et al. 2016, Rakha et al. 2001)
Queue length	Probe data (Zhao et al. 2019, Cetin 2012, Comert and Cetin 2009) Video recording (Sharma and Bullock 2008) Simulation (Kang 2000) License plate recognition (Luo et al. 2019) Field detectors (Liu et al. 2009, Comert and Cetin 2009)
Arrival type—arrival rate on green—intersection saturation—level of progression—split failure	Field detectors (Smaglik et al. 2005, Day et al. 2008b) High-resolution data (Li et al. 2016, Day and Bullock 2010).
Purdue Coordination Diagram	High-resolution data (Li et al. 2016)
Travel time and variability	Probe data (Sharma et al. 2018, Poddar et al. 2020) Bluetooth data (Day et al. 2014, 2015)

2.2 Case Studies of ATC

ATC has been studied in the USA and throughout the world for the last 40 years using both- field- and simulation-based methodologies. (While concern has often been expressed that ATC simulation fails to adequately represent field conditions, thorough experimental evaluation investigating simulation-based vs. field-based methodologies has demonstrated otherwise

(Kergaye et al. 2010). Therefore, several field- and simulation-based case studies are presented as follows, addressing first the benefits ATC has provided and then instances in which ATC has been found to provide no benefit—or even to produce worse results than before.

In one of the latest studies using probe-based data, travel time was shown to have reduced 32% under an iterative signal control algorithm, whereas another variation of an adaptive, optimized signal control algorithm reduced travel time by 23%, with the average delay times respectively reduced by 36% and 35%. In addition, the average number of stops under the iterative signal control algorithm was reduced by 43% and under the optimized signal control algorithm by 67% (Lian et al. 2021).

In a pilot study with the SURTRAC adaptive control system, an improvement of 25–40% in terms of travel time, speed, number of stops, and wait time has been shown along with a reduction in emissions of around 21.5% (Smith et al. 2013). In a study of an isolated intersection using reinforcement learning to adapt the traffic signal, travel time has been found found to decrease by 38–44% as compared to pretimed signal control (Abdulhai et al. 2003). A field study in Turkey has found an ATC-related reduction in travel time by 15%, which was associated with a reduction in cycle time by 10% (Gündoğan et al. 2014).

Along the same lines, a simulation-based study of small traffic networks has shown a reduction of average wait time from around 0.3 sec/veh to 0.15 sec/veh when all traffic signal systems were able to adapt by changing the cycle length, splits, and offsets (Chiu 1992). Another simulation-based study was conducted in France using vehicular ad hoc networks (VANET) and it has also revealed an improvement in the level of service to traffic by reducing wait times (Maslekar et al. 2011).

ATC has additionally been seen to improve corridor operations through reducing delay by 7%, increasing throughput, and enabling quicker handling of special events like game day for the City of Los Angeles. In another study conducted regarding seasonal traffic near the national parks of Utah, ATC has been seen to improve bandwidth and minimize split failures (Richardson et al. 2017).

In comparisons of ATC vs. time-of-day (TOD) signal-timing plans, the findings of a simulation model developed by SCATS have shown SCATS outperformed existing (TOD) signal-timing plans by about 20%, and it has also been seen to perform better than the best TOD plan obtained by applying long-term traffic data collection models (Stevanovic et al. 2012a). A Vissim-based simulation model of 12 intersection corridors has shown that adaptive control implemented by InSync outperforms TOD signal-timing plans on a variety of spatial levels. ATC has been found to perform better during nonrecurrent congestion as well (Stevanovic et al. 2012a).

A field study in São Paulo, Brazil, has shown that ATC provided greater benefits when implemented under different scenarios as compared to fixed-time plans (Mazzamatti 1998). Yet in another study of isolated intersections, it has been found that TOD plans have significant advantages over adaptive control strategies. Importantly, TOD benefits have been discovered to be highly dependent on the knowledge and power of prediction of the TOD system designed by a

City's traffic engineer. Specifically, in cases where traffic demand levels evolve slowly, it has been found possible for ATC to yield shorter travel times relative to all other types of control. However, in cases where rapid changes in demand are anticipated, the benefits of ATC were found to be second-best (Stewart et al. 1999).

In a study throughout the state of Washington, ATC was seen to reduce travel time up to 20% by improving the average speed of a corridor by 25% and decreasing its number of stops by 44%. However, these benefits for one direction of travel came at a cost to the opposite direction of traffic flow (Eghtedari 2006). In a study using field data from Orange County, Florida, the failure of InSync to perform better than manually retimed signals has been demonstrated with respect to travel time through the corridor, specifically as relates to left turns, total intersection queue/delay, and when saturation was reached at the intersection (Shafik 2017). In sum, ATC has often been seen to improve the performance of intersections where it has been deployed. However, such deployments have also been seen to not infrequently negatively impact the traffic system of the neighboring corridors (Ban et al. 2014).

Indeed, even with respect to arterial corridors, the impact of ATC implementation has not always been unequivocally positive. For example, in probe-based evaluation of ATC performance, mixed results have been obtained in relation to different arterial corridors in Des Moines, Iowa (Sharma et al. 2018). Similarly, a before-after study of the impact of ATC using probe-based data determined that there was no significant change from the before period to the after period except with one location where ATC was found superior to TOD intervention (Hunter et al. 2012). In fact, one study from Las Vegas, Nevada, found that arterial corridors were not getting any benefits whatsoever even after applying adaptive control to them (Zhao and Tian 2012).

Even where ATC has been found to make a positive difference, this difference in some cases has been only marginal. For example, in a simulation-based study in Park City, Utah, ATC was found to generate a profit of just 2% in terms of fuel consumption (Stevanovic et al. 2012b).

The safety impacts of ATC have also been found to vary. In a field-based safety-related study of ATC, it was found that ATC reduced the total crashes by 34% with a Crash Modification Factor (CMF) of 0.66 and fatal and injury crashes by 45% with a CMF value of 0.55 (Khattak 2016). However, another study related to the impact of crashes determined that there was no statistically significant reduction of fatal and injury crashes associated with ATC—the study found it was merely ATCs' reduction of property-damage-only crashes that was significant (Ma et al. 2016). Along the same lines, in a real-world study simulated by SCATS, it has been found that ATC generated fewer rear-end and total conflicts than traditional traffic control, but traditional control generated fewer crossing and lane-changing conflicts (Stevanovic et al. 2012a).

One reason such conflicting results have been obtained regarding the value of ATC has been identified in a comparative study of ATC technologies that determined that the performance of each ATC was specific to that technology. In particular, SCATS reduced travel time by 15–30%, SCOOT by 10–25%, InSync by 20–40%, and UTOPIA by 10–25% (Studer et al. 2015). Similarly, in another recent study evaluating the impact of adaptive control, a benefit-to-cost ratio varying between 5.79:1 and 11.58:1 has been found (Chen et al. 2021).

The three main issues associated with ATC—improper allocation of green time to critical movement, more-than-required green time in the critical direction of traffic, and improper alignment of offsets downstream of a bottleneck—have been highlighted in a field-based study in Los Angeles (Campbell and Skabardonis 2014).

In sum, while ATC has been repeatedly demonstrated to result in substantially improved traffic flow, among other variables, it has often in other cases been demonstrated to have significant drawbacks—and sometimes agencies have been left stranded with high expenses with marginal or no improvements after applying ATC in the field. It is therefore important for any agency considering implementing ATC to monitor their ATC pre- and post-implementation to maximize the chances that road users will indeed realize all targeted benefits.

CHAPTER 3 METHODOLOGY

3.1 Timeline of Events

The City of Omaha implemented a series of changes over time to utilize Intelight adaptive control on two of their arterial corridors—Dodge Street and 84th Street. Apart from this, ATC response to changes in demand owing to the spread of COVID-19, lockdowns, shutdown, and reopening were also evaluated. A timeline of these events is provided in Figure 1.

First, the City of Omaha carried out a series of changes to implement their Stage 1 ATC plans. This first ATC implementation began June 1, 2019. Evaluation of this first ATC implementation was completed on September 30, 2019, through which it became clear the results were not as expected. Therefore, the adaptive control parameters were tweaked through various efforts by Intelight, the adaptive control provider. As a result, in January 2020, a Stage 2 ATC implementation rolled out on the streets of Omaha. This ATC implementation was then switched off for the first week of February 2020 to obtain data for the off condition. Omaha's Stage 2 ATC implementation was again switched back on from February 10, 2020. On March 14, 2020, the state of Nebraska mandated a complete lockdown due to the coronavirus which significantly impacted the traffic demands.

A series of events followed after that, as shown in, as Omaha tried to get back to normal and on September 10, 2020, Nebraska's governor lifted the ban for almost all the restrictions that were in place. However, it should be kept in mind that people were still working in group settings in limited numbers and social distancing was still being implemented throughout the City of Omaha as this report was being prepared.

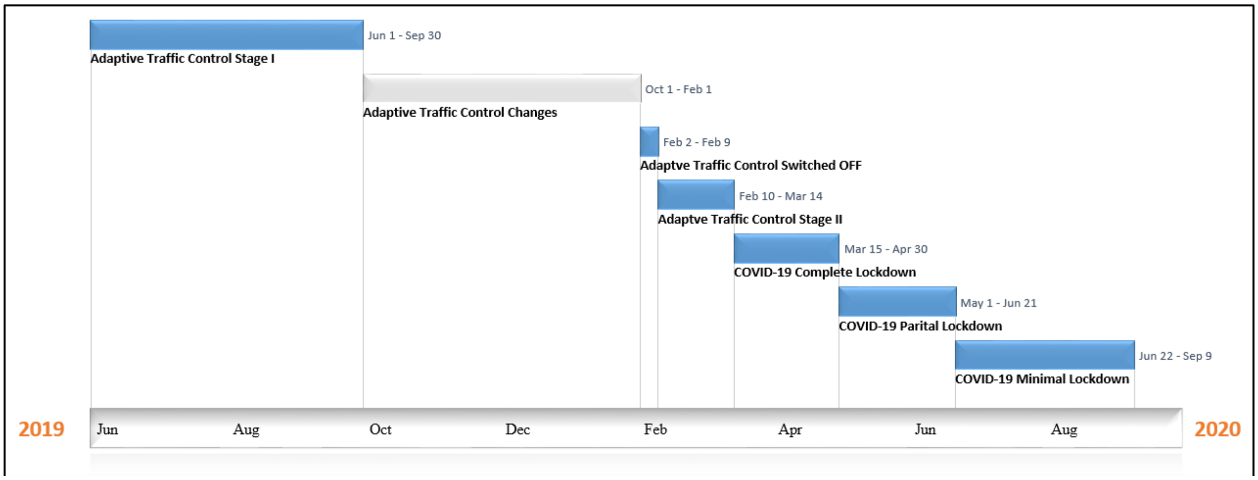


Figure 1. Events for Omaha's Intelight ATC implementation and COVID-19 lockdown

Analysis across Omaha's different stages of ATC implementation was conducted for different times of day as predefined by the Traffic Engineering Division of Omaha. Figure 2 presents the various time periods each day that were analyzed.

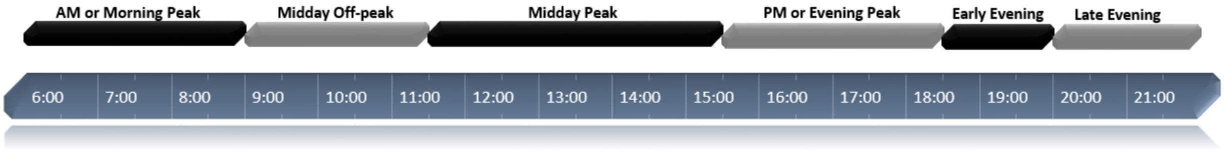


Figure 2. Daily time periods analyzed

3.2 Travel Time Evaluation

3.2.1 Data Description

Two methods of analyzing travel time were used in this study. The first method used GPS travel time runs conducted twice to eliminate the impact of normal seasonal variation in traffic flow so that the traffic signal performance before ATC implementation could be compared respectively with that of the Stage 1 and Stage 2 ATC implementations . The first set of before condition GPS travel time data versus Stage 1 data was collected respectively for the Dodge Street corridor only on Tuesday and Wednesday, June 11th and 12th, 2019. Another set of before condition GPS travel time data versus Stage 2 data was collected, again for the Dodge Street corridor only, on Tuesday and Wednesday during the first and second week of February 2020.

The second type of data used for this study's travel time evaluation was Bluetooth data, which were procured from units furnished by the commercial provider Blyncsy (Blyncsy n.d.) that were mounted along the two corridors. Blyncsy reported the Bluetooth travel time data obtained from these units at hourly intervals. (For consistency with this study's other measure of travel time, only Dodge Street was evaluated using the Bluetooth data.)

3.2.2 GPS Travel Time Runs

The GPS trajectories extracted from this study's GPS travel time runs were used to compute the travel time across the Dodge Street corridor. Once these travel time runs had been computed, a two-sample t-test was conducted to compare the before-after effect relative to the Stage 1 and Stage 2 ATC implementations respectively.

This study's GPS travel time analysis included overall and period-wise comparison of different performance metrics (travel time, number of stops, and duration of stops). Moreover, travel time run trajectories were illustrated using space-time diagrams. In order to avoid the impact of seasonal and temporal variation, this study's GPS travel time runs were conducted either on consecutive days (Stage 1) or in consecutive weeks (Stage 2) to ascertain the impact exclusively of adaptive control.

3.2.3 Bluetooth Travel Time

The Bluetooth travel time data were used to consolidate the observations and hypotheses derived from the GPS travel time runs during the different stages of adaptive control implementation. Apart from this, the Bluetooth travel time data were also used to compare travel time during the different stages of the COVID-19 lockdown when other travel time measurements were unreliable.

3.3 ATSPM Evaluation

3.3.1 Data Description

Ever since the development of the event-based data collection method, various agencies across the US have used event-based data to evaluate their performance. The National Electrical Manufacturers Association's actuated traffic signal controller standards require recording high resolution data for various timestamped detector events and phase state changes, which have been used to develop a variety of performance assessments related to arterial progression, phase capacity utilization, delay, and demand on a cycle-by-cycle basis (Smaglik et al. 2007a).

The data used in this study was recorded at 100-millisecond intervals for various intersections along two arterial corridors in Omaha. This dataset contains four major parameters—Signal ID, timestamp, event code, and event parameter. Signal ID records the respective signal, and timestamp records the event time to the nearest 100 milliseconds. The event code and event parameter are responses from the field that are stored based on a set of values predefined by Purdue University (Smaglik et al. 2007b).

The high resolution data used in this study were obtained for all the intersections along both of the arterial corridors of Omaha—Dodge Street (9 intersections) and 84th Street (22 intersections). The locations of these intersections are shown in Figure 3. As traffic signals' event detection at night is not very accurate, this analysis was restricted from 6 a.m. to 9 p.m. only.

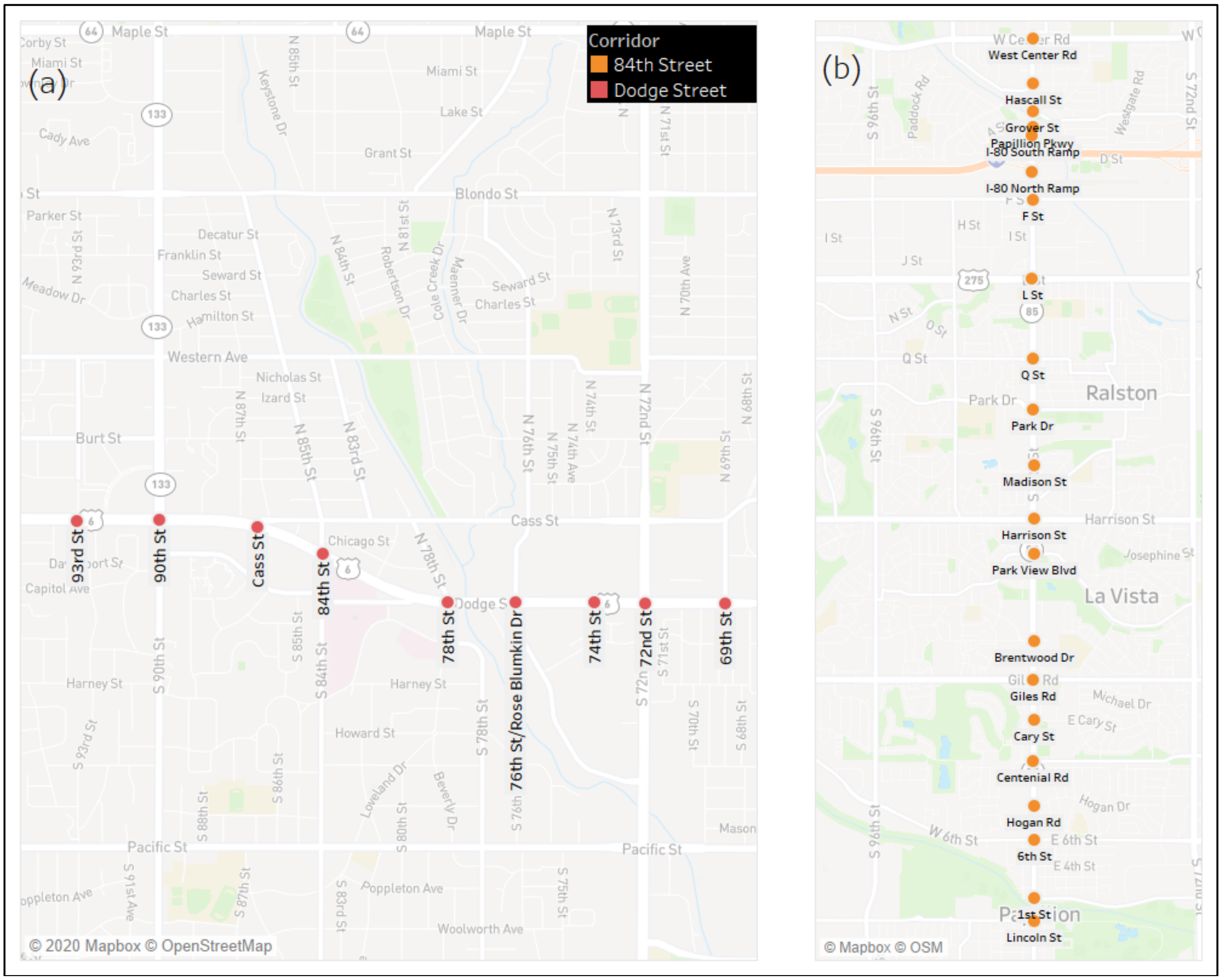


Figure 3. Intersection locations along the (a) Dodge Street and (b) 84th Street corridors

3.3.2 ATSPM Measures

High resolution traffic signal data have been used by different researchers over the past decade to evaluate the performance of arterial corridors and intersections. Most of the definitions for the measures used in this analysis have been taken directly from Utah's definitions. This study's analysis was conducted with information from detector actuations as well as from information gathered for calculating other parameters.

Detector and plan details for an example intersection location, namely the Dodge Street and 74th Street intersection, are shown in Figure 4. There are usually three types of detectors placed in the field —an advance detector, presence detector, and occupancy detector.

Advance detectors, marked in Figure 4 as ADV DET 15 and ADV DET 31, are usually placed ahead of an intersection along the route followed by the major movement to count the vehicles arriving at the intersection. For the corridors considered in this analysis, the advance detectors were usually 10-ft zones located 450 ft from the stop bar. (If the upstream intersection was closer than that range, the advance detector was about 30 ft from the upstream intersection.)

Presence detectors are used to determine the presence of any vehicle at an intersection. (They are marked for each lane in Figure 4 by the first number following the detector label DET—for example, the presence detectors for the eastbound through lanes 1, 2, and 3 are numbered 2, 3, and 4, respectively). Presence detectors usually determine if the “call” for a particular phase is made—that is, whether a phase needs to turn green for a particular cycle. The presence detectors in this study were 50-ft zones near the stop bar.

The third type of detector commonly present at intersections is the count detector, used to calculate the number of vehicles leaving a phase and entering the intersection, which in this study were 6-ft zones present at the stop bar. The count detector data were the most heavily relied upon for the performance evaluation in this study. They are marked as the second number following the detector label DET in Figure 4 (that is, for the eastbound through lanes 1, 2, and 3, the detector channels 35, 36, and 37 represent each lane’s occupancy detector, respectively).

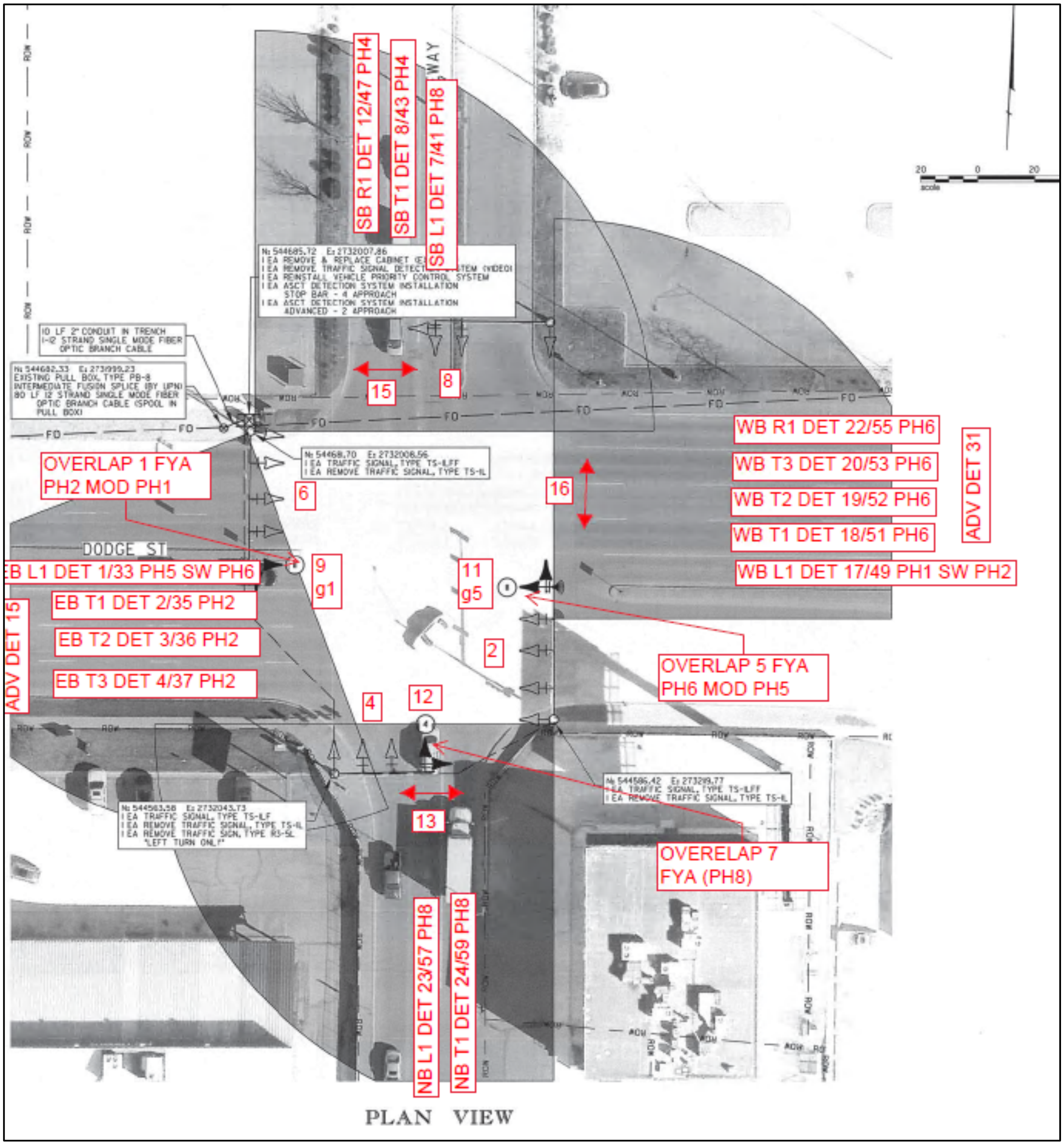


Figure 4. Intersection plan sheet with detector configuration for Dodge Street and 74th Street, Omaha

Another important concept of evaluation via ATSPMs is the signal phase. The *Manual on Uniform Traffic Control Devices* (MUTCD) defines a signal phase as the right-of-way, yellow change, and red clearance intervals in a cycle that are assigned to an independent traffic movement or combination of traffic movements (Koonce and Rodegerdts 2008).There are four main types of phasing that are used commonly. These are as follows:

- Vehicular Phase—the phase allocated to one or more vehicular traffic movements as timed by the controller unit
- Pedestrian Phase—the phase allocated to pedestrian traffic that may provide a pedestrian indication either concurrent with one or more vehicular phases or be separate from all vehicular phases
- Traffic Phase—the green, change, and clearance intervals in a cycle assigned to specified movement(s) of traffic
- Cycle—the total time to complete one sequence of signalization for all movements at an intersection (In an actuated controller unit, a cycle is the complete sequence of all signal indications.)

Using the concept of phases as well as detector events (actuations) and other controller data, the remaining part of this section describes this study's ATSPMs in more detail.

3.3.2.1 Approach Delay

The deterministic queue model is calculated based on a uniform vehicle arrival rate throughout a cycle. The departure rate is also assumed to be at a uniform rate, known as the saturation rate, from the start of the green phase till the queue is cleared. Following that, the departure rate is assumed to be the same as that of the arrival flow rate.

In the deterministic queue model, the total delay of a cycle is determined using the queue polygon method as described in previous research (Rouphail et al. 2001). However, the main drawback of this model is that neither vehicle arrival nor departure is, in fact, at a uniform rate.

Ideally, the queueing process at an intersection could be estimated by the actuation of vehicle arrival and departure information (McNeil 1968). This raises a concern for the current analysis, however, as not all study locations were equipped with advance detectors to calculate the time of vehicle arrival at particular intersections. In order to address this situation, a hybrid mechanism was proposed that evaluated the delay for each vehicle separately and then aggregated all vehicles' delay for an entire cycle to determine the total delay of the cycle. The following are a few concepts of this hybrid model:

- A uniform arrival pattern for vehicles with an arrival flow rate throughout the cycle(s)
- A departure pattern assumed to be the actual time when a vehicle leaves an intersection as determined by the stop bar actuation (Rouphail et al. 2001)

Analysis for this hybrid model was undertaken for each through-movement approach, with the calculation of delay based on the following definitions:

- $h(i)$ – Headway between the i^{th} and $(i-1)^{th}$ vehicle for a particular cycle
- h_{max} – Maximum headway for a particular cycle
- MAH – Maximum allowable headway for the saturation condition or saturation headway

- Delay(i) – Delay for vehicle i
- EAT(i) – Estimated arrival time for vehicle i
- DT(i) – Departure time for vehicle i

The following is the step-by-step procedure that was carried out to determine the traffic delay per vehicle.

First, the appropriate events corresponding to red and green phase times were obtained, along with the corresponding stop bar detector actuation time that provides information about the time when a particular vehicle leaves a given intersection—that is, DT(i). After that, all detector actuations (vehicle exit times) were associated with their corresponding cycles. Next, the headway of all the vehicles for a particular cycle—h(i)—was determined from the stop bar detector. This was followed by the determination of the maximum headway (h_{max}) for a particular detector for a particular cycle.

Then, based on this maximum headway, the saturation condition for a particular cycle was defined. As the stop bar detectors were 6 ft in length and vehicles are usually 18 ft in length, an effective actuation of occupancy time was determined to be 24 ft rather than 6 ft. Hence, saturation headway was calculated as 6 seconds rather than 2 seconds as described in the traffic signal timing manual. Therefore, the saturated condition was defined as:

$$Saturation = if\ (hmax \geq MAH)\ then\ unsaturated\ else\ saturated$$

In the case of unsaturated cycles, the number of vehicles was counted till the queue had cleared (h(i) ≥ MAH). Once this had been reached, the arrival profile was achieved by joining the point in the cumulative vehicle arrival diagram to the start of the red phase (see Figure 5).

In the case of saturated conditions, the departure profile was extended till the queue clearance condition, (h(i) ≥ MAH), had been achieved in the next possible cycle (Cycle 3 in Figure 5Figure). After the queue clearance condition had been achieved, the arrival profile was back-propagated to the start of the red phase in the initial cycle (Cycle 2 in Figure 5). Once the arrival profile had been determined, the delay for each vehicle was identified as follows:

$$Delay(i) = DT(i) - EAT(i)$$

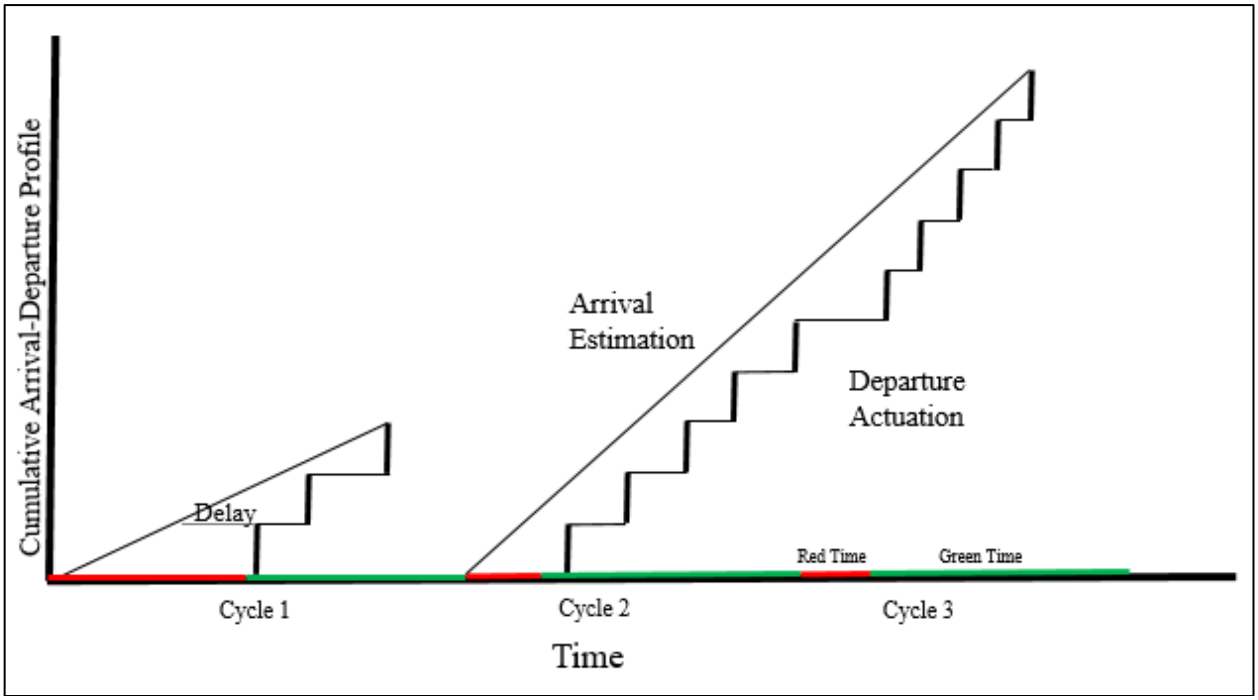


Figure 5. Cumulative arrival-departure profile

The delay for each vehicle could then be aggregated for a specific time period simply by adding them all up.

3.3.2.2 Platoon Ratio

ATC is supposed to improve vehicle progression through an arterial corridor. As such, there are a couple of evaluations that can be computed to determine the performance of a corridor in terms of progression. One such measure is the platoon ratio.

Usually, the evaluation of progression has been conducted using the percentage of vehicles arriving during a green phase. However, this is strongly influenced by the duration of green time (Ryus et al. 2011). It is possible to correct this measure by dividing the percentage of vehicle arrivals during red time by the g/C (green-to-cycle-length) ratio. This quantity is known as the platoon ratio (Rp) and has been used extensively in previous research ever since it was introduced in the 2010 *Highway Capacity Manual* (HCM). Mathematically, the platoon ratio formulation can be given as:

$$Rp = (\frac{Nr}{N})/(\frac{g}{C})$$

where Nr = Number of vehicles arriving during a red phase
N = Number of vehicles arriving during a particular cycle
g = A particular cycle’s green time

C = Cycle length

Based on HCM exhibit 15-4, a higher Rp means better performance, with a platoon ratio of grearter than 2 meaning that progression is exceptional (Ryus et al. 2011). The details of performance for the other possible platoon ratios are noted in Table 2.

Table 2. Progression quality based on platoon ratio from the 2010 *Highway Capacity Manual*'s Exhibit 15-4

Range of Platoon Ratio	Progression Quality
$Rp \leq 0.50$	Very poor
$0.50 < Rp \leq 0.85$	Unfavorable
$0.85 < Rp \leq 1.15$	Random arrivals
$1.15 < Rp \leq 1.50$	Favorable
$1.50 < Rp \leq 2.00$	Highly favorable
$Rp \geq 2.00$	Exceptional

CHAPTER 4 RESULTS AND DISCUSSION

There are four major objective criteria that any traffic control has to optimize and balance. These main criteria are as follows:

- Minimize main-street travel time
- Minimize side-street delay
- Handle events effectively, thus reducing personnel workload
- Improve safety

It should be noted that often reduction in main-street travel time and reduction in side-street delay are competing for a signalized intersection's green time.

In this study, we present results for the first three criteria. As mentioned earlier, this study's planned safety evaluation could not be performed, as there were significant changes in demand due to COVID affecting the amount of data collection time available after the Stage 2 ATC implementation.

4.1 Travel Time Evaluation

This study's main-street travel time evaluation was performed using the traditional GPS runs to see the overall trends, which were then statistically validated using Bluetooth data.

4.1.1 Dodge Street Period-Wise Performance Measures

GPS travel time runs were conducted across the Dodge Street corridor during this study's two main ATC implementation stages. The GPS travel time runs conducted for the before condition versus Stage 1 ATC were computed during the month of June 2019. Similarly, GPS travel time runs were conducted for the before condition versus Stage 2 ATC during the month of February 2020. (As mentioned earlier, in order to eliminate seasonal variation in traffic flow, the before and after conditions were implemented and evaluated on either consecutive days [for Stage 1] or in consecutive weeks [for Stage 2]). In each case, as much as possible an equal number of runs was conducted for the same time periods per day.

A statistical summary of the results from these GPS travel time runs is shown in Table 3. The overall spread of the GPS travel time runs for the before condition versus Stage 2 ATC implementations is shown in Figure 6. (Our focus in this presentation of results is on the Stage 2 ATC implementation evaluation, as several parameter changes and software updates were made after Stage 1 to improve the performance of the ATC technology.)

Comparison of the before condition and Stage 2 ATC implementation yielded p-values of 0.014 and 0.063 for the eastbound and westbound directions of traffic flow respectively. This strongly suggests that there was a difference in travel time after implementing the ATC technology for the eastbound direction at the 5% confidence level and a difference in travel time for the westbound direction at the 10% confidence level. The t-statistic calculated for the one-sided values also produced a negative value, suggesting that travel time increased after implementing adaptive control. The biggest negative impact of the ATC technology investigated in this study was observed during the PM peak in the westbound direction. This could potentially be due to an inability of ATC to accommodate oversaturated conditions.

Table 3. Descriptive statistics for Dodge Street GPS travel time runs under the before condition vs. after Stage 2 ATC implementation

Condition	Direction	Number of Runs	Mean Travel Time (secs)	Std. Dev. of Travel Time (secs)
Before	East	41	300	58.7
After Stage 2 ATC	East	35	334	57.4
Before	West	38	335	64.2
After Stage 2 ATC	West	38	372	99

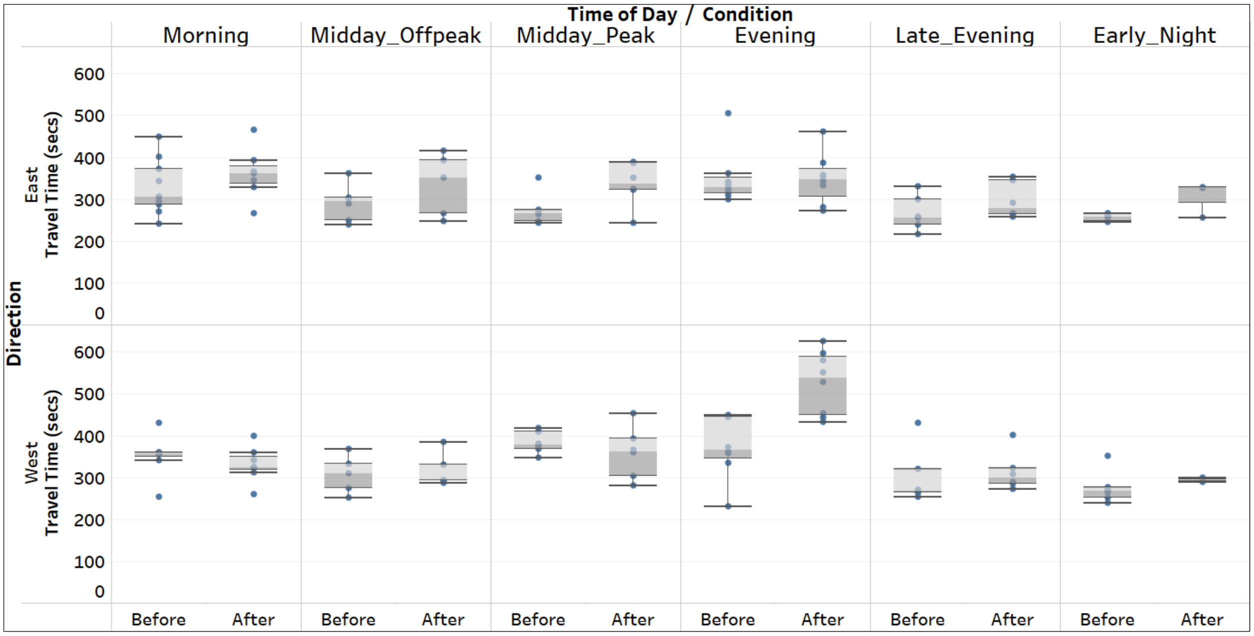


Figure 6. Dodge Street GPS runs by direction for the before condition vs. after Stage 2 ATC implementation

4.1.2 84th Street Period-Wise Performance Measures

The analysis of the 84th Street corridor was conducted by Iteris, Inc., and its system performance is summarized as follows in terms of travel time, number of stops, and stop duration for the before condition versus after Omaha's Stage 2 ATC implementation. Both analyses were performed under similar traffic conditions—on a non-holiday with fair weather for the same duration. The number of GPS travel time runs for the 84th Street study is presented in Table 4.

Table 4. Summary of 84th Street GPS travel time runs

Condition	Direction	Number of Runs
Before	North	31
After Stage 2 ATC	North	24
Before	South	33
After Stage 2 ATC	South	25

A comparative summary of different metrics for the before versus after conditions for different periods of the day are presented in Table 5 through Table 9 . The results reveal that for both directions of 84th Street during almost all periods of the day (except for the southbound direction during the PM peak), all average performance measures worsened after the ATC technology's implementation. In most cases, the travel time increased between 2–11% after the implementation of the ATC technology. Nevertheless, in two of the ten scenarios, the travel time did reduce by 1–15%.

Table 5. Comparison by direction of 84th Street weekday a.m. peak metrics

AM PEAK 6:00AM – 9:00AM			AVERAGE			
Study Corridor	Direction	Study	Travel Time (secs)	Number of Stops	Avg. Speed (mph)	Total Delay (secs)
84th Street	North	Before	756	5.2	27	263
		After[1]	819	6.5	25	326
		Change[1]	8%	25.00%	-7.70%	24%
	South	Before	655	4.2	31.2	112
		After[1]	727	5	27.7	234
		Change[1]	11%	19.00%	-11.30%	45%

[1] After Stage 2 ATC

Table 6. Comparison by direction of 84th Street weekday A.M. OFF peak metrics

OFF-PEAK (AM) 9:00AM – 11:00AM			AVERAGE			
Study Corridor	**Direction**	**Study**	**Travel Time (secs)**	**Number of Stops**	**Avg. Speed (mph)**	**Total Delay (secs)**
84th Street	North	Before	632	3.4	31.6	139
		After[1]	646	4	30.8	153
		Change[1]	2%	17.60%	-2.40%	11%
	South	Before	595	2.3	33.4	102
		After[1]	596	3.5	33.4	104
		Change[1]	0%	50.00%	0.00%	1%

[1] After Stage 2 ATC

Table 7. Comparison by direction of 84th Street weekday midday peak metrics

MD PEAK 11:00AM – 3:30PM			AVERAGE			
Study Corridor	**Direction**	**Study**	**Travel Time (secs)**	**Number of Stops**	**Avg. Speed (mph)**	**Total Delay (secs)**
84th Street	North	Before	691	5.2	28.9	-18
		After[1]	716	6	27.9	224
		Change[1]	4%	15.40%	-3.70%	13%
	South	Before	675	3.9	29.9	-33
		After[1]	703	5.3	28.7	211
		Change[1]	4%	36.40%	-3.90%	16%

[1] After Stage 2 ATC

Table 8. Comparison by direction of 84th Street weekday PM peak metrics

PM PEAK 3:30PM – 6:30PM			AVERAGE			
Study Corridor	Direction	Study	Travel Time (secs)	Number of Stops	Avg. Speed (mph)	Total Delay (secs)
84th Street	North	Before	749	6.2	27.1	41
		After[1]	770	7.8	25.9	278
		Change[1]	3%	25.70%	-4.80%	8%
	South	Before	883	8.2	22.7	175
		After[1]	753	6.4	27	260
		Change[1]	-15%	-22.00%	18.80%	-33%

[1] After Stage 2 ATC

Table 9. Comparison by direction of 84th Street weekday PM OFF peak metrics

OFF-PEAK (PM) 6:30PM – 8:30PM			AVERAGE			
Study Corridor	Direction	Study	Travel Time (secs)	Number of Stops	Avg. Speed (mph)	Total Delay (secs)
84th Street	North	Before	635	3.8	31.5	143
		After[1]	630	3.3	31.6	137
		Change[1]	-1%	-14.50%	0.20%	-4%
	South	Before	560	1.3	36	67
		After[1]	578	1.5	34.5	85
		Change[1]	3%	12.50%	-4.20%	26%

[1] After Stage 2 ATC

In essence, in most cases, deployment of the adaptive system had a negative impact on travel time on the main Dodge Street corridor as well as on the 84th Street corridor.

However, GPS runs generally provide relatively small samples and are thus primarily used for understanding generic trends. The Bluetooth study presented next was used to statistically verify this study's GPS run observations using much larger samples.

4.1.3 Bluetooth Data Evaluation

Bluetooth units were installed for the corridors at its end points. The Bluetooth travel time data were extracted from the Blyncsy website hourly.

In order to study the performance of the ATC technology during the COVID-19 lockdown, first Omaha's series of COVID-19 timeline events was determined. Based upon this, different lockdown periods were identified. The five COVID-19 lockdown ATC performance evaluation periods used for this study are as follows.

1. **February 2–February 9: before** (when the ATC was turned off and traffic could be said to be operating under the before condition)
2. **February 10–March 15: after** (when the ATC was turned on and traffic could be said to be operating under the after Stage 2 ATC implementation condition)
3. **March 16–April 30: strict lockdown** (during the period of strict lockdown)
4. **May 1–June 21: minimum relaxation** (during the period of minimum relaxation of lockdown measures)
5. **June 22–September 9: minimum restriction** (during the period of minimum lockdown restrictions)

The hourly travel time data were used to determine via a one-way analysis of variance (ANOVA) (Enderlein 1961) whether there were any differences between the five periods of the study for either direction of traffic. The p-value for each intersection of these factors was determined to be less than 0.05, which suggests that we can reject the null hypothesis of equal means (equal travel time) across these five periods.

The results for the eastbound direction clearly show that there was a difference in travel time between before and after ATC implementation (see Table 10). There was a significant increase in travel time in the westbound direction after Omaha's ATC implementation. The other significant difference in travel time was observed for both directions relative to the before period, in this case in relation to the minimum restriction period, when things were slowly returning to "normal," as shown in Table 10 and Table 11 respectively.

Table 10. Tukey's HSD results for Bluetooth travel time on eastbound Dodge Street

A	B	mean (A)	mean (B)	diff	SE	T	p-Tukey
Before	After	4.92	5.35	-0.43	0.18578	-2.3381	0.1328
Before	Strict lockdown	4.92	4.9	0.02	0.17773	0.096	0.9
Before	Minimum relaxation	4.92	5.14	-0.22	0.18082	-1.193	0.5
Before	Minimum restriction	4.92	5.43	-0.51	0.17725	-2.8796	0.03*
After	Strict lockdown	5.35	4.9	0.45	0.09262	4.87405	0.001*
After	Minimum relaxation	5.35	5.14	0.21	0.09843	2.22125	0.17
After	Minimum restriction	5.35	5.43	-0.08	0.0917	-0.8293	0.9
Strict lockdown	Minimum relaxation	4.9	5.14	-0.24	0.08224	2.83074	0.037*
Strict lockdown	Minimum restriction	4.9	5.43	-0.53	0.07405	-7.1233	0.001*
Minimum relaxation	Minimum restriction	5.14	5.43	-0.29	0.0812	-3.6291	0.0026*

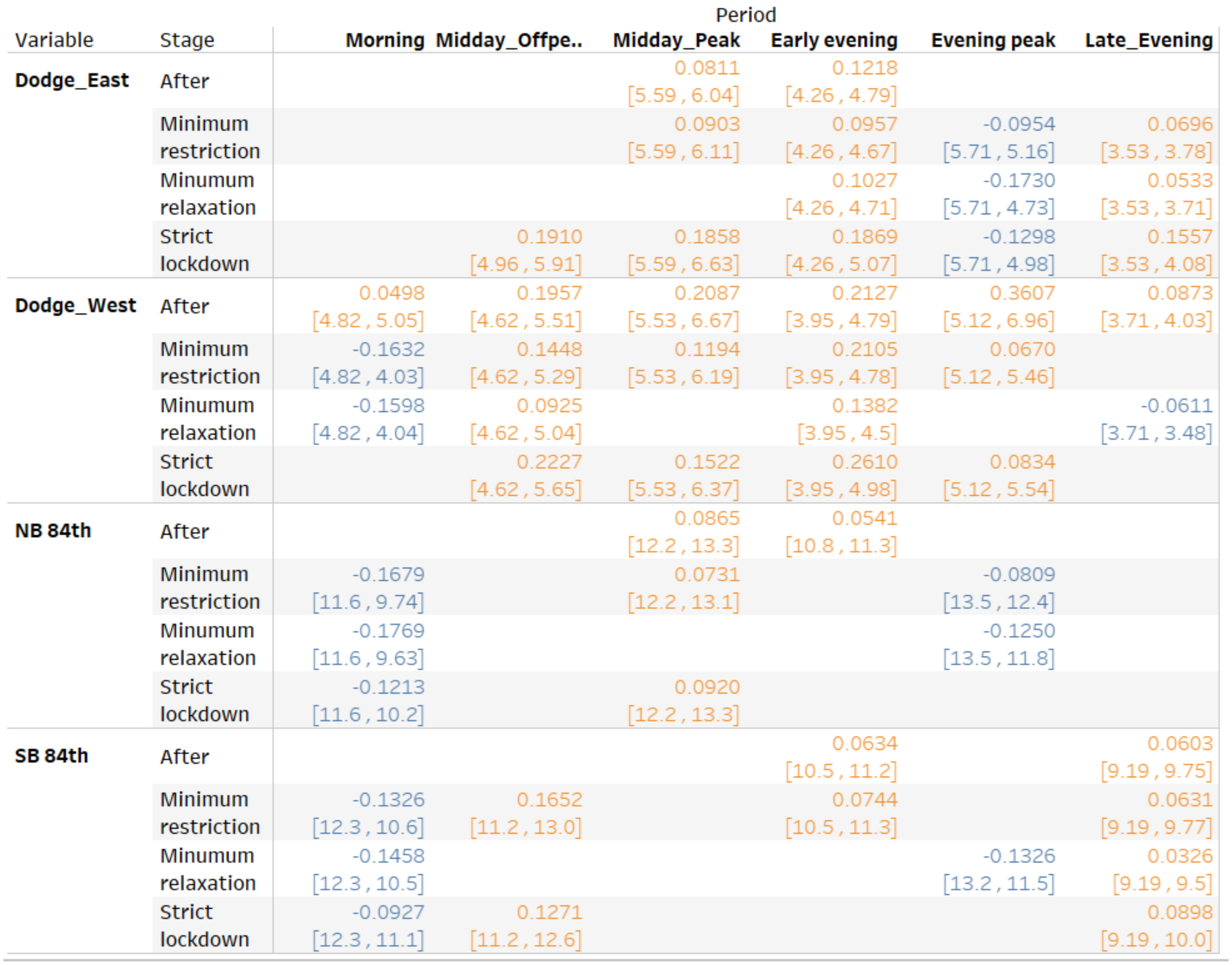
Table 11. Tukey's HSD results for of Bluetooth travel time on westbound Dodge Street

A	B	mean (A)	mean (B)	diff	SE	T	p-Tukey
Before	After	4.8	5.72	-0.92	0.15696	-5.8736	0.001**
Before	Strict lockdown	4.8	4.92	-0.12	0.15014	-0.8326	0.9
Before	Minimum relaxation	4.8	5.03	-0.23	0.1528	-1.5296	0.5
Before	Minimum restriction	4.8	5.34	-0.54	0.14975	-3.6402	0.002*
After	Strict lockdown	5.72	4.92	0.8	0.07822	10.1876	0.001*
After	Minimum relaxation	5.72	5.03	0.69	0.08322	8.26967	0.001*
After	Minimum restriction	5.72	5.34	0.38	0.07748	4.8628	0.001*
Strict lockdown	Minimum relaxation	4.92	5.03	-0.11	0.06951	-1.564	0.5
Strict lockdown	Minimum restriction	4.92	5.34	-0.42	0.06253	-6.7193	0.001*
Minimum relaxation	Minimum restriction	5.03	5.34	-0.31	0.06867	-4.5348	0.001*

Lastly, in order to find the difference between the distribution of travel times for each period of the study relative to the before condition, a two-sample K-S test was conducted on the percentile values of the two sample distributions (i.e., on the before period relative to each other period). The percent changes of the medians of the before period relative to every other period are summarized in Table 12. It should be noted that, in all cases, travel time increased after the deployment of adaptive control, with the percentage of increase varying between 5%–36%. In other words, rather than decreasing travel time as intended, adaptive control increased the travel time on the main street. The negative impacts were more severe for this higher demand corridor, with very poor performance during oversaturated conditions. The adaptive control was thus shut down for PM peak periods on the Dodge Street corridor owing to its performance. It can also be seen in Table that the change in demand due to COVID had impact on reported travel time during the later periods of the study.

Table 12. Statistically significant mean percentage change of travel time and mean travel time for two sample distributions (i.e., the before period with every other period) for all

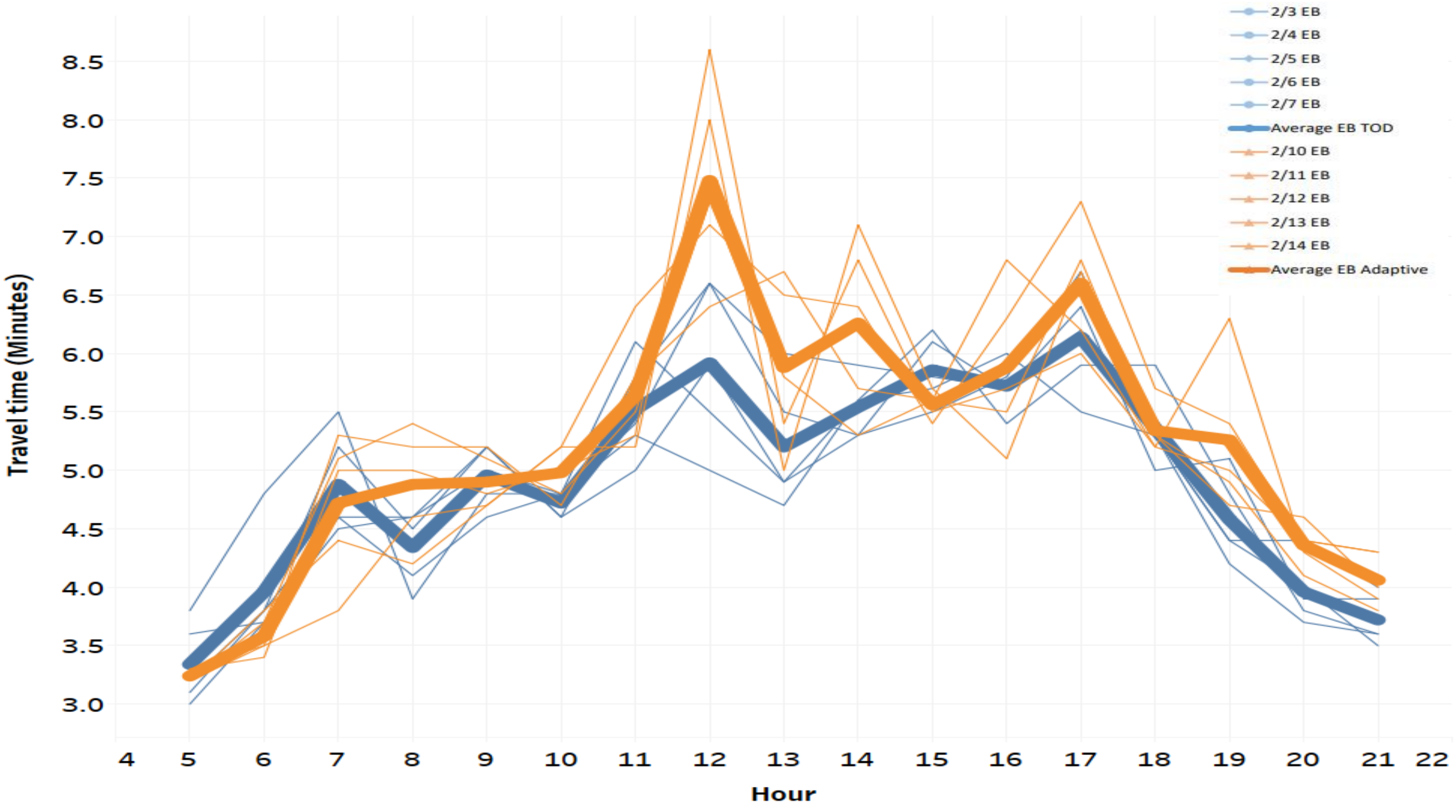
corridors and periods (period-wise)



Variable	Stage	Period Morning	Midday_Offpe..	Midday_Peak	Early evening	Evening peak	Late_Evening
Dodge_East	After			0.0811 [5.59 , 6.04]	0.1218 [4.26 , 4.79]		
	Minimum restriction			0.0903 [5.59 , 6.11]	0.0957 [4.26 , 4.67]	-0.0954 [5.71 , 5.16]	0.0696 [3.53 , 3.78]
	Minumum relaxation				0.1027 [4.26 , 4.71]	-0.1730 [5.71 , 4.73]	0.0533 [3.53 , 3.71]
	Strict lockdown		0.1910 [4.96 , 5.91]	0.1858 [5.59 , 6.63]	0.1869 [4.26 , 5.07]	-0.1298 [5.71 , 4.98]	0.1557 [3.53 , 4.08]
Dodge_West	After	0.0498 [4.82 , 5.05]	0.1957 [4.62 , 5.51]	0.2087 [5.53 , 6.67]	0.2127 [3.95 , 4.79]	0.3607 [5.12 , 6.96]	0.0873 [3.71 , 4.03]
	Minimum restriction	-0.1632 [4.82 , 4.03]	0.1448 [4.62 , 5.29]	0.1194 [5.53 , 6.19]	0.2105 [3.95 , 4.78]	0.0670 [5.12 , 5.46]	
	Minumum relaxation	-0.1598 [4.82 , 4.04]	0.0925 [4.62 , 5.04]		0.1382 [3.95 , 4.5]		-0.0611 [3.71 , 3.48]
	Strict lockdown		0.2227 [4.62 , 5.65]	0.1522 [5.53 , 6.37]	0.2610 [3.95 , 4.98]	0.0834 [5.12 , 5.54]	
NB 84th	After			0.0865 [12.2 , 13.3]	0.0541 [10.8 , 11.3]		
	Minimum restriction	-0.1679 [11.6 , 9.74]		0.0731 [12.2 , 13.1]		-0.0809 [13.5 , 12.4]	
	Minumum relaxation	-0.1769 [11.6 , 9.63]				-0.1250 [13.5 , 11.8]	
	Strict lockdown	-0.1213 [11.6 , 10.2]		0.0920 [12.2 , 13.3]			
SB 84th	After				0.0634 [10.5 , 11.2]		0.0603 [9.19 , 9.75]
	Minimum restriction	-0.1326 [12.3 , 10.6]	0.1652 [11.2 , 13.0]		0.0744 [10.5 , 11.3]		0.0631 [9.19 , 9.77]
	Minumum relaxation	-0.1458 [12.3 , 10.5]				-0.1326 [13.2 , 11.5]	0.0326 [9.19 , 9.5]
	Strict lockdown	-0.0927 [12.3 , 11.1]	0.1271 [11.2 , 12.6]				0.0898 [9.19 , 10.0]

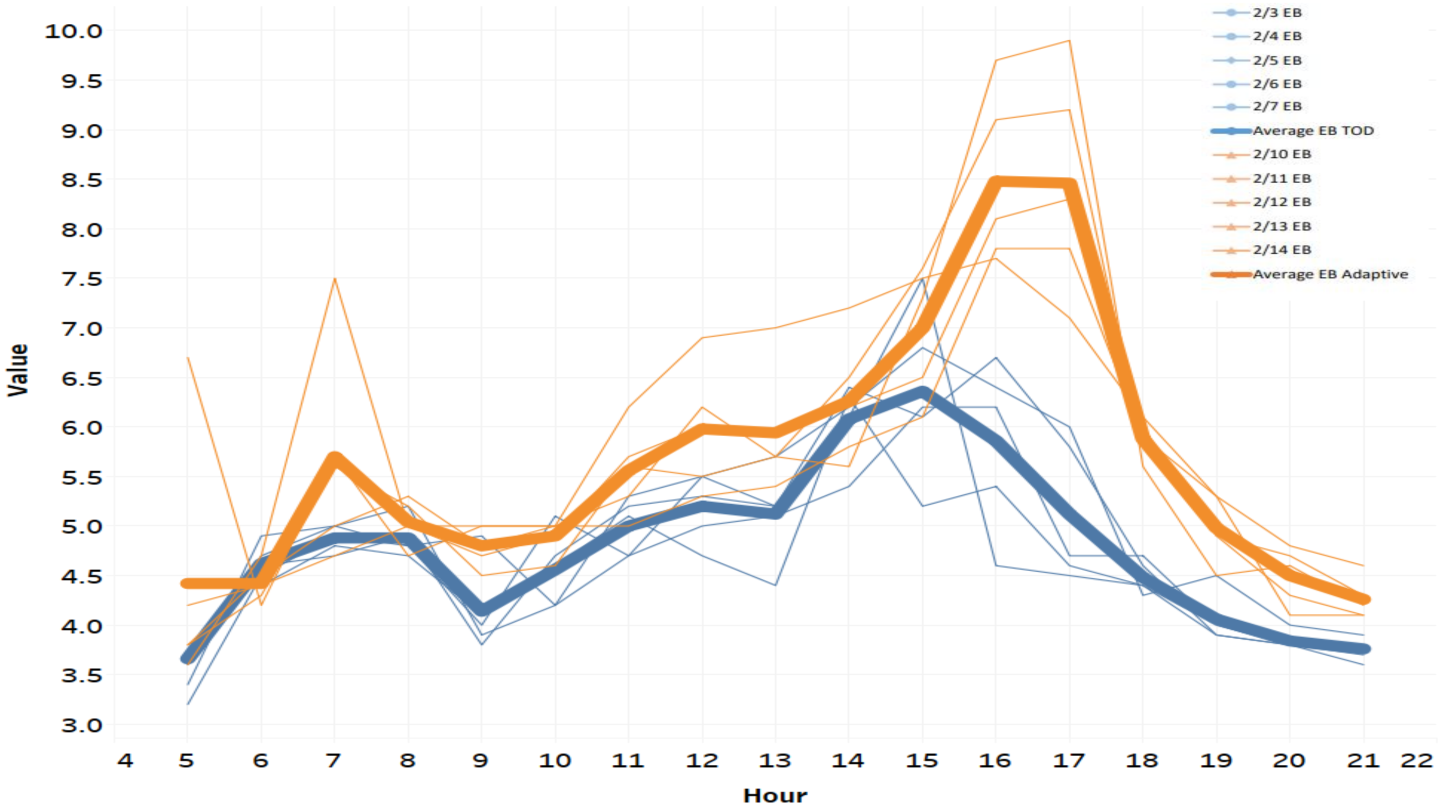
Travel time comparisons based on TOD for the before versus after conditions in both directions on Dodge Street and 84th Street are presented in Figure 7 through Figure 10.

Hour	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**
% Difference	3.2 %	2.1 %	3.2 %	2.3 %	11.6 %	13.3 %	7.6 %	16.0 %	4.2 %	15.4 %	10.0 %	10.5 %	0.6 %	14.1 %	10.2 %	5.6 %	
Before	8.7	9.0	12.1	11.8	10.7	10.8	11.8	11.4	12.4	11.3	14.2	14.1	13.9	10.9	10.8	10.3	10.2
After	8.9	9.2	12.5	12.0	12.0	12.2	12.6	13.2	12.9	13.0	15.6	15.5	14.0	12.4	11.9	10.9	



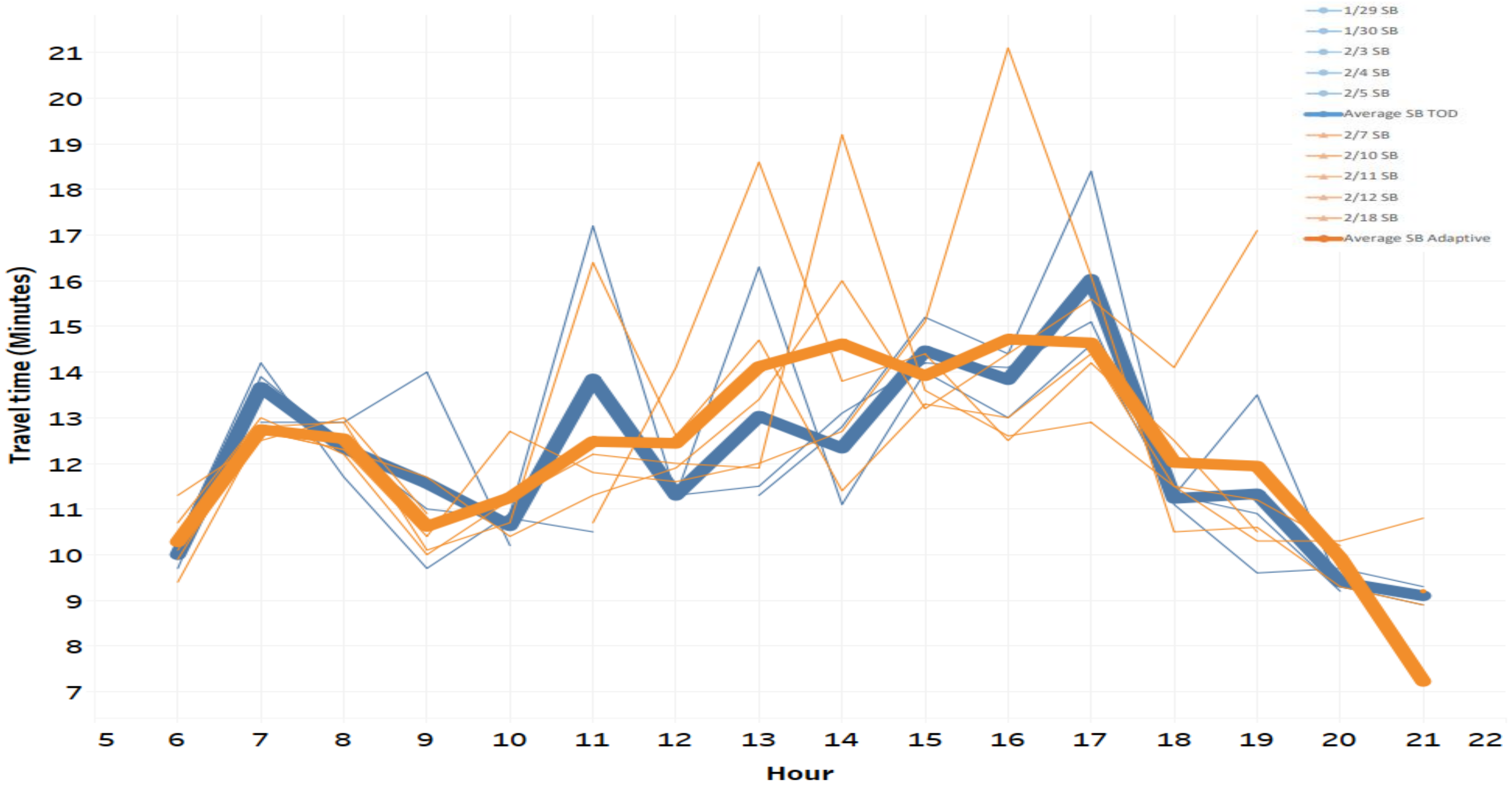
Hour	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**
% Difference	-3.0%	-9.6%	-3.3%	12.4%	-1.2%	5.5%	2.2%	26.4%	13.1%	13.0%	-5.1%	2.8%	7.5%	-0.4%	14.8%	10.1%	9.1%
Before	3.3	4.0	4.9	4.3	5.0	4.7	5.5	5.9	5.2	5.5	5.9	5.7	6.1	5.4	4.6	4.0	3.7
After	3.2	3.6	4.7	4.9	4.9	5.0	5.6	7.5	5.9	6.3	5.6	5.9	6.6	5.3	5.3	4.4	4.1

Figure 7. Comparison of travel time for eastbound Dodge Street



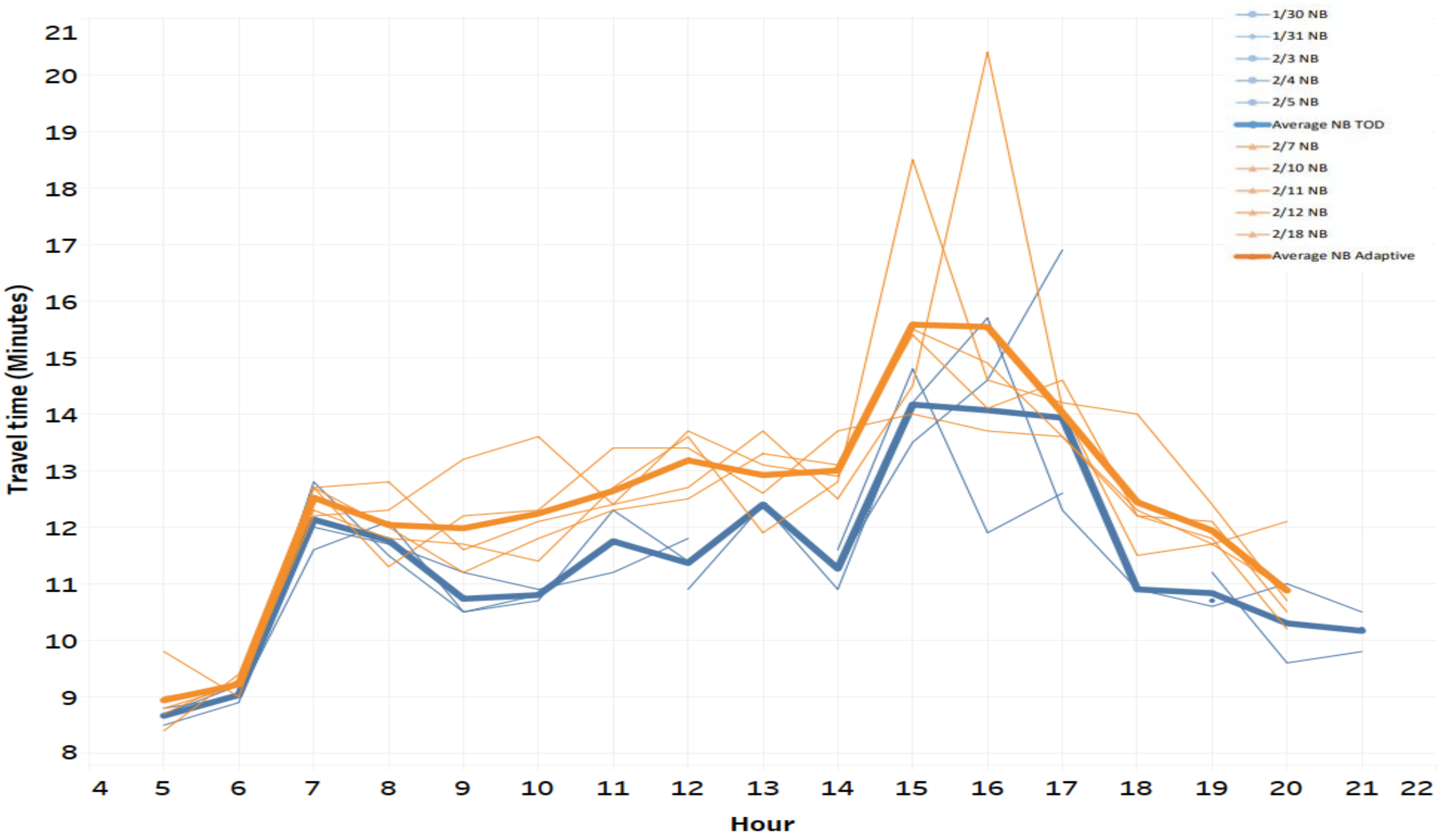
Hour	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
% Difference	20.8%	-4.3%	16.8%	3.3%	15.9%	7.5%	11.2%	15.0%	16.0%	3.0%	10.1%	44.7%	65.2%	31.3%	22.7%	17.2%	13.3%
Before	3.7	4.6	4.9	4.9	4.1	4.6	5.0	5.2	5.1	6.1	6.4	5.9	5.1	4.5	4.1	3.8	3.8
After	4.4	4.4	5.7	5.0	4.8	4.9	5.6	6.0	5.9	6.3	7.0	8.5	8.5	5.9	5.0	4.5	4.3

Figure 8. Comparison of travel time for westbound Dodge Street



Hour	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**
% Difference	2.8%	-6.8%	1.7%	-8.2%	5.8%	-9.9%	10.1%	8.3%	18.5%	-3.8%	6.4%	-8.7%	7.0%	5.4%	5.7%	-20.6%
Before	10.0	13.7	12.3	11.6	10.6	13.9	11.3	13.0	12.3	14.5	13.8	16.0	11.2	11.3	9.4	9.1
After	10.3	12.7	12.5	10.6	11.2	12.5	12.4	14.1	14.6	13.9	14.7	14.6	12.0	11.9	9.9	7.2

Figure 9. Comparison of travel time for southbound 84th Street



Hour	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
% Difference	3.2%	2.1%	3.2%	2.3%	11.6%	13.3%	7.6%	16.0%	4.2%	15.4%	10.0%	10.5%	0.6%	14.1%	10.2%	5.6%	
Before	8.7	9.0	12.1	11.8	10.7	10.8	11.8	11.4	12.4	11.3	14.2	14.1	13.9	10.9	10.8	10.3	10.2
After	8.9	9.2	12.5	12.0	12.0	12.2	12.6	13.2	12.9	13.0	15.6	15.5	14.0	12.4	11.9	10.9	

Figure 10. Comparison of travel time for northbound 84th Street

After the evaluation of each main street's performance, we evaluated performance on the side streets and the adaptive control's response to changes in side street demand. Since the main street travel time had deteriorated after adaptive control implementation, we expected to see improvement in side street performance demonstrating there had been a trade-off. However, if both the main street and side street performance were negatively impacted, then it could be concluded that the adaptive control solution implemented was not able to handle the recurring demand conditions as efficiently as a well-timed corridor. The exploration of side street delays will be done in subsequent section.

4.2 ATSPM Evaluation

ATSPM evaluation using high resolution data was conducted for one week each on weekdays only during four different stages of the study. The following is the timeline of this ATSPM evaluation.

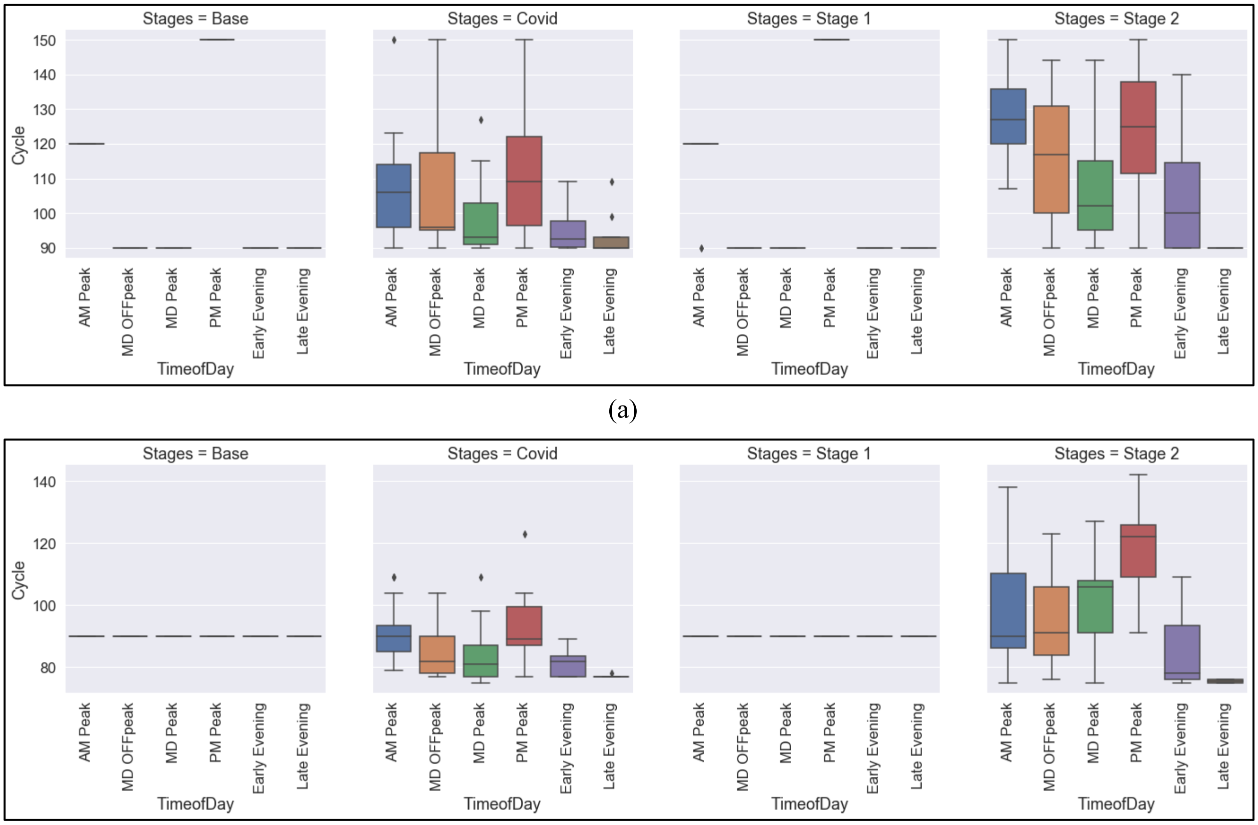
- Base case—for Dodge Street, February 3, 2020, to February 7, 2020; and for 84th Street, January 30, 2020, to February 5, 2020 (except the weekend)
- Stage 1 ATC implementation—August 26, 2019, to August 30, 2019
- Stage 2 ATC implementation—February 17, 2020, to February 21, 2020
- COVID (during the complete lockdown period)—March 23, 2020, to March 27, 2020

4.2.1 Cycle Length Study

With the implementation of adaptive control, it was expected that both the Dodge Street and 84th Street corridors would be able to adjust and change signal cycle length as needed.

Figure 11(a) and (b) presents box plots for cycle length on the Dodge Street and 84th Street corridors during the base (TOD) case, stage 1 ATC implementation, stage 2 ATC implementation, and COVID (during the complete lockdown period). The following important points can be observed:

- For the Dodge Street corridor:
  - Cycle lengths during stage 2 ATC implementation were mostly longer than for the base case TOD plan. Only the PM peak cycle lengths during stage 2 ATC implementation were shorter than the TOD cycle lengths. (It should be noted that, in general, longer cycle lengths lead to increased side street delay.)
  - Cycle lengths during the COVID period were shorter than during Stage 2 ATC implementation. This shows that the adaptive control succeeded at reducing cycle length in accord with reduction in demand.
- For the 84th Street corridor:
  - Cycle lengths during stage 2 ATC implementation were again mostly longer than base case TOD cycle lengths.
  - Cycle lengths during COVID conditions again reduced as compared to Stage 2 ATC cycle lengths.



(a)

(b)

Figure 11. Cycle length for (a) Dodge Street (at 74th Street) and (b) 84th Street (at Grover Street) by TOD during the different stages of the study

4.2.2 Platoon Ratio Profile

Another important measure of the performance of an ATC technology is how well it can manage a platoon of traffic arriving at an intersection for the coordinated phases, while maintaining an appropriate amount of green time for all the other phases. This is assessed using the platoon ratio of vehicles arriving at an intersection during its different phases. An example platoon ratio distribution from this study is shown in Figure 12's box plot for the intersection of Dodge Street and 74th Street during the morning peak (AM Peak) hours.

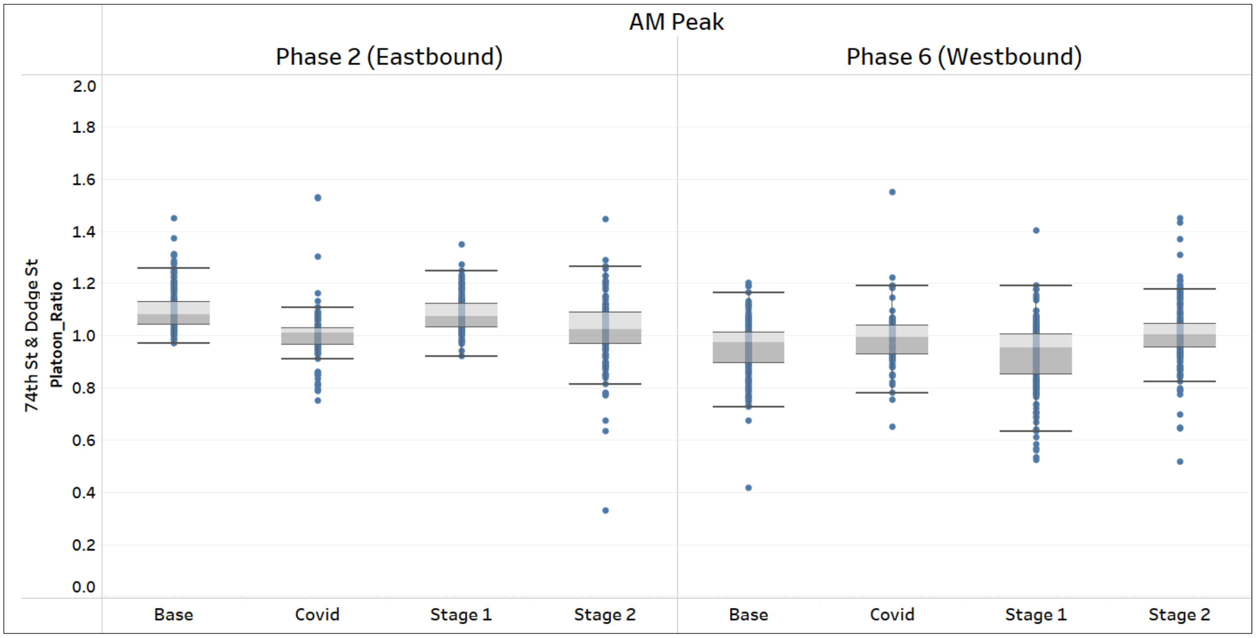
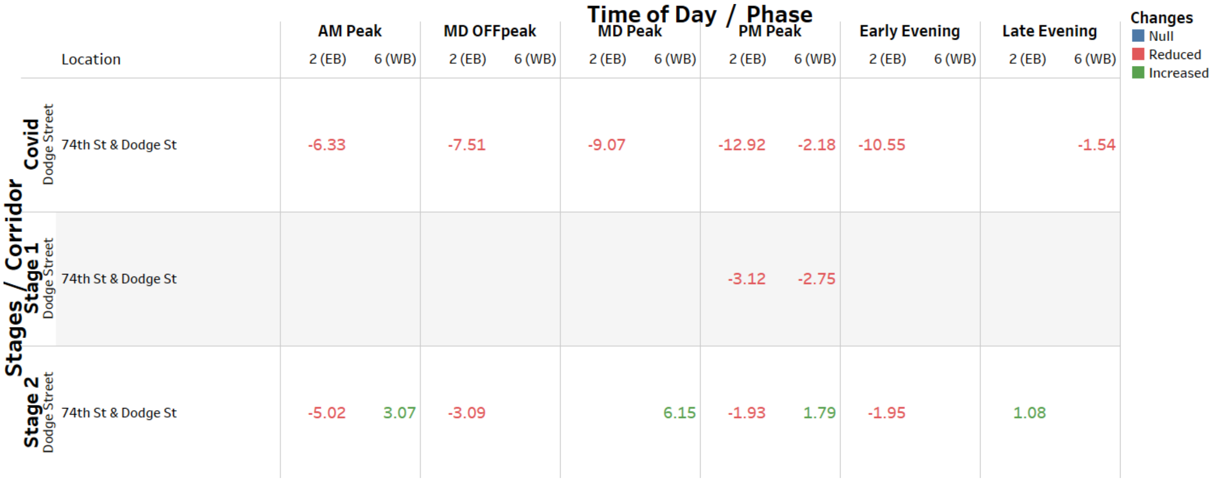


Figure 12. Platoon ratio for the Dodge Street and 74th Street intersection during the morning peak (AM Peak) hours during the different stages of the study

From Figure 12, it appears that the Stage 2 ATC implementation period had a more variable platoon ratio as compared to the other three stages of this study. It is important to understand whether intersections' platoon ratios have changed over the course of an ATC technology's implementation. For this reason, cumulative distribution plots of each intersection's platoon ratio across the four stages of this study were first plotted and then the K-S test was conducted for the resulting curves.

The Dodge Street and 74th Street intersection's cumulative distribution analysis by TOD is tabulated in Figure 13, showing that for this intersection, the platoon ratio worsened for the various peak hours during Stage 2 ATC implementation as well as for most TODs during the COVID-19 lockdown.



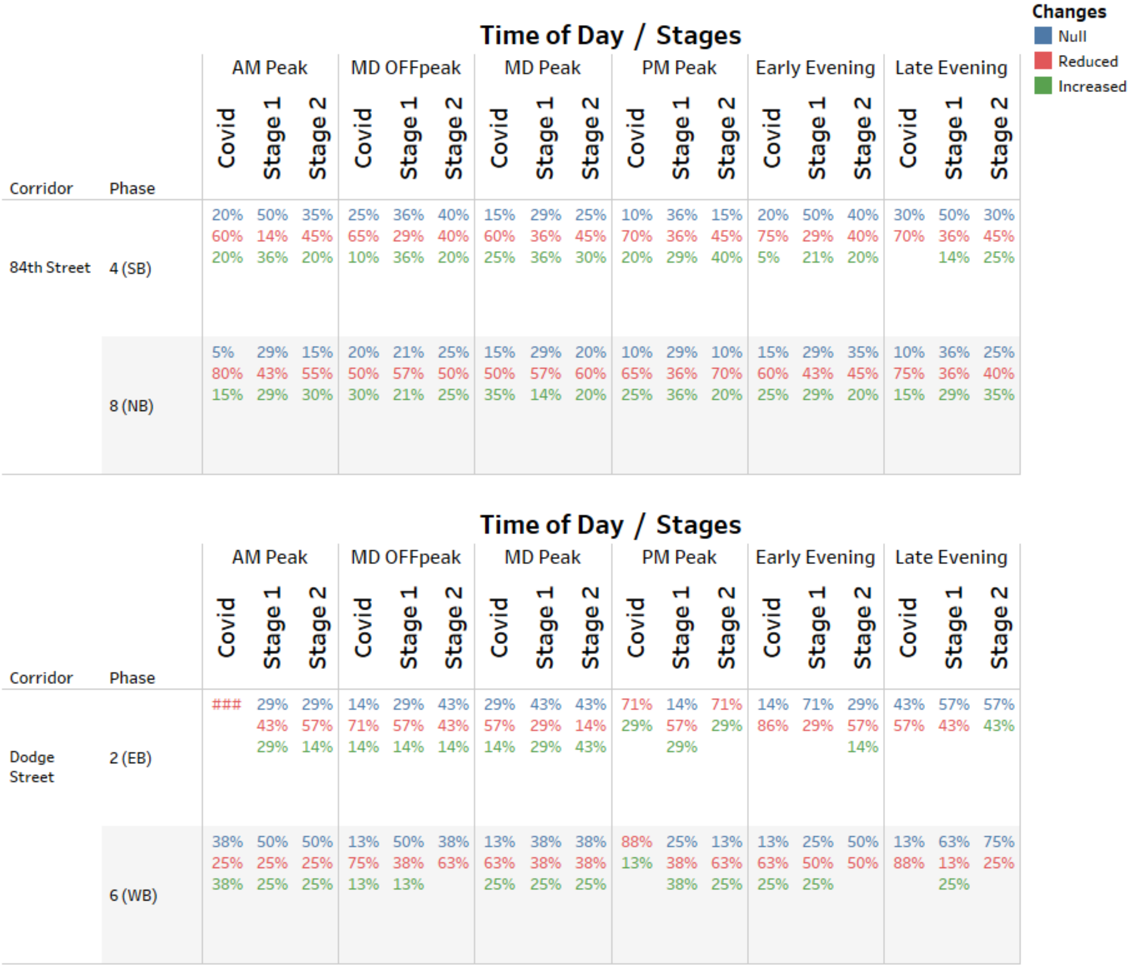
Time of Day / Phase

Stages / Corridor	Location	AM Peak		MD OFFpeak		MD Peak		PM Peak		Early Evening		Late Evening	
		2 (EB)	6 (WB)	2 (EB)	6 (WB)	2 (EB)	6 (WB)	2 (EB)	6 (WB)	2 (EB)	6 (WB)	2 (EB)	6 (WB)
Covid Dodge Street	74th St & Dodge St	-6.33		-7.51		-9.07		-12.92	-2.18	-10.55			-1.54
Stage 1 Dodge Street	74th St & Dodge St							-3.12	-2.75				
Stage 2 Dodge Street	74th St & Dodge St	-5.02	3.07	-3.09			6.15	-1.93	1.79	-1.95		1.08	

Changes
🟦 Null
🟥 Reduced
🟩 Increased

Figure 13. Change in platoon ratio (in terms of difference in percentage of median with respect to the base period) by TOD for the Dodge Street corridor at the Dodge Street and 74th Street intersection during the different stages

The changes in the platoon ratio for the various Dodge Street and 84th Street intersections across the four stages of this study with respect to the base period are summarized in Figure 14, which presents the percentage of intersections showing no significant change in, a lower, or a higher platoon ratio. It will be noted that the Stage 2 ATC implementation platoon ratio for most of the intersections became worse than for the base condition. This is consistent with the higher Bluetooth travel times observed during Stage 2 ATC implementation. One point of concern is that for most times of day the platoon ratio seems to have become worse even during the COVID-19 lockdown period when there was relatively little traffic.



Changes
🟦 Null
🟥 Reduced
🟩 Increased

Time of Day / Stages

Corridor	Phase	AM Peak			MD OFFpeak			MD Peak			PM Peak			Early Evening			Late Evening		
		Covid	Stage 1	Stage 2	Covid	Stage 1	Stage 2	Covid	Stage 1	Stage 2	Covid	Stage 1	Stage 2	Covid	Stage 1	Stage 2	Covid	Stage 1	Stage 2
84th Street	4 (SB)	20% 60% 20%	50% 14% 36%	35% 45% 20%	25% 65% 10%	36% 29% 36%	40% 40% 20%	15% 60% 25%	29% 36% 36%	25% 45% 30%	10% 70% 20%	36% 36% 29%	15% 45% 40%	20% 75% 5%	50% 29% 21%	40% 40% 20%	30% 70%	50% 36% 14%	30% 45% 25%
	8 (NB)	5% 80% 15%	29% 43% 29%	15% 55% 30%	20% 50% 30%	21% 57% 21%	25% 50% 25%	15% 50% 35%	29% 57% 14%	20% 60% 20%	10% 65% 25%	29% 36% 36%	10% 70% 20%	15% 60% 25%	29% 43% 29%	35% 45% 20%	10% 75% 15%	36% 36% 29%	25% 40% 35%

Time of Day / Stages

Corridor	Phase	AM Peak			MD OFFpeak			MD Peak			PM Peak			Early Evening			Late Evening		
		Covid	Stage 1	Stage 2	Covid	Stage 1	Stage 2	Covid	Stage 1	Stage 2	Covid	Stage 1	Stage 2	Covid	Stage 1	Stage 2	Covid	Stage 1	Stage 2
Dodge Street	2 (EB)	###	29% 43% 29%	29% 57% 14%	14% 71% 14%	29% 57% 14%	43% 43% 14%	29% 57% 14%	43% 29% 29%	43% 14% 43%	71% 29%	14% 57% 29%	71% 29%	14% 86%	71% 29%	29% 57% 14%	43% 57%	57% 43%	57% 43%
	6 (WB)	38% 25% 38%	50% 25% 25%	50% 25% 25%	13% 75% 13%	50% 38% 13%	38% 63%	13% 63% 25%	38% 38% 25%	38% 38% 25%	88% 13%	25% 38% 38%	13% 63% 25%	13% 63% 25%	25% 50% 25%	50% 50%	13% 88%	63% 13% 25%	75% 25%

Figure 14. Percentage change by TOD of 84th Street and Dodge Street corridor intersections' platoon ratio with respect to the base period during the different stages

4.2.3 Side Street Delay Evaluation

Side street delay per vehicle was evaluated to understand the behavior of the Dodge Street and 84th Street corridors during each of the four stages of this study. The hourly side street delay per vehicle is shown in Figure 15 for the Dodge Street and 74th Street intersection (with the mean of the five days evaluated for each stage of the study marked as a dark line surrounded by its 95% confidence interval).

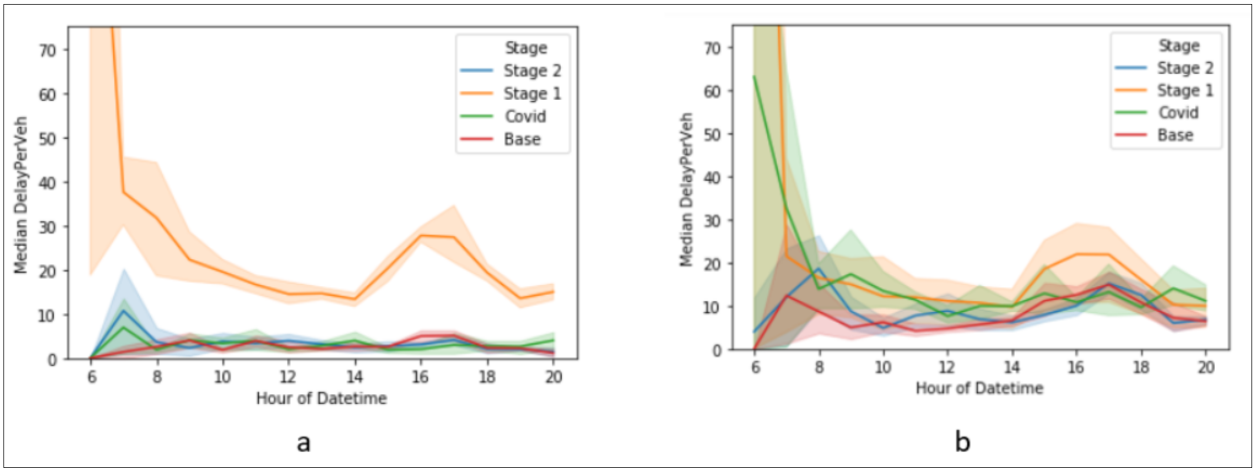


Figure 15. Hourly variation in side street delay per vehicle with a 95% confidence interval for the (a) southbound through direction (Phase 4) and (b) northbound through direction (Phase 8) of traffic flow for the Dodge Street and 74th Street intersection during the different stages

From Figure 15, it can be seen that the early morning peak was associated with very high delay per vehicle, the reason being that the side street volume was very low during this period, which meant that whatever vehicles arrived had to wait longer than usual. Also, it can be observed during Stage 1 that delay throughout the entire day was higher for the southbound direction of travel.

As with the previous performance measures, the 30-minute side street delay distribution during each stage of the study was evaluated for each TOD and plotted via CDF plot as shown in Figure 16.

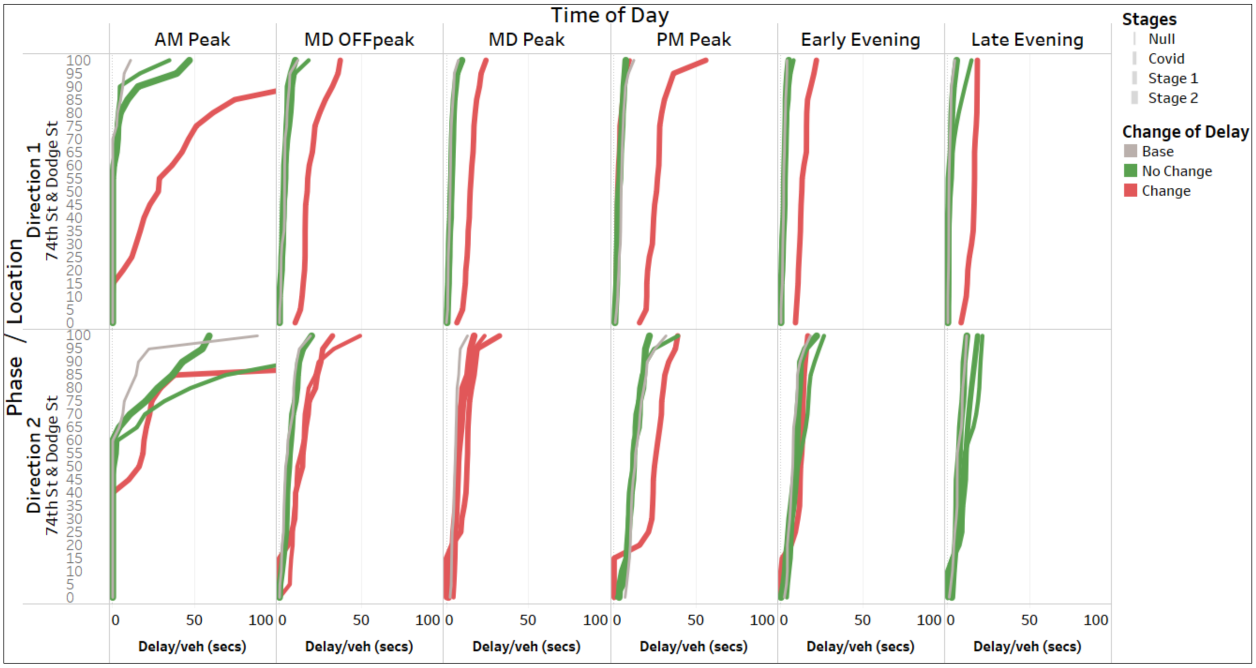
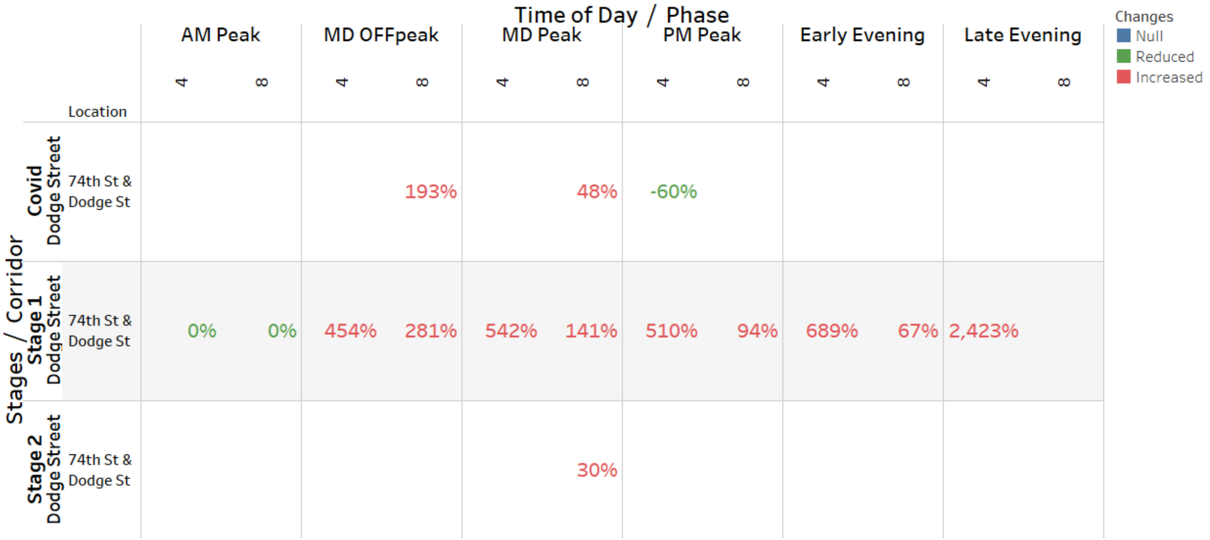


Figure 16. Cumulative distribution function plots of side street delay per vehicle for the Dodge Street and 74th Street intersection by direction and TOD during the different stages

The CDF plots for the different stages of this study were then compared to the base period using the K-S test followed by a multiple-test p-value correction. Differences in the median side street delay performance during each TOD with respect to the base period are shown as a percentage value in Figure 17.



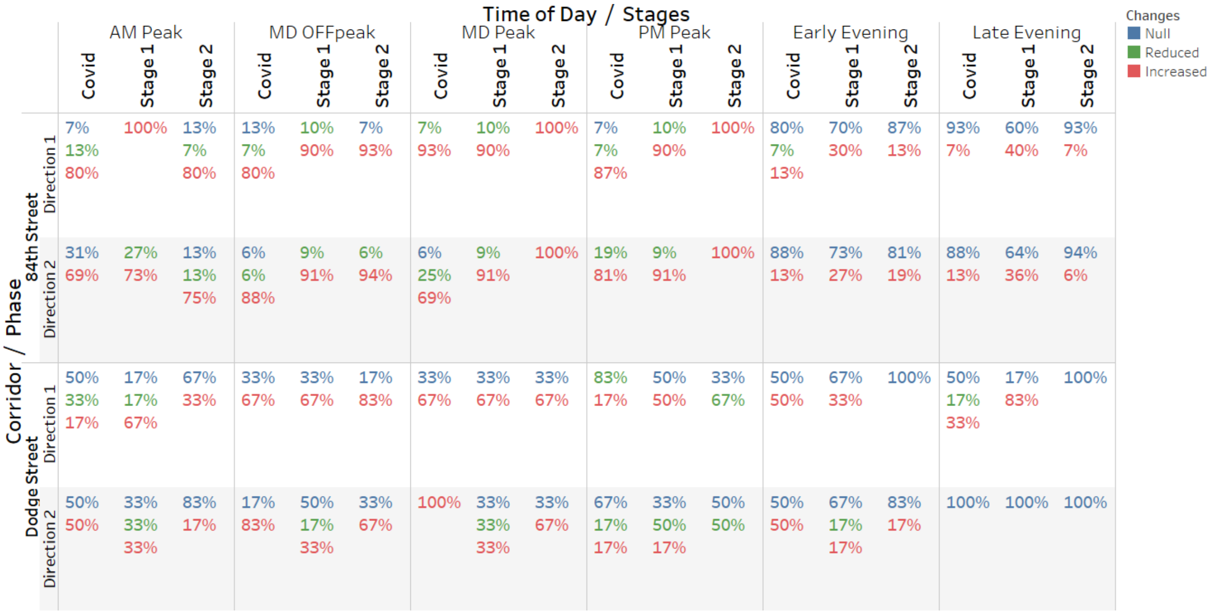
Stages / Corridor	Location	AM Peak 4	AM Peak 8	MD OFFpeak 4	MD OFFpeak 8	MD Peak 4	MD Peak 8	PM Peak 4	PM Peak 8	Early Evening 4	Early Evening 8	Late Evening 4	Late Evening 8
Covid Dodge Street	74th St & Dodge St				193%		48%	-60%					
Stage 1 Dodge Street	74th St & Dodge St	0%	0%	454%	281%	542%	141%	510%	94%	689%	67%	2,423%	
Stage 2 Dodge Street	74th St & Dodge St						30%						

Figure 17. Change in side street delay (in terms of difference in percentage of median with respect to the base period) by TOD for the Dodge Street and 74th Street intersection during different stages

As seen in both the line plots of Figure 15 and the CDF plots of Figure 16, the median side street delay per vehicle increased for the Dodge Street and 74th Street intersection during the Stage 1 ATC implementation.

In Figure 18, the changes in all side streets' delay performance along the Dodge Street and 84th Street corridors are aggregated and reported as a percentage of each corridor's intersections. From this figure, the following can be observed:

- Throughout the daytime—that is, except during the evening hours—side street delay per vehicle increased for most intersections on the 84th Street corridor.
- For the Dodge Street corridor during Stage 2 ATC implementation, side street delay increased during most TODs except during PM Peak conditions. This is consistent with the lower cycle lengths observed during the PM peak period.



Time of Day / Stages

Corridor / Phase		AM Peak			MD OFFpeak			MD Peak			PM Peak			Early Evening			Late Evening		
		Covid	Stage 1	Stage 2	Covid	Stage 1	Stage 2	Covid	Stage 1	Stage 2	Covid	Stage 1	Stage 2	Covid	Stage 1	Stage 2	Covid	Stage 1	Stage 2
84th Street	Direction 1	7% 13% 80%	100%	13% 7% 80%	13% 7% 80%	10% 90%	7% 93%	7% 93%	10% 90%	100%	7% 7% 87%	10% 90%	100%	80% 7% 13%	70% 30%	87% 13%	93% 7%	60% 40%	93% 7%
	Direction 2	31% 69%	27% 73%	13% 13% 75%	6% 6% 88%	9% 91%	6% 94%	6% 25% 69%	9% 91%	100%	19% 81%	9% 91%	100%	88% 13%	73% 27%	81% 19%	88% 13%	64% 36%	94% 6%
Dodge Street	Direction 1	50% 33% 17%	17% 17% 67%	67% 33%	33% 67%	33% 67%	17% 83%	33% 67%	33% 67%	33% 67%	83% 17%	50% 50%	33% 67%	50% 50%	67% 33%	100%	50% 17% 33%	17% 83%	100%
	Direction 2	50% 50%	33% 33% 33%	83% 17%	17% 83%	50% 17% 33%	33% 67%	100%	33% 33% 33%	33% 67%	67% 17% 17%	33% 50% 17%	50% 50%	50% 50%	67% 17% 17%	83% 17%	100%	100%	100%

Changes
🟦 Null
🟩 Reduced
🟥 Increased

Figure 18. Percentage change by TOD with respect to the base period in side street delay per vehicle for the 84th Street and Dodge Street corridor intersectionsduring the different stages

CHAPTER 5 CONCLUSION

Traffic signals require intervention from time to time. Needed changes are usually brought about manually or by changing signals to adaptive control. Adaptive control has been seen to be beneficial for some agencies, whereas it has not been able to provide expected benefits to others. Hence, a thorough investigation is a necessity for any agency implementing adaptive control. This present report highlights such an evaluation for two arterial corridors in the City of Omaha, Nebraska, namely Dodge Street and 84th Street.

This study's evaluation was conducted using several data sources and their corresponding performance measures. After performance issues were reported with Omaha's first stage of ATC implementation, there was a second stage of ATC carried out. Even in the second stage, travel time on the main street investigated in the study was found to be negatively impacted in both the eastbound and westbound directions. This was verified using Bluetooth travel time data. The next stage was to evaluate the ATC technology's performance during the various phases of the COVID-19 lockdown, which unsurprisingly showed that travel time reduced significantly when there was strict or partial lockdown. However, as life came back to normal, travel time slowly kept on increasing.

The next type of evaluation was conducted using high resolution data from both of the corridors investigated in this study. Three measures were used—cycle length, platoon ratio, and side-street delay. It was found that cycle length increased during most times periods of the day except the PM peak. Further, shorter cycle lengths were observed during the COVID-19 lockdown. The platoon ratio also became worse for the majority of locations throughout the study, which was reflected in an increase in travel time for the Dodge Street corridor. In addition, the evaluation of side-street delay showed poorer performance during most time periods of the day. Dodge Street, which is the highest-volume-carrying corridor in the City of Omaha, saw an increase in side-street delay except during PM peak conditions. As for 84th Street, side-street delay performance was also worse throughout the ATC stages of the study.

The city also noted the following qualitative observation during the operation of ACT system.

- Complaints from the public have not increased
- Typically, staff does not have to intervene for lane closures or incidents that may alter the typical demand/capacity for a roadway
- The ASCT system selects cycles and splits well (very few split failures)
- The ASCT struggles to progress traffic and select alternate phase sequences.
- Difficult to understand ASCT offset selection.

In conclusion, this report presents an overall evaluation of ATC as applied to two arterial corridors. It can be said that during recurring demand conditions, adaptive control was found in this study to have underperformed as compared to a well-timed signal for both the high-volume and low-volume corridors. The performance of the ATC implementation investigated in this study was particularly bad during oversaturated conditions (i.e., during the PM peak on Dodge Street), which resulted in a shutting down of the adaptive mode during that time period. However, on a positive note, adaptive control did reduce cycle length as demand dropped during COVID, showing a move in the right direction. In essence, the ACT system does provide adjustments during atypical conditions but cannot outperform static timing patterns during recurring traffic demand.

Future work can be to study the effect of ATC as things start getting back to normal and doing a cost-benefit analysis of ATC for these corridors. Also, a safety evaluation can be carried out using videography and by evaluating gap acceptance for the left-turning movement before and after ATC implementation.

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