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A Data-Driven Methodology for Prioritizing Traffic Signal Retiming Operations

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A Data-Driven Methodology for Prioritizing Traffic Signal Retiming Operations

by

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Abstract

A Data-Driven Methodology for Prioritizing Traffic Signal Retiming Operations

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Signal retiming is one of the chief responsibilities of municipal transportation agencies and is an important means for reducing congestion and improving transportation quality and reliability. Many agencies conduct signal retiming and adjustment in a schedule-based manner. However, leveraging a data-driven, need-based approach to the prioritization of signal retiming operations could better optimize use of agency resources. Additionally, the growing availability of probe vehicle data has made it an increasingly popular tool for use in roadway performance measurement. This thesis presents a methodology for utilizing segment-level probe-based speed data to rank the performance of traffic signal corridors for retiming purposes. This methodology is then demonstrated in an analysis of 79 traffic signal corridors maintained by the City of Austin, Texas. The analysis considers 15-minute speed records for all weekdays in September 2016 and September 2017 to compute metrics and rank corridors based on their relative performance across time periods. The results show that the ranking methodology compares corridors equitably despite differences in road length, functional class, and traffic signal density. Additionally, results indicate that the corridors prioritized by the ranking methodology represent a much greater potential for improving travel time than the corridors selected under the schedule-based approach. This methodology is then packaged into a web-based tool for integration into agency decision-making. Finally, consideration is given to how this methodology might be used to identify candidate corridors for implementing adaptive signal control techniques.

Keywords: ranking, prioritization, traffic signal retiming, operations, corridor performance, probe vehicle data, adaptive signal control, candidate corridors

Table of Contents

List of Tables

List of Figures

PART 1: DEVELOPMENT OF PRIORITIZATION METHODOLOGY

Chapter 1: Introduction and Project Motivation

Maintaining traffic signal timing plans is one of the most pressing responsibilities facing municipal transportation agencies. The National Traffic Signal Report Card has continually called for better signal maintenance and management across the country (National Traffic Operations Coalition, 2012). US vehicle miles traveled (VMT) has resumed a trend of steady increase following the economic recession of 2008 (Polzin, 2017). Simple solutions, such as regularly retiming traffic signals, have been recommended to offset the effect of growing congestion (Schrank et al., 2015). Regularly retiming traffic signals requires agencies to continually revisit and update traffic signal timings to provide citizens the best possible travel conditions. Most agencies conduct these signal retiming operations by following a rotating schedule determined by agency resources, or simply by responding to citizen comments on a case-by-case basis (Gordon, 2010). However, the proliferation of data in the transportation field has made quantitative assessment of roadway performance more realistic for many agencies. Probe vehicle data has become an increasingly popular tool for traffic assessment both in real time and over extended time periods. Available commercial products aggregate probe vehicle data to provide segment-level speed and travel time information. Such data is based on vehicle position and speed information collected from a user base through cellular phones or other mobile devices.

Applications for assessing roadway performance using probe vehicle data have thus far dealt with freeways or major arterials, roadways with a lower density of traffic signals and often limited access points. However, most agencies maintain traffic signals across a wide range of functional classifications, including a significant portion on low-speed and relatively low-volume collector roads and local streets. There has yet to be a study which compares the performance of such a variety of roadways across a geographic area.

The Transportation Department for the City of Austin, Texas is charged with retiming one third of the city's approximately 1,000 traffic signals every year, with the goal of ensuring the signals are timed to optimize safety and performance. Currently, signals are selected for retiming based on a three-year fixed schedule. However, the City of Austin (CoA) has wanted to develop a data-driven methodology that would identify the traffic signal corridors for which retiming was most critical in a given year. Transitioning from a schedule-based system to a needs-based system will lead to increased operational efficiency and improved system performance for travelers in Austin.

This thesis represents an initial step towards leveraging data to inform municipal decision-making regarding traffic signal and corridor retiming prioritization. It presents a methodology for prioritizing corridors for traffic signal retiming operations based on metrics computed using probe vehicle speed data. The proposed metrics assess the relative performance of corridors for selected time periods. This study was conducted on 79 corridors in Austin, Texas, consisting of 1,026 traffic signals spread over 300 square miles. The following chapters detail the motivation behind the study, the development of the methodology and associated results, and the exploration of the applicability of this work in selecting corridors for deployment of adaptive signal control.

Chapter 2: Project Background and Data Selection

2.1 Existing CoA Signal Retiming Process

The CoA develops its signal retiming schedule by grouping traffic signals into corridors. There are 90 such corridors, and the CoA divides them into three groups to create a rotating three-year schedule for retiming. The number of corridors in each group is adjusted based on the total number of signals, so that approximately one-third of the City's signals are retimed each year.

The City assesses the effectiveness of retiming operations using floating car travel time runs. Floating car (or "test vehicle") runs have been the traditional method for collecting travel time data since the 1950s (Turner, 2014). This technique involves driving a corridor as many times as possible during the peak hour and recording travel time measurements. The CoA conducts the timed runs in a consistent manner, at carefully chosen times before and after a corridor has been retimed. This allows for the computation of a travel time reduction metric, which is the principle measure of effectiveness for the retiming of the corridor. However, given that each corridor is usually driven only three to five times while conducting the floating car runs, many factors could disrupt the accuracy of the metric, particularly seasonal fluctuations and random variation.

2.2 Review of Potential Data Sources

The CoA had invested in or piloted several different sources of data at the beginning of this project. These different sources were each considered for use in the development of the initial corridor ranking methodology. A key factor for this project was the coverage of a given data type over the study area, since the goal of the work was to compare performance of signal corridors across the whole city. Three of the main data sources considered were Bluetooth sensors, GRIDSMART detection cameras, and Wavetronix radar sensors. All three of these data sources depend on sensors deployed and maintained by the CoA. GRIDSMART and Wavetronix have only been deployed in limited numbers, with both exhibiting coverage on 18 percent of the CoA corridors. The CoA has installed Bluetooth sensors more extensively, with 53 percent of corridors containing at least two sensors, the minimum necessary for gathering travel time data. This level of data coverage still proved too low for effectively assessing the performance of corridors across the whole city.

Figure 1 shows that there were very few corridors containing more than three Bluetooth sensors, indicating a lack of both data coverage and granularity available when using these sensors as a primary data source. Although these data sources may be explored further for future use by the CoA, they were not suitable for the immediate needs of this project.

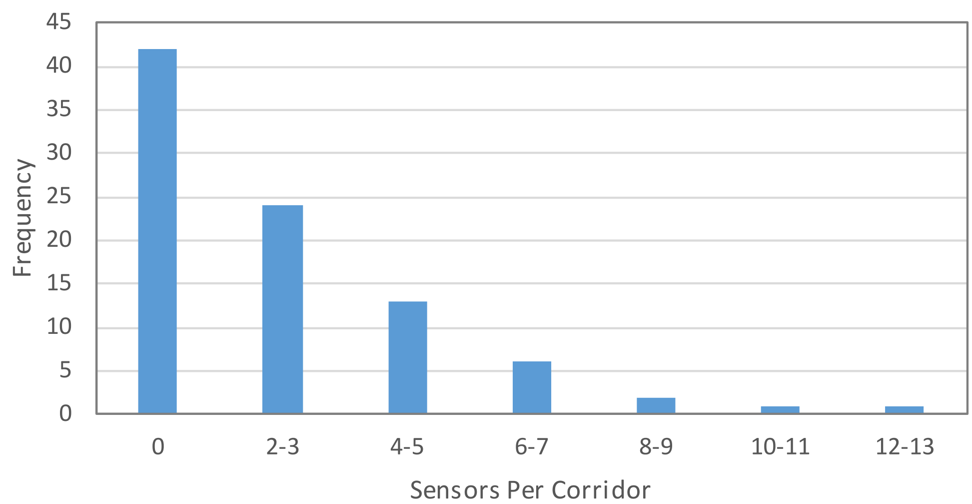


Figure 1: Number of Bluetooth sensors per corridor in Austin.

In addition to these data sources, the CoA purchased a probe vehicle dataset from third-party vendor INRIX for general transportation applications; this data was chosen for use in this study because it presented significantly better coverage than any of the alternatives. When the CoA initially purchased the data, its coverage was limited to major roads, and it did not cover every signalized corridor in the city. However, the City successfully requested an expansion of the coverage area from INRIX, which resulted in reliable coverage on 79 of the 90 City-defined corridors, or 87% data coverage, shown in

Figure 2. A major advantage of probe vehicle data, in addition to the flexible coverage, is that it does not require the installation or maintenance of sensors by the agency.

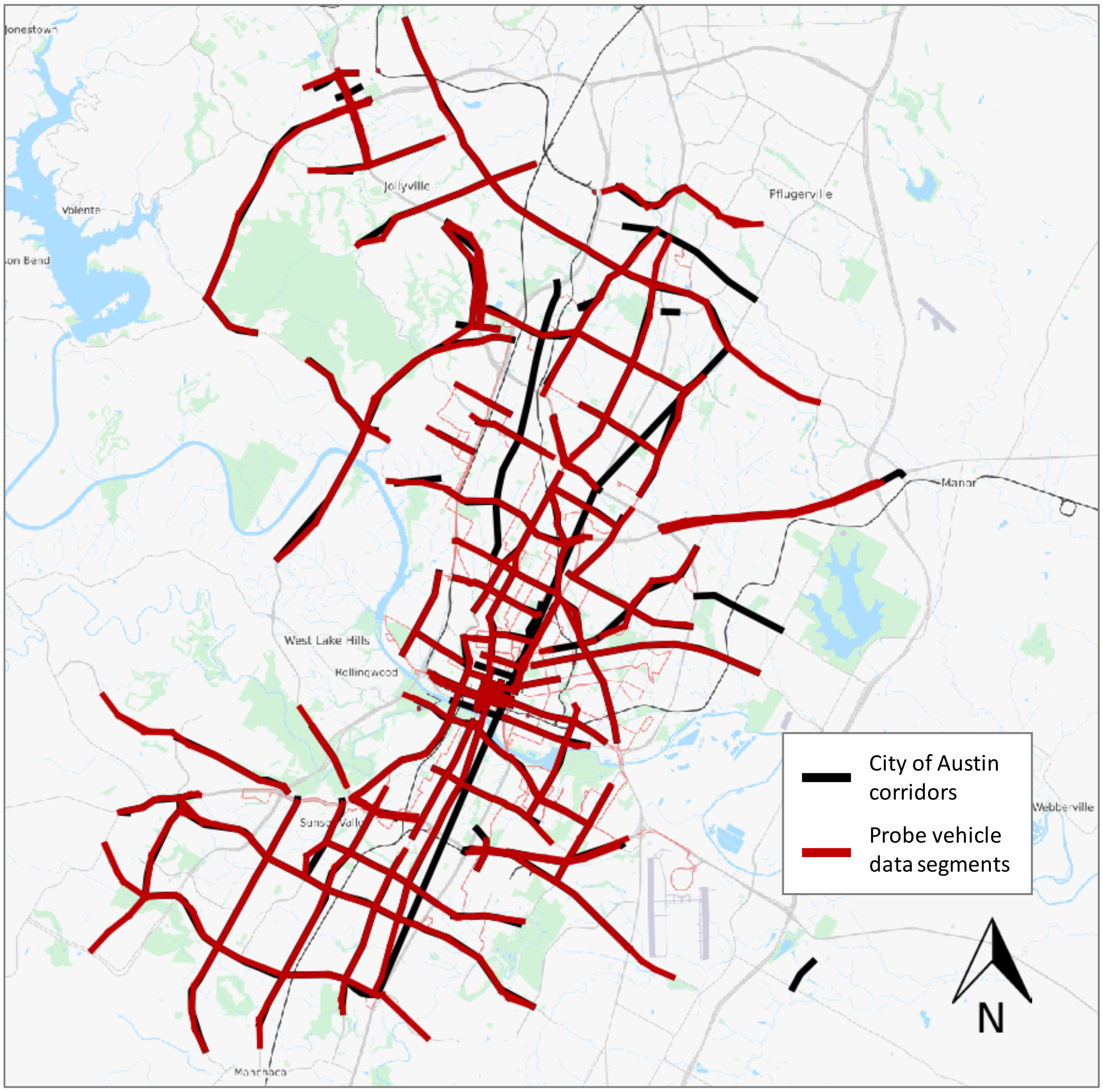


Figure 2: Map of INRIX probe vehicle data coverage for Austin.

The probe vehicle data is collected by INRIX primarily through a network of participating users' cellular phones, and is supplemented by other sensors where necessary or possible. This data is delivered in records detailing the average vehicle speed over a given segment of roadway for a given period of time. Segments generally range from 0.1 to 0.5 miles in length, though they can be as short as 10 yards and as long as a mile. The finest data granularity is 1-minute speed averages, though the granularity can also range up to 1-hour averages. Since the data also logs the length of each pre-defined segment, a travel time can be calculated based on the measured speed. By stringing together consecutive segments, corridors can be defined and studied individually.

There are some concerns in using probe vehicle speed data, particularly in the context of an urban road network. The first is that this data only includes vehicle speeds, and does not contain information on the associated demand or vehicle volumes. Additionally, INRIX does not publish information on the specific data penetration rates for individual roads or regions. While these concerns were considered in assessing the effectiveness of the data source, ultimately the probe vehicle speed data was selected for use in this study, primarily due to the benefit of its stellar coverage over the study area.

2.3 Summary of Existing CoA Methods and Data Selection

The current schedule-based approach to prioritizing traffic signal retiming used by the CoA leaves significant potential for improvement. Developing a data-driven system would improve the agency's ability to allocate resources in a more efficient manner and would be more effective at identifying the locations most in need of retiming. Probe vehicle data (such as the INRIX data selected here) is the best foundation for a system such as this, because it presents thorough coverage of a wide area, and does not require the agency to deploy or maintain sensors.

Understanding the current CoA process for prioritizing traffic signal retiming operations and selecting a primary data source was a crucial first step for this work. The capabilities and preferences of the agency and, more critically, the data at hand, significantly informed the types of metrics that were developed later in the project. This ultimately shaped the ranking methodology. The next step involved exploring the literature to further understand traffic signal performance measurement and prioritization techniques.

Chapter 3: Review of Literature

The literature review for this project explored the relevant academic literature pertaining to signal retiming practices and corridor performance measurement, as well as the signal retiming operations conducted by other agencies across the country. The latter information, of a more practical, agency-specific nature, was more difficult to uncover, so a survey regarding retiming practices was developed and distributed to augment the literature review. The following sections include summaries of both phases of the literature review.

3.1 Signal Retiming Practices

The CoA is currently in-line with the majority of US agencies, which retime their signals on a three- to five-year cycle (Gordon, 2010). The CoA developed its retiming schedule by grouping traffic signals into corridors. As previously discussed, there are 90 City-defined corridors, divided into three groups to create a rotating three-year schedule for retiming. The three-year cycle was chosen to match the availability of agency resources and the capacity for signal retiming in a given year.

The "three-year rule" is generally considered the industry standard and rule-of-thumb. It dictates that signals should be retimed every three years to maintain an adequate standard of operation. However, there is little research to support it (Humphreys & Click, 2018). In fact, so many factors affect traffic signals that it is not productive to rely on a universal rule for retiming frequency. For instance, arterials benefit from frequent retiming, but downtown urban networks generally do not. Thus, certain traffic signal corridors may require retiming every one or two years, while others may only need adjustment every five years. The fairly strict schedule-based system used by the CoA and many other agencies is not designed to anticipate or adjust for these various factors.

In a given year, the CoA's schedule may be adjusted due to unexpected changes in performance, resource availability, or other reasons, but the three-year schedule serves as a foundational plan for retiming. Previous surveys explored the factors that most often affect signal retiming and the triggers that may cause an agency to disrupt its retiming schedule (Dazhi et al., 2012). Primary triggers for retiming include requests from the public, significant changes in land use, changes in traffic volume or congestion patterns, and crash history, among others. The CoA takes many of these triggers into account, particularly citizen feedback, but the main motivation to retime is usually the three-year rule.

Some agencies have developed methods for prioritizing corridors based on performance. One case study (Pulipati, 2006) analyzes the North Central Texas Council of Governments' ranking model that uses travel time delay (the difference between the actual travel time and the desired, or free-flow, travel time) to rank corridors for retiming. The ranking process is based on a calculated score for each corridor that considers delay per intersection, average stops per vehicle, and the level of coordination present on the corridor. While the data currently available for Austin does not enable replication of this method, it provides an interesting framework for combining multiple metrics to produce a ranking. Additionally, Pulipati proposed an alternate model that assesses broader societal benefits as opposed to just the severity of existing traffic conditions. The proposed ranking model utilized linear regression to calculate benefits in three areas: delay, fuel consumption, and emissions. This is an interesting approach to a holistic corridor performance assessment and could be considered in future extensions of this work.

Another case study proposes the use of Multi-Layer Prioritizing (MLP), a technique for implementing multiple ranking criteria, to combine both safety and operational considerations in a prioritization methodology (Lu & Wang, 2005). MLP operates by clustering criterion into different "layers" based on their assigned weight or priority. The use of MLP was considered in this work, but ultimately it was decided that this technique introduced unnecessary complications to the ranking methodology, particularly given the exploratory nature of this study. Should future work expand the data sources utilized, MLP might be a valuable tool.

3.2 Performance Measures

There are three goals to keep in mind when selecting performance measures for a signal system: The metric should cover the whole system, should be measurable using existing information or information that is relatively easy to obtain, and should minimize the need for subjective judgment in accomplishing evaluation. In other words, criteria must possess technical reliability and availability. There are a variety of different metrics that have been used to assess intersection and corridor performance. Their use depends heavily on the data available and the specifics of the application.

The fundamental metrics used to assess the operational effectiveness of signalized roadways are turning movement volume counts and travel time/delay. Delay is the most commonly used measure of effectiveness for signalized intersections. Other metrics include stopped time delay, approach delay, travel time delay, and time-in-queue delay. Day et al. (2014) categorize delay as a "progression performance measure" as defined in the Highway Capacity Manual (HCM, 2010). The concept of delay is also used to calculate more intricate measures, such as the progression factor (PF) and platoon ratio (R_p).

Day et al. (2014) also outline other performance measures related to capacity, such as measures of the allocation of signal time and of the number of vehicles served by each phase. Some of these performance measures include Green Occupancy Ratio (GOR) and Red Occupancy Ratio (ROR), which are computed using stop bar detector data. Performance measures such as these are well-suited to using high resolution traffic signal controller data. The CoA is pursuing the implementation and collection of high-resolution data, so these metrics could be valuable additions to this methodology once the data becomes available. Additional capacity performance measures include examining cycle length, phase termination, and volume of traffic served, among others (Day et al., 2014).

Measures used to quantify system performance can vary depending on the level of system saturation, or whether the evaluation time is during peak or off-peak periods (Dazhi et al. 2012). Dazhi et al. propose the measures that are best suited for these different situations, as shown in Table 1.

Table 1: Performance Measures for Varying Traffic Conditions

Volume Condition	Period	Performance Measure
Unsaturated	Peak	Average travel speed Average stop rate Queue storage
	Off-Peak	Total delay
Over-saturated	Peak and Off-Peak	Number of segments with spillback Duration of over-saturation Total travel time

Other metrics are used less frequently, and often serve as supplements in various agency decision-making processes. Cost/benefit assessment is a valuable tool in quantifying the benefits of a retiming project, and there are many different methods by which to do this. They are generally based on calculating cost savings due to decreased travel time and decreased vehicle emissions. The HCM (2010) identifies two performance measures for signalized intersections in addition to delay: level of service (LOS) and queue storage ratio. However, few agencies use intersection LOS or queue storage ratio in their regular retiming practices. Pedestrian LOS is an increasingly popular metric used to account for pedestrian activity at an intersection. It measures pedestrian delay and can consider intersection geometry, vehicle volumes and speed, and pedestrian/vehicle conflicts (HCM, 2010). While these metrics either require additional data sources or are outside the scope of this study, they all represents possibilities for augmenting the analysis proposed here.

3.3 Signal Performance Monitoring and Use of Probe Vehicle Data

The literature also touched on methods for monitoring signal performance, indicating that the most common was citizen feedback, followed by anecdotal or video observation, floating car travel time runs, and finally level-of-service analysis. The CoA predominately uses floating car travel time runs to assess the effectiveness of retiming. The City conducts such runs in a consistent manner, on carefully chosen days before and after retiming a corridor. The collected data is used to compute a percent travel time reduction metric, the principal measure of effectiveness for the retiming of the corridor. However, this metric is only used to demonstrate performance improvements due to retiming, and is not used to prioritize corridors for future retiming operations.

Use of probe vehicle traffic data has been on the rise in the last ten years, and has been increasingly employed by researchers and practicing engineers alike to explore traffic patterns, congestion, and mobility in a variety of applications. Many US states have recently produced reports that leverage this sort of data to assess statewide mobility by examining congestion on major freeways, including Indiana (Day et al., 2016), Maryland (Mahapatra et al., 2017), California (California DOT, 2013), Alabama (Hainen & Dunn, 2015), and Washington (Washington State DOT, 2017). The body of research that has been conducted in this area has focused on subsets of freeways and major arterials, as opposed to a cross-section of all road types in a given region. A smaller portion of this work has explored ranking these higher-volume roads based on their performance, including ranking arterial corridors (Day et al., 2015) and freeway bottlenecks (Gong & Fan, 2018).

Given that most transportation agencies conduct signal retiming operations with little-to-no quantitative prioritization, this project has the potential to significantly improve the efficiency of transportation operations. Current literature does not contain decisive research in using crowd-sourced probe vehicle data to compare a wide variety of corridors. The methodology developed in this study has the potential to significantly increase the quality of service that agencies can deliver to their stakeholders.

3.4 Survey Distribution and Results

It was determined that, in addition to findings from academic literature sources, it would be valuable to understand how a broad range of agencies handle traffic signal retiming. To collect this information, an informal survey was posted to the Institute of Transportation Engineers (ITE) online member forum. This method was selected over a more prescriptive survey technique in hopes that it would more accurately communicate the intricacies of different agencies' processes. The survey, developed in collaboration with CoA staff, contained some guiding questions, but generally left the respondents with a fair amount of autonomy. The message follows:

The Center for Transportation Research at the University of Texas at Austin is currently working with the City of Austin to improve the process by which traffic signals and corridors are prioritized and chosen for retiming. We are hoping to collect information about how agencies from around the country handle this process, as a survey of the state of practice.

Please take 5 minutes to send us replies to the questions below. When our summary report is complete, we can email it to anyone who is interested.

- *How many signals does your agency maintain, and of those how many are retimed each year?*
- *Does your agency have any sort of guidelines or rules used to prioritize intersections or corridors to be retimed? If so, what are those?*
- *Does your agency measure the effectiveness of retiming operations? What metrics are preferred? What data sources (e.g., travel time runs, INRIX or other probe data) are used?*
- *Has your agency used or explored the use of Adaptive Signal Control? If so, how do you evaluate candidate corridors, and measure the effectiveness?*

Any information you can share regarding this process would be appreciated. Thank you for your time!

Twelve responses were received; nine answered the survey questions in some form. Additionally, some respondents sent other reports detailing similar or relevant studies. Responses to the survey represented agencies ranging in size from small communities and counties to large metropolitan areas. Interestingly, most agencies that responded were located on the West Coast and in the Pacific Northwest. For a complete enumeration of the survey responses, see Appendix A. Table 2, shown on the following page, summarizes the responses, which provided an interesting cross-section of different methods. Overall, the results confirmed the findings in the literature, which stated that many agencies retime on a fixed schedule and primarily use floating car travel time runs and citizen requests as measures of priority and effectiveness.

3.5 Summary of Literature Review

The literature review provided a solid background for the study, especially in the area of performance measurement. It confirmed that the CoA is generally in-line with most agencies regarding signal retiming practices, but also hinted at different areas for potential improvements. Additionally, both the literature review and agency survey revealed that the creation of an easily-implementable, effective prioritization methodology would be a novel and valuable addition to the retiming practices of the average agency. In addition to confirming the value of this work, the literature review showed a clear path forward for future effort that might be made to further this study. Gathering relevant information through surveys of the literature and the practices of other agencies provided a strong foundation for moving into the next stage of the project, exploration of the probe vehicle speed data.

Table 2: Summary of Survey Responses

	Hennepin County, MN	Campbell, CA	Washington County, OR	Clark County, WA	Salt Lake City, UT	Federal Way, WA	Medford, OR	Toronto, Canada
Number of signals	460	44	300	100	1220	82	120	2350
Per year	80-100	Varies based on funding	50	Varies, no schedule	Varies based on funding, needs	Retime all at once, every 3-5 years	--	260
Prioritization criteria	Crash rates, volumes, traffic pattern changes, citizen requests	Traffic pattern changes, time since last retiming	Measure and observed congestion, citizen requests	Citizen requests	ASTPMs, volumes, progression quality	Citizen requests	Citizen requests	Major arterials, changes in traffic patterns and volumes
Measures of effectiveness	LOS, delay, stops, emissions, travel times	Travel time, delay	Travel time, queue spillback, cycle/split failures	Travel time	Travel time, split failures, platoon ratios	Travel time	Travel time, volume	Delay, stops, speed, fuel consumption, emissions, benefit/cost
Data sources	Floating car	Floating car	Bluetooth, controller data, CCTV	Currently comparing floating car, Bluetooth, and INRIX	HERE (crowdsourced probe data)	Floating car	Floating car	Floating car, Bluetooth, HERE
Adaptive Signal Control	No	No, but considering	Yes, 42 in operation and 27 in consideration	No, but considering	Yes	Currently implementing	Yes, one corridor	300 signals on SCOOT, 20 piloting new systems

Chapter 4: Data Acquisition and Aggregation

4.1 Data Exploration and Discovery of INRIX Error

Data was accessed through the INRIX Analytics web-based interface. While the interface contains valuable tools for visualizing certain aspects of the data (namely, individual segment or corridor data for short time periods), it was not adequate for the needs of this study. For this reason, data was downloaded and examined independently. The INRIX interface allows the user to select groups of roadway segments and save them as corridors. Each of the seventy-nine corridors covered by INRIX were defined within the interface according to the CoA's signal corridor definitions, made available through the Austin Transportation Data and Performance Hub. Some corridors (as defined by the CoA) included signals nearby or on adjacent roadways, as opposed to on the main thru-corridor. For this analysis, each corridor was defined as the principle collection of signals along the same roadway.

Each direction for each corridor was defined and saved separately. The INRIX interface is generally good at filling in intermediate segments when the first and last segments have been selected. However, there were numerous instances where bugs within the INRIX interface caused errors in the selected segments. By double-checking the segments chosen by the interface (to make sure they were all in the same direction, on the right road, etc.) major data errors were avoided. This process was performed manually, though exploration of methods for automating parts of this process could be an area for future improvement.

This study utilized the portion of the data corresponding to weekdays in September 2016 and September 2017. This was done due to an error with the INRIX data downloader. An anomaly in the INRIX data was identified when plotting corridor travel times at 15-minute intervals for the full two-year period (2016-2017). An example of this can be seen in Figure 3, where travel times for the Lavaca corridor flat-line for a stretch of about 8 months between 2016 and 2017, and again around the same months in 2017-2018. This same pattern occurred consistently across all the corridors analyzed.

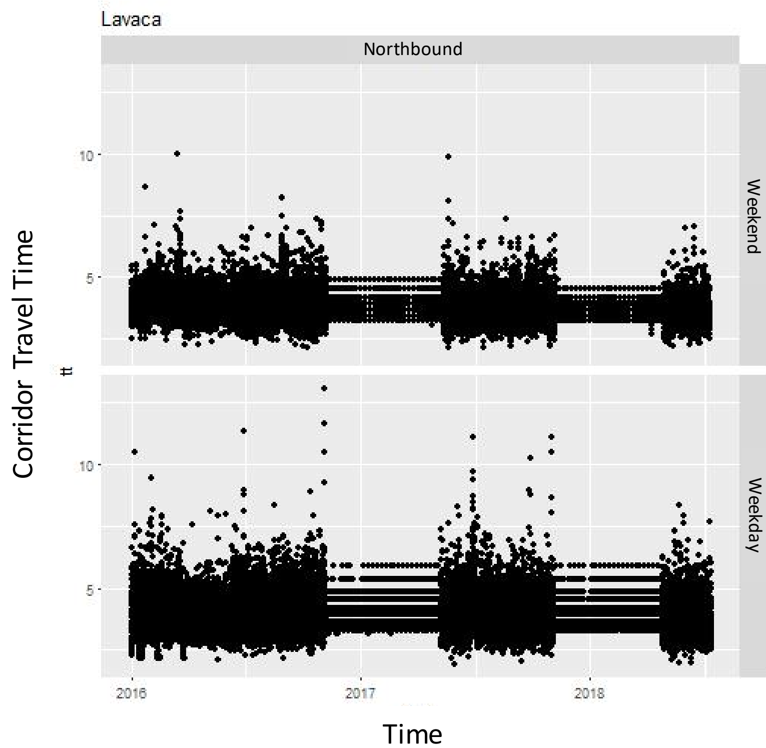


Figure 3: Fifteen-minute travel times for the Lavaca corridor, Jan. 2016 to Aug. 2018.

The INRIX data includes a three-part data score which provides information on the source of the speed data for each data point. The three facets of the data score are Score 30, Score 20, and Score 10. Each of the scores communicates the portion of a data point that was calculated by each of three methods. Score 30 represents data acquired from real-time speed measurements of minute-level data. Score 20 represents data filled in from the historical speed data profile. Score 10 represents data filled in with the "reference speed," INRIX's proxy free flow speed, which is constant for the entire day (INRIX, 2018). Since each score is given as a percentage, the three scores for each data point always sum to 100. Ideally, Score 30 should be 100, indicating that all the data was calculated using measured minute-level data, but that is not always possible given imperfect data penetration and other issues.

Given these definitions and plots such as the one shown in Figure 3, it seemed that the issue was stemming from this data source question. It was speculated that this was the result of INRIX populating the data during this period with historical averages or simply the free-flow speed. Given the striations in the data during this period, it appeared that different travel times were used for different times of day, and the pattern was different between weekdays and weekends. To explore this issue further, trends in the data scores were explored over the two years for which data had been downloaded for a sample of twenty corridors. This analysis is shown in Figures 4 and 5.

Figure 4 tracks the percentage of data points during each month that corresponded to certain conditions. The green line tracks the percentage of data points for which Score 30 was equal to 100, meaning that the data point was calculated entirely using real measured data. Similarly, the yellow and red lines depict the percentage of data points for which Score 20 and Score 10 were equal to 100. Finally, the black line shows the percentage of data points where greater than 70 percent was calculated based on real measured data. This figure shows that around November of 2016, the percentage of real-time measured data drops off and the percentage of data points calculated exclusively with the historical average shoots up to approximately 90 percent. Around May of 2017 they each return to normal, and the pattern appears to repeat in November 2017. Additionally, the red line shows that INRIX is almost never exclusively using the free flow speed to compute the data.

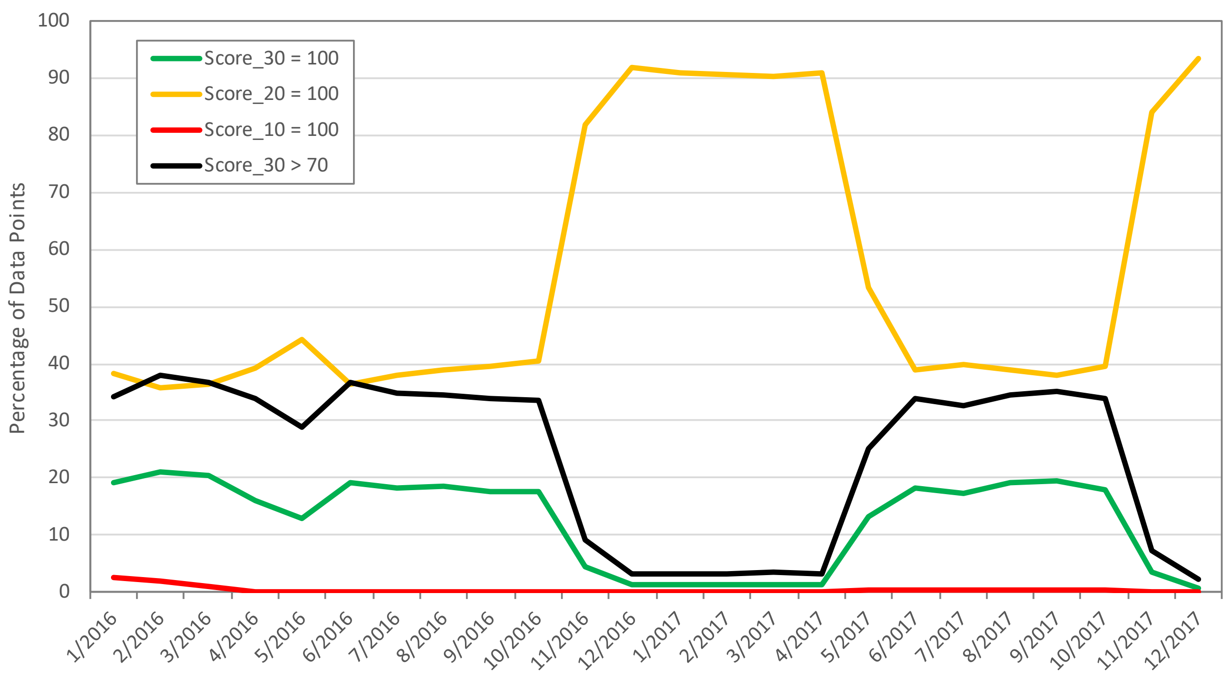


Figure 4: Percent of data points during each month for which the data scores satisfied various conditions.

Figure 5 shows the average of each of the three score components for each day over the two-year period. Notice that it depicts a similar pattern to Figure 4, with the precipitous decrease in Score 30 and increase in Score 20 from November 2016 to May 2017.

After discovering the error, a summary of this information, as well as a documented workflow for analyzing the anomaly, was presented to the CoA and INRIX. INRIX explored the issue further and determined that it stemmed from an error within the data downloader tool that was overriding the correct data when large portions of data (such as two years' worth) were downloaded at once. INRIX worked to develop and implement a solution to the bug in the downloader. Limiting the data in the initial analysis to only the month of September had the benefit of effectively avoiding any issues that might arise due to seasonal variation. This is discussed further in the "Data Aggregation" section and is something which could be explored in future work.

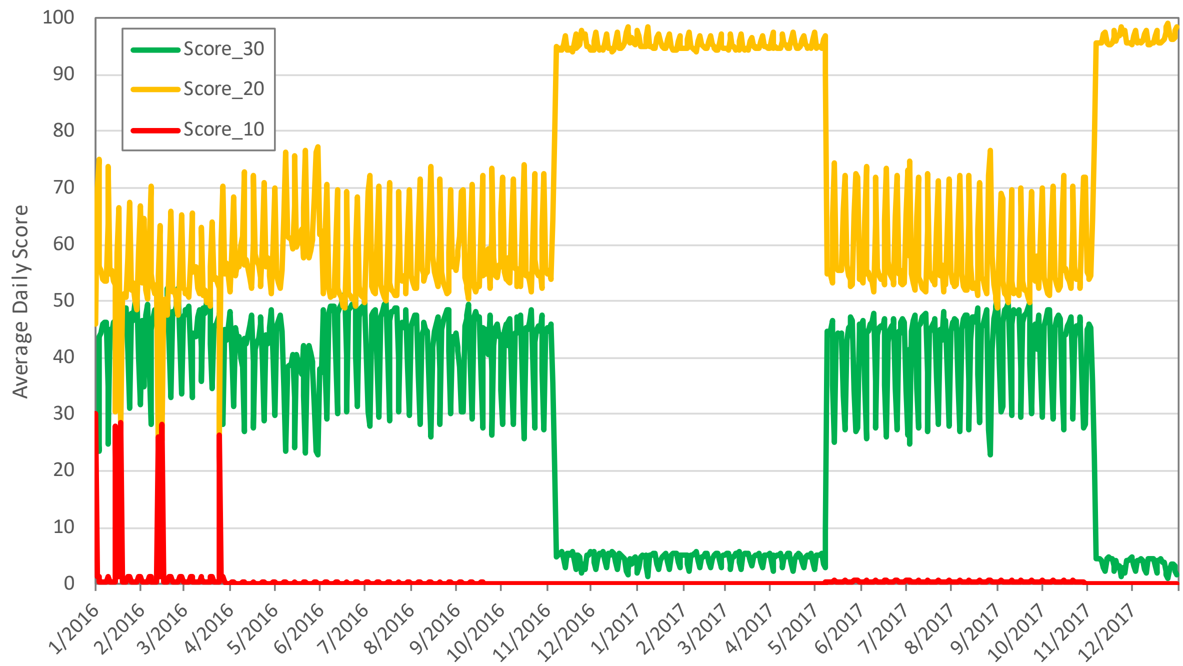


Figure 5: Daily average for each data score.

4.2 Data Acquisition Process

Once downloaded, the data for each corridor consisted of two .csv files. The first, the "data" file, contains the individual speed records for every segment on the corridor for every timestamp in the study period. The second file, the "metadata" file, is much smaller and contains information describing each segment on the corridor (segment ID, length, start and end latitude and longitude, road name, etc.). The unique segment ID for each segment relates these two files to each other.

After downloading the data files, two columns were added to the metadata file. The first, "CoA Corridor," was filled with the corridor name defined by the City of Austin. This was done because in some cases the City of Austin corridor definitions spanned multiple roads. Having one consistent name associated with each corridor was essential for later analysis. The second column was called "CoA Direction" and it performed a similar function: creating a consistent directional definition for the corridor in question. This was necessary because some corridors were not straight over their entire length, and as such INRIX may have defined some of the segments on the corridor as north-south aligned, while others might be east-west. Figure 6 below depicts an example of both phenomena for further illustration.

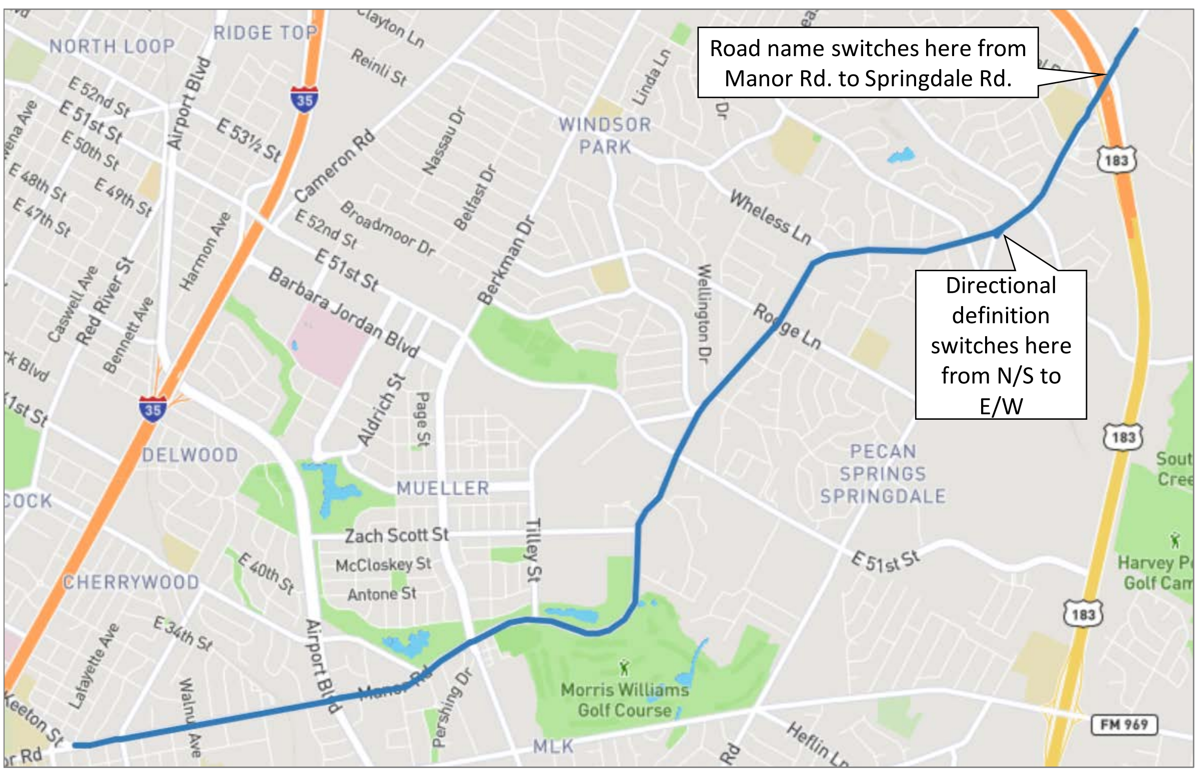


Figure 6: Manor corridor in INRIX web interface, displaying mid-corridor switches in road name and directional definition.

The data was then ingested into two separate tables in a Postgres database (one for the data files and one for the metadata files). This process was automated using a Linux script. Having the data in a database made it easier to search, aggregate, and compare across the seventy-nine study corridors.

For a full step-by-step guide to the process of defining corridors within the INRIX Analytics web interface, using the INRIX data downloader tool, and ingesting the data into the database, see Appendix B.

4.3 Data Aggregation

Data was downloaded at 15-minute granularity for each study corridor. This was done to compromise between computational speed and data granularity. Two years of data for the 79 corridors was acquired from the provider's internet-based user interface and ingested into PostgreSQL, an open-source database management system, for ease of handling. The 79 corridors were made up of 1,759 roadway segments, and all told there were 116,278,732 speed records. This study utilized the portion of the data corresponding to weekdays in September 2016 and September 2017, due to the INRIX data download error discussed in the previous chapter. This had the added benefit of avoiding any issues that might arise due to seasonal variation. Furthermore, September is a good candidate month for a case study in Austin. In addition to school being in session (grade school as well as The University of Texas), September is free from major disruptive events that occur in other "school months." These include the Austin City Limits Music Festival, the South by Southwest Conference and Festivals, and the Formula 1 US Grand Prix. It should be noted that no major filtering was performed on the data set. This is because INRIX had already performed data cleaning measures to remove outliers. The data was inspected graphically to ensure that this was the case.

A significant challenge in developing meaningful metrics arose in choosing how to aggregate the data both spatially and temporally to best communicate the need for retiming. Through exploration of the data, it was determined that computing corridor-level metrics based on averaging values across all corresponding segments could lead to problematic sections of the corridor being balanced out by other sections that were operating well. This was particularly an issue on the longer corridors, which were more likely to operate very differently along the length of the corridor. Therefore, the most effective way to communicate corridor performance given these concerns was to produce corridor-level metrics from segment-level analyses. In other words, it was desirable to avoid over-aggregating the data as much as possible, while also distilling the large amount of data down to draw clear conclusions.

In a similar way, given that most roads experience volume approaching or exceeding capacity for only a handful of hours in a day, averaging values across an entire day tended to "wash out" some of the trends. However, leaving the data in 15-minute bins would make drawing clear conclusions across a lengthy study period difficult. For this reason, the 15-minute data was rolled into three time-of-day periods: morning peak (7-9 AM), midday (11 AM-1 PM), and evening peak (4-6 PM). It was particularly important to analyze both morning and evening peaks due to the directional nature of traffic throughout the day on many urban streets.

It is entirely possible that certain performance issues may still be obscured by aggregating the 15-minute data into two-hour bins. It may be more difficult to identify trouble spots or times on corridors that display more isolated congestion or exaggerated peaking than on corridors that are consistently congested across the two-hour period. However, given the large scale of the data and the exploratory nature of this study, it was necessary to compromise somewhat on data granularity to efficiently compare many different corridors across different days and times of day. In response, it was desirable to identify a selection of metrics that would minimize this concern.

4.4 Summary of Data Acquisition and Aggregation

The process for acquiring data from the INRIX interface and ingesting it into a database was thoroughly documented for future repetition by either researchers or practitioners. This led to the discovery of an error within the INRIX data downloader. Documenting this error and presenting it to INRIX and the CoA provided an excellent opportunity for becoming more familiar with the data and the information it could communicate. This proved to be important as the study moved into more uncharted territory, and work began on developing the specific metrics which would be used to rank and compare the signal corridors.

Chapter 5: Development of Metrics for Prioritization

Given the desire to apply the ranking methodology as a tool for regular use by practicing signal timing engineers, the chief goal was to develop ranking metrics that were easy to understand and that communicated the underlying need for corridor retiming clearly and accurately. This simplicity of the ranking metrics is important due to the sheer volume of data, and because transportation engineers must be able to easily explain and defend retiming decisions to City officials, the public, and other stakeholders.

5.1 Development of Corridor Plots

A significant challenge in developing meaningful metrics arose in choosing how to aggregate the data both spatially and temporally to best communicate the need for retiming. The first step in developing these metrics was to inspect and explore the data. This was done by producing a variety of plots, examples of which are shown below. The plots were produced by accessing the database through R, an open-source software environment for statistical analysis and graphing.

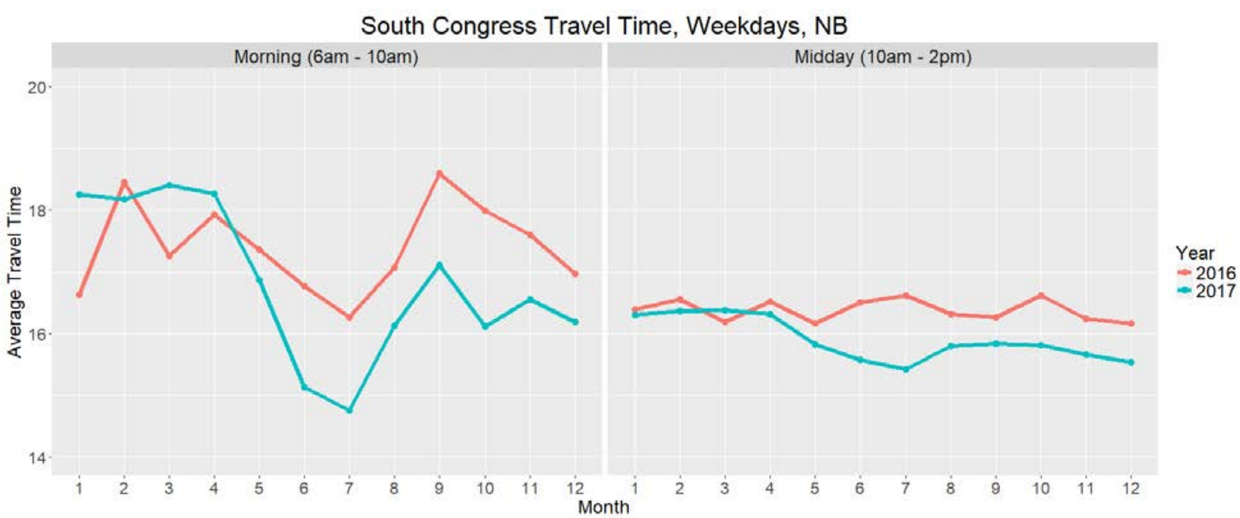


Figure 7: Travel time by month for pre-defined time periods.

The plot in Figure 7 depicts the travel time on the northbound South Congress corridor for specific time-of-day periods during each month of 2016 and 2017. Plots such as this one show variation throughout the year as well as between different times of day for the entirety of the corridor.

Similarly, the plot in Figure 8 shows the average hourly travel time for the corridor over the course of a weekday, differentiating between 2016 and 2017. This plot clearly shows the directional effects present on the corridor, with a distinct peak in the northbound direction during the morning and in the southbound direction during the evening.

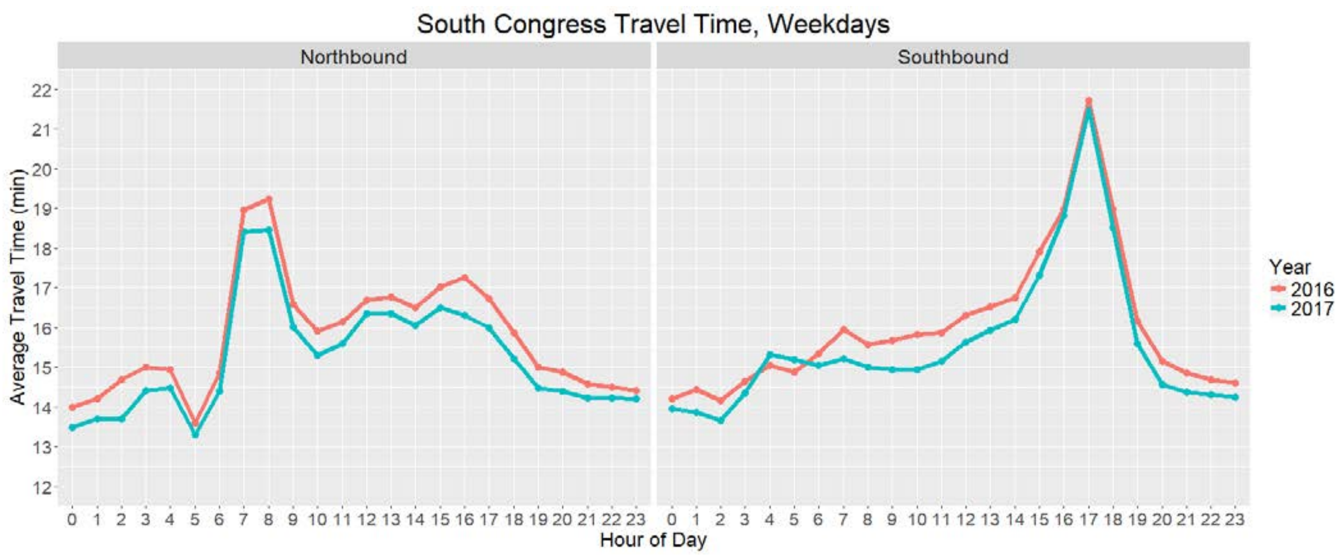


Figure 8: Travel time by time-of-day for pre-defined date ranges.

The third type of plot developed to visualize the data is shown in Figure 9. It depicts the average speed on each segment of the corridor in question, where each bar in the plot is a segment on the corridor. The varying width of the bars represents the varying length of the segments. This allows for the distinction between, for example, a speed decrease of 3 mph on a 300-foot segment and a (more notable) speed increase of 2 mph on a half-mile segment.

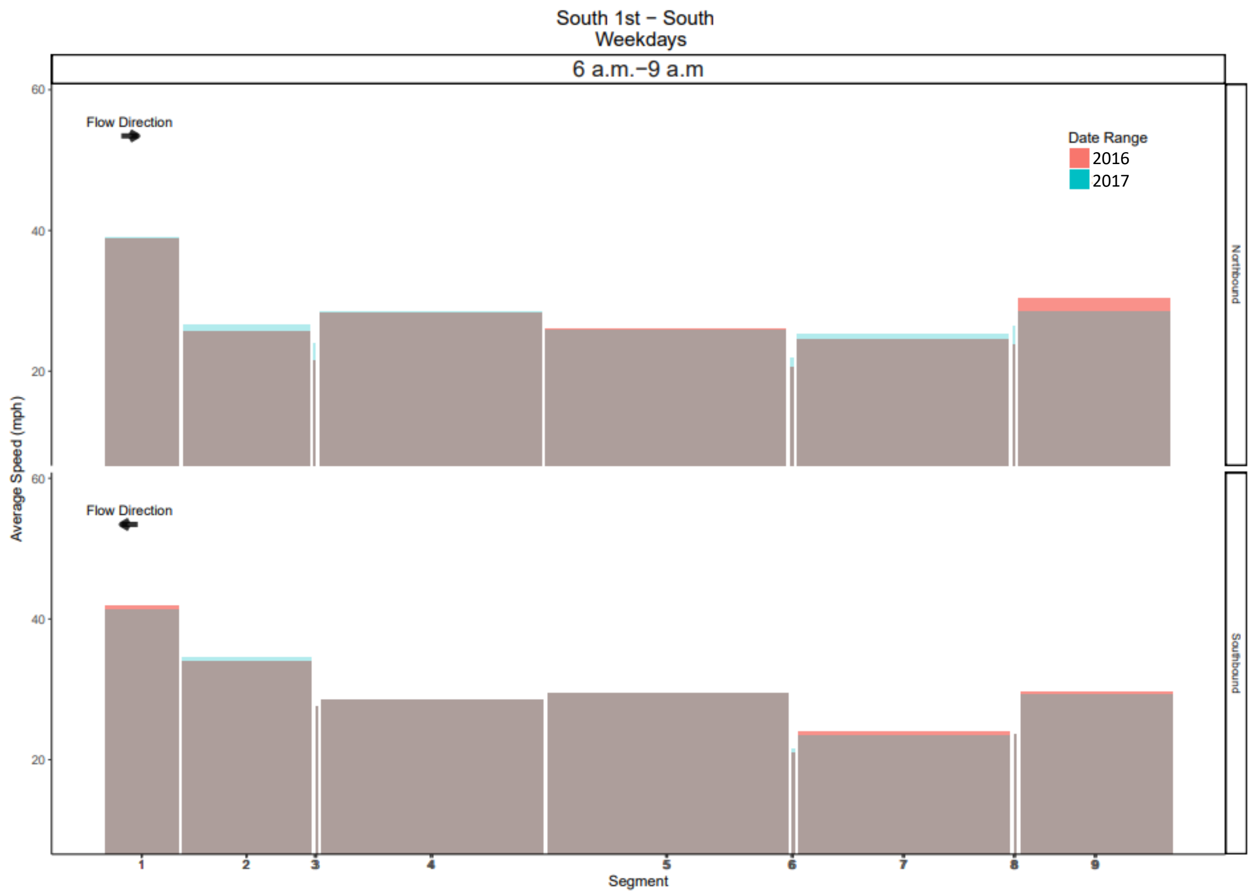


Figure 9: Segment speed plot for South 1st – South corridor.

Various iterations of these plots were presented to CoA traffic signal timing engineers and other personnel, to gather feedback on which visualizations were the most helpful in assessing the condition of a corridor. This significantly informed the process for developing ranking metrics.

5.2 Development of Metrics and Metric Calculations

Developing appropriate metrics involved many iterations of calculations, and a few challenges were noted. One problem was that travel time is not effective in comparing corridors of different lengths. Focusing on segment speed, as opposed to travel time, as the basis of the metrics allowed for comparison between corridors of differing lengths. Another issue was that absolute speed, particularly without any vehicle volume information, is not effective for comparing corridors with different functional classifications or speed limits. To compare roads with different speed limits or functional classifications, the methodology was built around calculating speed change on a corridor between two comparison periods. These comparison periods could represent weeks, months, or years that would be compared to assess whether corridor performance had improved or worsened between the periods. In this study, September 2016 and September 2017 were used as the two comparison periods. A third challenge was in capturing the under-performance of one section of a corridor when another section (or even most of the rest of the corridor) was performing well. To account for this, the metrics focus on the portions of the corridor that have experienced a decrease in speed between the two comparison periods.

When comparing sample means, it is always desirable to use a statistical test to ensure that the difference in the means is significant. This was considered during the earlier stage of data exploration and the development of the metrics. The proprietary cleaning techniques used by INRIX tended to mask much of the variation, resulting in very smooth data but relatively small changes when aggregating over a large period of time, such as a month. Further exploration of the significance of differences between comparison periods is a chief priority for future refinement and development of the ranking methodology.

The three metrics used in the final ranking process are: percent of the corridor (by length) that experienced a decrease in speed between comparison periods; percent of the corridor that experienced a decrease in speed of three miles per hour or greater between comparison periods; and, the maximum speed decrease for any one segment on the corridor. The three mile-per-hour threshold for speed reduction was chosen after testing several values. It is important to note that this methodology is designed to analyze changes in performance over time as the major indicator of the need to retime a corridor. Further extensions to this work could consider the ideal threshold for minimum desirable speed or maximum allowable speed decrease. The third metric, maximum speed decrease for any one segment on the corridor, was designed to identify corridors with isolated spots or times of poor performance.

Each record in the data set is represented by $s_{i,t,d}$, where s is the segment speed for segment i during 15-minute interval t on day d. The average segment speed for a given time-of-day period T (morning peak, midday, or evening peak) on day d is therefore calculated by taking the average of the speed records for all 15-minute intervals in that time-of-day period (Equation 1). Since all of the time-of-day periods for this study were two hours long, the number of 15-minute intervals per time period, $|T|$, is 8.

$$a_{i,T,d} = \frac{\sum_{t \in T} s_{i,t,d}}{|T|} \tag{1}$$

The average segment speed for each of the comparison periods for time-of-day period T is given by Equation 2, where $|P|$ is the number of days in comparison period P.

$$A_{i,T,P} = \frac{\sum_{d \in P} a_{i,T,d}}{|P|} \tag{2}$$

Finally, the speed difference on segment i during time-of-day period T between comparison periods P_1 and P_2 can be computed using Equation 3.

$$D_{i,T} = A_{i,T,P_2} - A_{i,T,P_1} \tag{3}$$

This segment speed difference then forms the basis for the metrics used to rank corridors j. The first of these is the length of the corridor, in miles, that has experienced a decrease in speed between the comparison periods, and is computed according to Equation 4.

$$l_{j,T,0} = \sum_{i \in j} l_i \left[D_{i,T} < 0\right] \tag{4}$$

The condition $D_{i,T}$ less than zero represents a decrease in speed for time-of-day period T. This is used to compute the percent of the corridor which has experienced a speed decrease, $K_{j,T,0}$, shown in Equation 5. In this equation, L_j represents the total length of corridor j.

$$K_{j,T,0} = \frac{l_{j,T,0}}{L_j} \tag{5}$$

It follows then that a similar metric could be computed for a certain threshold speed decrease, by calculating the mileage along the corridor that experienced a speed decrease greater than m miles per hour:

$$l_{j,T,m} = \sum_{i \, \epsilon \, j} l_i \left[D_{i,T} < -m\right] \tag{6}$$

$$K_{j,T,m} = \frac{l_{j,T,m}}{L_j} \tag{7}$$

The third and final metric used for ranking is the largest speed decrease among all segments on the corridor, given by Equation 8. It should be noted that this metric seeks to identify the largest negative speed change, which is why it is computed using a minimum. If every segment on a corridor experienced an increase in speed between comparison periods, then this metric would result in a positive number for that corridor.

$$M_{j,T} = \min_{\mathrm{i} \, \epsilon \, \mathrm{j}} D_{i,T} \tag{8}$$

5.3 Summary of Metric Development

The probe vehicle data was plotted in a variety of ways to visualize the data and begin developing metrics. Throughout this process, feedback was gathered from signal timing engineers at the CoA. This feedback was used to develop the three metrics for use in the ranking methodology. Once these metrics had been developed, the chief remaining step was to develop a method for producing a composite rank, and then implement the full methodology by calculating the results of the metrics for all 79 Austin corridors.

Chapter 6: Implementation, Results, and Validation

6.1 RANKING OF CORRIDORS

The final prioritization of corridors combines the three metrics (percent of corridor experiencing speed decrease $K_{j,T,0}$, percent of corridor experiencing speed decrease greater than m miles per hour $K_{j,T,m}$, and maximum segment speed decrease $M_{j,T}$) for each of the three time-of-day periods, and ranks the result.

Figure 10 summarizes the ranking process. All corridors were ranked by each of the three metrics for each of the three time-of-day periods to determine each corridor's worst-performing direction. The practice of ranking corridors based on their worst-performing direction assumes that an agency would retime both directions of a corridor simultaneously. The final ranking for a corridor is then computed by taking the average of that corridor's place (accounting for ties) in each of the preliminary rankings.

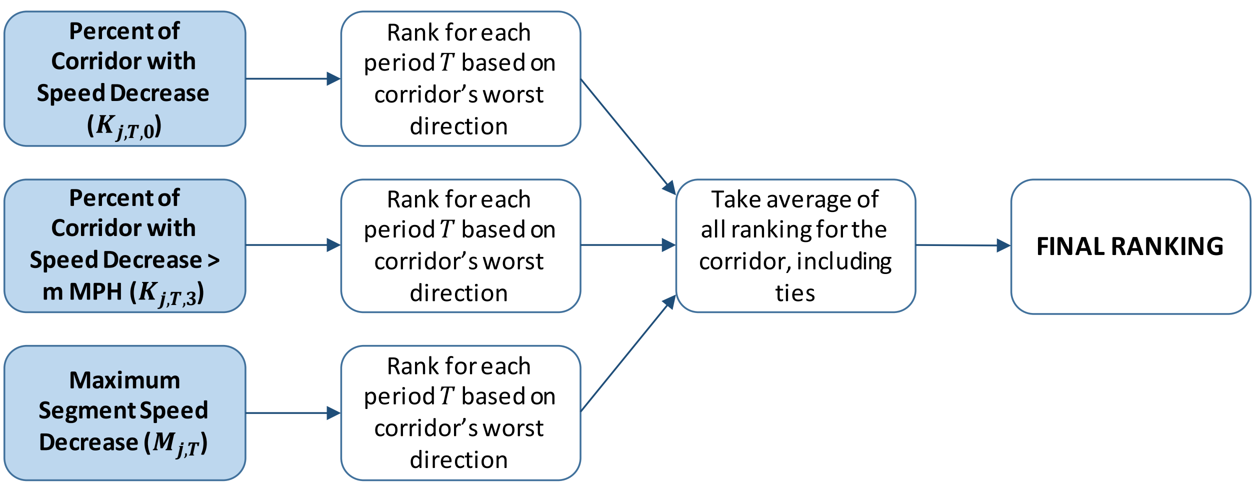


Figure 10: Corridor ranking process.

6.2 RESULTS

Table 3 presents an excerpt of the ranking and results of the different metrics. The average rank for each corridor is shown in addition to the final rank, to illustrate the process of averaging each individual metric ranking for each time-of-day period T. The top 22 corridors are shown because they account for 373 signals, and the CoA aims to retime approximately 375 signals per year. Note that the average of the three metrics for the three time-of-day periods can result in ties between multiple corridors. Here, the 10^{th} rank and 12^{th} rank both show that two corridors tied for these spots.

There are a few results to note from the corridor ranking. Most significantly is the ranking of three major frontage road systems in the first three places (US 290 – East, US 183 – Central, and US 183 – South). Signalized frontage roads along limited-access facilities are a common feature in Austin, and throughout Texas. Examining the results for these frontage roads reveals that each corridor exhibited a relatively high percentage of speed decrease and high maximum speed decrease values. However, significant roadway construction projects were ongoing throughout the latter half of 2017 on all three corridors, which certainly affected their performance. It is therefore important to note that knowledge of the local roadway network, ongoing and planned construction, special events, and other factors impacting traffic flow should be considered outside of the ranking methodology presented here.

Note that a full version of Table 3, showing the ranking results for all 79 corridors, can be found in Table 5 in Appendix C.

Table 3: Excerpt of Corridor Ranking Results

Rank	Avg. Rank	Corridor	Percent of Corridor Experiencing Speed Decrease			Percent of corridor Experiencing Speed Decrease > 3 MPH			Maximum Speed Decrease			Total Length (mi)	Number of Signals
			AM	Midday	PM	AM	Midday	PM	AM	Midday	PM		
1	6.1	US 290 - East	95.93	85.36	96.85	21.30	22.48	25.62	-28.38	-27.31	-28.25	5.30	19
2	6.9	US 183 - Central	86.29	100.00	86.14	48.51	48.51	30.02	-19.61	-16.75	-5.17	2.79	10
3	12.1	US 183 - South	48.37	65.58	65.08	47.65	35.90	48.68	-11.35	-10.52	-11.23	3.08	15
4	14.3	51st	70.75	69.59	94.57	24.87	24.87	24.87	-3.82	-3.78	-5.79	3.26	12
5	15.0	Airport	63.07	74.65	80.88	14.66	16.87	21.64	-3.82	-5.59	-7.30	6.41	27
6	15.1	MLK - East	60.12	85.10	89.35	19.54	18.03	13.38	-3.55	-7.59	-6.04	5.42	15
7	17.3	Lamar - North	75.65	100.00	86.24	7.93	7.93	7.93	-3.69	-3.69	-5.45	5.88	15
8	17.7	Enfield	56.49	76.61	100.00	8.28	8.53	21.47	-3.21	-6.02	-4.09	1.30	9
9	20.0	Ben White - East	91.28	52.06	52.72	37.55	0.19	28.08	-5.43	-3.17	-9.35	3.61	14
10	20.1	Manor	79.88	57.12	67.69	3.55	3.55	3.55	-4.96	-6.03	-6.47	3.83	15
10	20.1	Pleasant Valley	80.22	80.22	99.05	0.00	1.67	42.95	-2.16	-3.33	-8.38	2.93	11
12	20.4	IH 35 SRVC RDS	46.65	33.61	67.96	16.66	13.12	55.77	-6.09	-5.23	-6.40	2.27	16
12	20.4	Southwest Parkway	46.57	48.05	71.24	21.57	9.33	21.57	-5.99	-3.34	-6.96	5.16	18
14	20.7	Parmer - West	44.31	52.13	74.05	11.13	5.26	14.86	-10.02	-4.44	-8.85	13.99	29
15	21.8	Loop 360 - North	26.26	54.34	49.05	3.60	19.46	31.89	-8.31	-8.12	-13.48	8.17	14
16	22.4	Brodie	100.00	78.71	70.96	0.17	0.00	8.28	-4.09	-2.65	-4.37	6.55	19
17	23.3	Slaughter	49.52	38.84	67.71	17.30	16.34	20.29	-5.20	-3.50	-5.37	9.75	31
18	24.2	7th - East	66.31	57.41	89.97	0.96	0.96	20.79	-3.28	-3.38	-3.90	2.38	12
19	25.2	Riverside	63.00	67.76	83.07	0.77	0.00	13.76	-3.35	-2.91	-5.37	3.79	24
20	25.7	Braker	59.18	89.63	63.70	0.36	2.25	0.00	-4.03	-7.14	-2.48	5.56	19
21	26.1	Lamar - Central	90.14	62.31	63.44	0.00	10.88	0.95	-2.51	-5.19	-3.35	3.78	15
22	28.4	Cameron - South	61.16	46.32	59.75	6.67	5.84	0.00	-3.98	-4.57	-2.72	2.10	14

One concern was that the ranking methodology might unnecessarily favor corridors based on length. This trend does appear, but there is significant unexplained variability, leading to a low R^2 value that is not statistically significant, shown in Figure 11. Additionally, results show that the methodology slightly favored corridors with lower traffic signal density, as seen in Figure 12. This is unsurprising, as corridors with lower signal density are often more difficult to coordinate. However, although there is once again a linear pattern, the unexplained variability is significant and the R^2 for the linear relationship is not statistically significant.

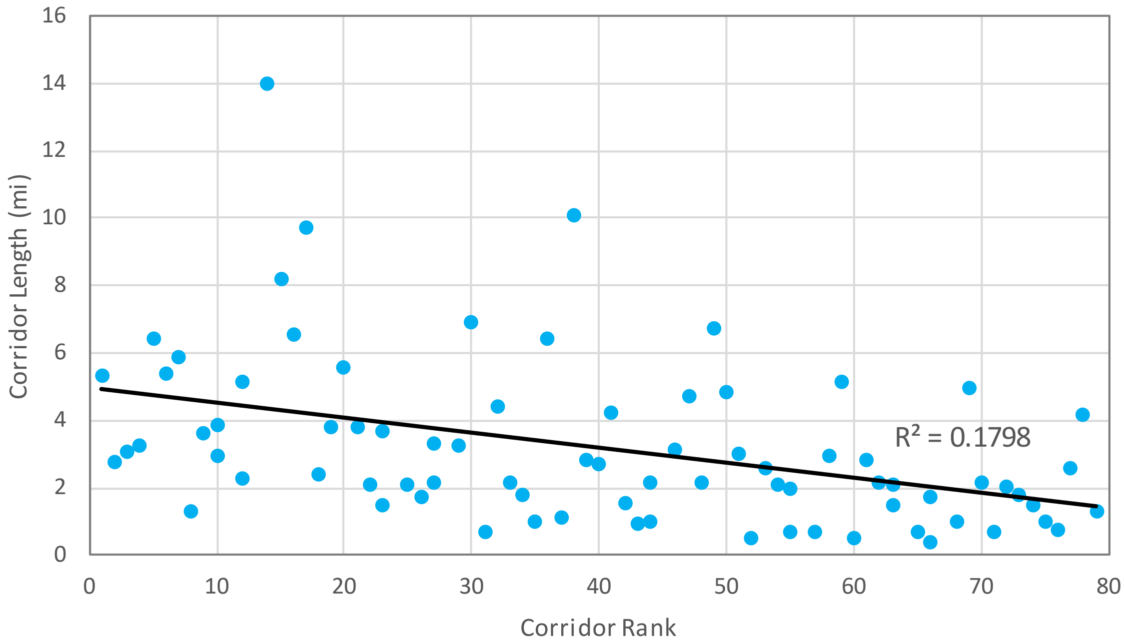


Figure 11: Corridor rank vs. corridor length.

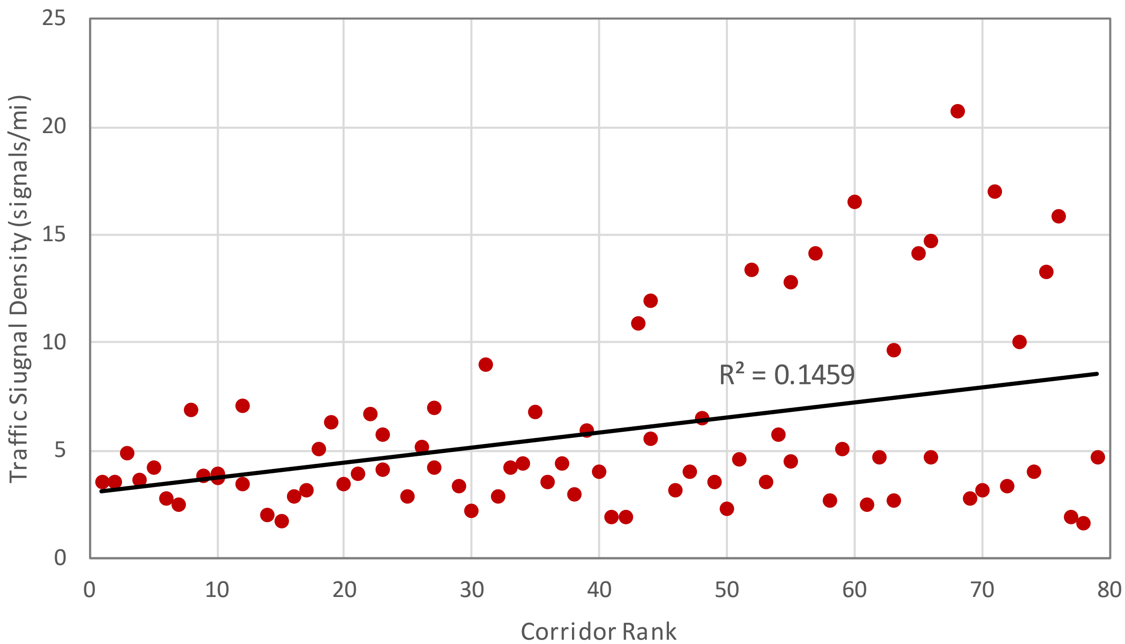


Figure 12: Corridor rank vs. traffic signal density.

It appears at first glance that the data presented in Figures 11 and 12 may be better communicated using models other than the linear ones shown here. However, due to the concentration of data points in a linear fashion along the bottom of both plots, an exponential model presented a lower R^2 value than the linear model. Alternately, a logarithmic model presented signs of overfitting the data.

Additionally, Figures 11 and 12 seem to indicate that there may be heteroscedasticity on non-constant variance present in these relationships. This means that the variance of one variable is non-constant across the range of values of the variable that predicts it. One of the assumptions of least squares regression is that this variance is constant. One of the major techniques for dealing with heteroscedasticity involves using logarithmic transformation, but this complicates the interpretation of the least squares regression equations. The relationships between these variables presents a significant area for further study.

The distributions of the proposed ranking metrics, shown in Figure 13 provide additional insight into the meaning of the observed results and the operation of the ranking methodology. The metric for percent of the corridor experiencing a speed decrease shows a distribution that appears normal (Figure 13a, b, and c). However, the distribution for the percent of the corridor that experienced a speed decrease greater than 3 MPH is skewed significantly to the left. This is due to the introduction of the 3 MPH threshold, which allows for the clear identification of problematic corridors (shown by the points farthest to the right in the distribution in Figure 13d, e, and f). Finally, the distribution for maximum segment speed decrease shows a narrow pattern with most corridors experiencing a maximum speed change between -5 and zero MPH (Figure 13g, h, and i). However, there are a few corridors that are far to the left on the distribution, indicating a large speed decrease. The differing distribution of the metrics allows the ranking methodology to evenly assess the corridors and to easily identify particularly problematic cases.

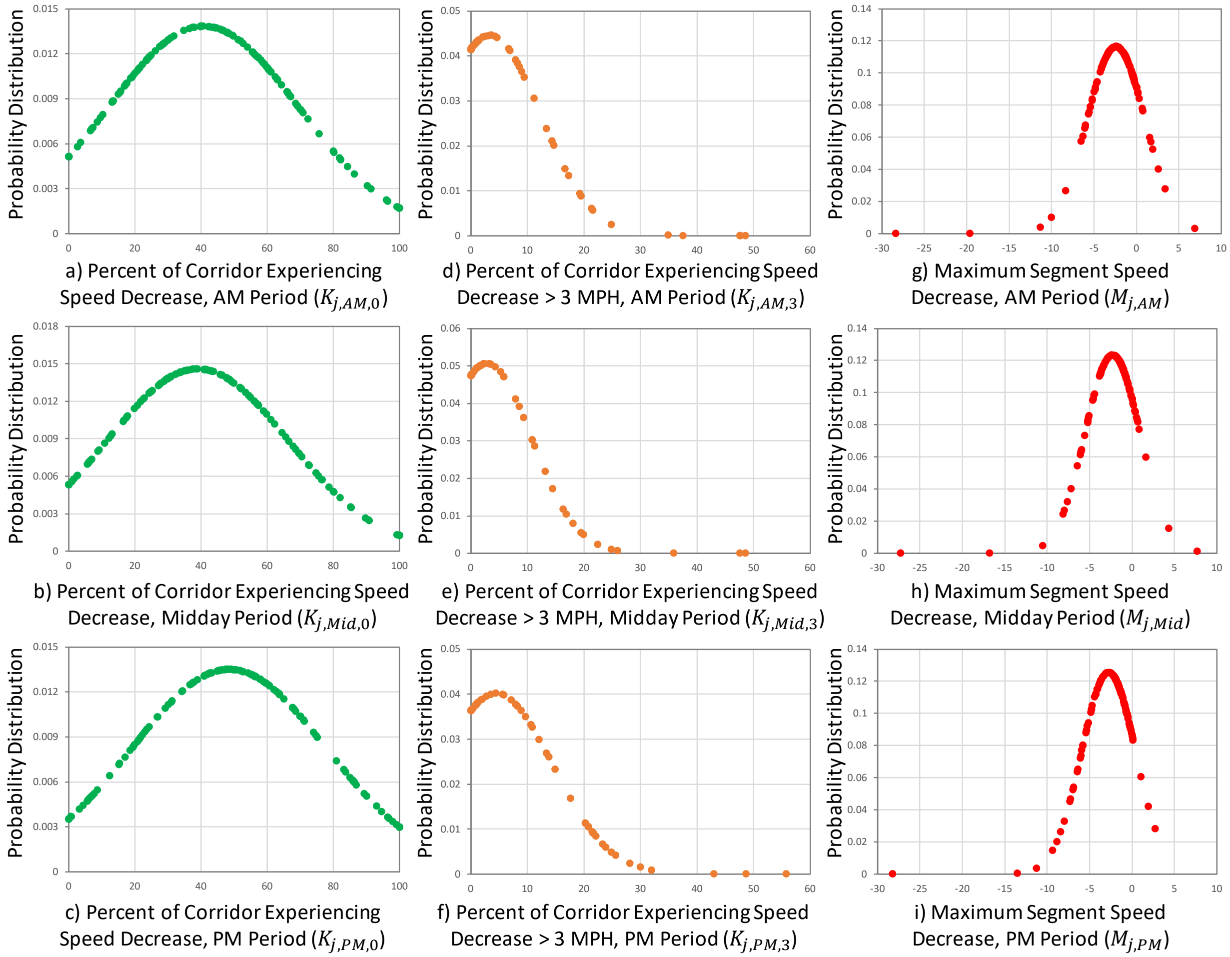


Figure 13: Distributions of metrics used for ranking.

6.3 Validation of Ranking

Of the 27 corridors selected by the CoA for retiming in the 2017-2018 fiscal year (the schedule set), only seven appeared in the corridors selected by the ranking methodology (the ranking set). Of the 20 that did not, 16 were in the lowest-ranked third of the corridors, meaning they were not ideal candidates for retiming in the near future. Despite this fact, assigning a quantitative value to the result of this ranking methodology is difficult, as it involves a "what if" scenario: What if the CoA had retimed the corridors selected by the ranking methodology instead of the ones they retimed based on their schedule? It is, however, possible to assess the potential for improvement of both sets of corridors. By assuming that retiming a corridor would result in improving the travel time along that corridor at least to what it had been in the previous comparison period, a measure of corridor travel time improvement potential $I_{j,T}$ can be computed using Equation 9.

$$I_{j,T} = \sum_{i \in j} [C_{i,T,P_2} - C_{i,T,P_1}) > 0 \quad (9)$$

In this equation, $C_{i,T,P}$ represents the average segment travel time for the corresponding time-of-day period and comparison period, computed as a ratio of the average speed $A_{i,T,P}$ and the segment length l_i.

$$C_{i,T,P} = \frac{l_i}{A_{i,T,P}} \quad (10)$$

The travel time difference only contributes to the metric when a segment's travel time has increased between the comparison periods, so that $I_{j,T}$ represents the potential travel time improvement contained within the corridor. To reiterate, the comparison periods can represent days, weeks, or months between which the methodology will compare changes in corridor performance. This travel time improvement potential can be calculated for each of the three time-of-day periods established in the methodology and for both directions on each corridor.

It follows then, that improvement potential can be compared between the set of corridors chosen by the ranking methodology (the ranking set) and the set chosen for retiming by the CoA (the schedule set). The results in Table 4 clearly show that retiming the roads selected by the ranking methodology would address a larger performance deficit and thus present a greater potential for improvement.

Table 4: Ranking Validation Results

Ranking Set				Schedule Set			
	Travel Time Improvement Potential (minutes)				Travel Time Improvement Potential (minutes)		
Corridor	AM	Midday	PM	Corridor	AM	Midday	PM
US 290 - East	1.39	0.42	0.80	US 290 - East	1.39	0.42	0.80
US 183 - Central	0.60	0.70	1.87	Lamar - North	2.94	1.48	3.76
US 183 - South	0.70	0.26	0.82	Manor	1.16	0.39	2.01
51st	1.02	0.89	1.03	Southwest Parkway	1.21	0.65	1.30
Airport	3.92	2.26	7.51	7th - East	0.36	0.68	1.13
MLK - East	4.29	0.35	3.30	Riverside	2.46	1.95	3.97
Lamar - North	2.94	1.48	3.76	Cameron - South	1.88	0.70	2.21
Enfield	0.73	0.26	1.63	Oltorf	2.26	1.06	3.02
Ben White - East	1.52	0.89	1.48	St Johns	0.91	0.06	0.12
Manor	1.16	0.39	2.01	RM 620	3.07	1.81	5.85
Pleasant Valley	0.93	0.88	4.19	Far West	0.47	0.34	0.51
IH 35 SRVC RDS	1.11	1.36	8.73	12th - West	0.36	0.39	0.30
Southwest Parkway	1.21	0.65	1.30	Exposition	1.64	0.21	2.09
Parmer - West	7.71	1.86	8.26	Woodward	0.77	0.25	0.44
Loop 360 - North	8.75	2.13	14.73	8th	0.16	0.38	0.46
Brodie	4.26	0.98	4.15	Stassney - West	1.81	0.77	2.33
Slaughter	5.18	2.33	7.49	San Jacinto	0.15	0.28	0.11
7th - East	0.36	0.68	1.13	RM 2222 - Central	1.34	0.48	1.21
Riverside	2.46	1.95	3.97	Anderson	0.89	1.56	1.68
Braker	3.52	2.56	5.75	6th	0.26	0.58	0.94
Lamar - Central	3.01	1.60	5.56	11th	0.28	0.27	1.21
Cameron - South	1.88	0.70	2.21	Trinity	0.08	0.25	0.32
				Congress - North	0.45	0.52	1.61
				7th - West	0.34	0.31	0.66
				5th	0.67	0.58	0.88
				Lavaca	0.08	0.21	0.42
				Guadalupe - South	0.28	0.08	1.58
Sum	58.68	25.59	91.70	Sum	27.68	16.67	40.91

The AM and PM periods show a significant difference in total travel time improvement potential between the ranking set and the schedule set. As expected, the midday period shows a more tempered improvement. This amounts to an average increase in travel time improvement potential of 96% across the three time-of-day periods. Note that the difference in size between the ranking set and the schedule set is due to the number of traffic signals each contains. As stated above, the CoA aims to retime around 375 signals each year, and the ranking set was chosen to fit that constraint. Additionally, the corridors in each set are ordered according to their placement using the ranking methodology.

This validation method represents an initial exploration into quantifying the benefit of prioritizing traffic signal retiming operations. There are still many factors involved here that are not fully understood, or not quantifiable given the data at hand. Future work may explore more comprehensive techniques for assessing the full impact of a ranking methodology such as this on the operational effectiveness of the agency.

6.4 Summary of Implementation, Results, and Validation

After developing the methodology for aggregating the chosen metrics, the calculations were performed on the data for all 79 Austin corridors. This resulted in a prioritization of the corridors for signal retiming. Additionally, an initial attempt was made to quantitatively validate the effectiveness of the ranking methodology. This technique showed that the methodology provided a significant benefit over using a schedule-based approach, though this presents a significant area for future work.

Chapter 7: Retiming Prioritization Tool

The final step in the process of developing the initial ranking methodology was to develop a tool that would package the methodology in a way that would be straightforward to implement in CoA workflows. This tool would present the ranking of the corridors, and other relevant information, as a supplement to the existing process for setting the signal retiming schedule.

7.1 Development of Initial Tool

The tool was developed using Shiny, a package in R used to build web applications. Shiny was chosen because it is a simple, straightforward method for building applications and then hosting them on the web. Additionally, since exploratory plotting of the INRIX probe vehicle data was performed in R, using Shiny would allow for easy incorporation of these plots into the tool's interface. Shiny also offers the opportunity to extend the app with various other web development tools like CSS, HTML, and JavaScript. This allows for expansion of the tool as future work improves upon this initial analysis.

The vision for the tool was to present the results of the ranking methodology in a table, and then provide supplementary information in the form of plots for each corridor. As shown in Figure 14, the interface prominently displays these two pieces. The table at the top, containing the ranking of all 79 corridors and the results of each metric, can be adjusted to show more than the default 10 rows of results and sorted based on any of the columns. It can also be searched using the dialogue box at the top right of the page.

The Segment Speed Plot section below the table contains a drop-down selector which can be used to pull up the segment speed plot (shown in more depth in Figure 9) for any corridor. This allows CoA traffic engineers to further explore the results of the ranking and the performance of the corridors.

The code for this initial version of the tool can be found in Appendix D.

rank	corridor	perdecr_am	perdecr_mid	perdecr_pm	perdecr3_am	perdecr3_mid	perdecr3_pm	maxdecr_am	maxdecr_mid	maxdecr_pm	length	num_signals
1	US 290 - East	95.93	85.38	96.85	21.3	22.48	25.62	-28.38	-27.31	-28.25	5.3	19
2	US 183 - Central	86.29	100	86.14	48.51	48.51	30.02	-19.61	-16.75	-5.17	2.79	10
3	US 183 - South	48.37	65.58	65.08	47.65	35.9	48.68	-11.35	-10.52	-11.23	3.08	15
4	51st	70.75	69.59	94.57	24.87	24.87	24.87	-3.82	-3.78	-5.79	3.26	12
5	Airport	63.07	74.65	80.88	14.66	16.87	21.64	-3.82	-5.59	-7.3	6.41	27
6	MLK - East	60.12	85.1	89.35	19.54	18.03	13.38	-3.55	-7.59	-6.04	5.42	15
7	Lamar - North	75.65	100	86.24	7.93	7.93	7.93	-3.69	-3.69	-5.45	5.88	15
8	Enfield	56.49	76.61	100	8.28	8.53	21.47	-3.21	-6.02	-4.09	1.3	9
9	Ben White - East	91.28	52.06	52.72	37.55	0.19	28.08	-5.43	-3.17	-9.35	3.61	14
10	Manor	79.88	57.12	67.69	3.55	3.55	3.55	-4.96	-6.03	-6.47	3.83	15

Figure 14: Web-based corridor ranking tool interface.

7.2 ONGOING WORK ON TOOL

This tool was presented to CoA representatives, including signal timing engineers and management. They were impressed with the simplicity and usability of the tool and were hopeful that it would integrate with their processes for corridor analysis. They provided some feedback which will be used to direct ongoing work over the coming months to add new features to the tool as the ranking methodology is improved and adjusted.

The main area of improvement for the tool is to make it more flexible. This would include allowing the user to adjust variables that affect the calculation of the ranking, and providing built-in weighting factors that the user can vary for each metric. Some changes will be made to the segment speed plot, including adjusting the layout of the plot to provide easier comparison between different time-of-day periods. Additionally, street or intersection names will be added to the plot to assist the engineers in identifying key points along the corridor. Ideally, the hourly travel time plot (shown in Figure 8), will also be added. The segment speed plot gives the user valuable information about the spatial distribution of corridor performance, and the addition of the hourly travel time plot will provide temporal information as well. Together, the two plots can tell a significant portion of the “story” of how the corridor is performing. Additional features to increase flexibility can be added by allowing the user to adjust the time-of-day periods and comparison periods used to generate the plots.

7.3 Summary of Tool Development Section

A web-based application was developed to house the results of the ranking methodology and allow signal timing engineers to view and explore them. This will make it easier for the ranking methodology to be incorporated into the process for prioritizing traffic signal retiming operations. The initial incarnation of this tool was presented to CoA engineers and management, who responded favorably and provided feedback. Ongoing work will incorporate this feedback as well as future improvements to the methodology.

Chapter 8: Conclusions for Part 1

This study explored a technique for utilizing probe vehicle speed data to rank the performance of traffic signal corridors for prioritizing signal retiming operations. A methodology for computing metrics and developing a corridor ranking system was presented, and an analysis was conducted on 79 traffic signal corridors in the City of Austin, Texas, utilizing 15-minute average speed data acquired from INRIX, a probe vehicle data vendor. The data corresponded to roadway segments ranging in length from ten yards to one mile, and the 79 corridors ranged in length from 0.4 miles to 14 miles.

Metrics were computed using data at the segment level for three time-of-day periods to address daily variation in traffic patterns and to avoid over-aggregating the data. The data used to compute the metrics was drawn from all weekdays in September 2016 and September 2017, and the two months were compared to generate three metrics based on speed change: percent of the corridor that exhibited a decrease in speed between the comparison periods; percent of the corridor that exhibited a decrease in speed greater than three miles per hour between the comparison periods; and the maximum decrease in speed for any segment on the corridor. These metrics were chosen for their ability to compare across corridors of differing length and functional classification.

Results showed that the ranking methodology did not significantly favor corridors based on length or traffic signal density, indicating that the metrics equitably assessed corridor performance regardless of such factors, which varied widely across the corridors utilized in the study. Additionally, the corridors prioritized by the ranking methodology presented a significantly higher potential for travel time improvement than did those chosen in the schedule-based system.

Finally, a tool was developed to provide easy access to the results of the ranking methodology, and to allow it to be used as a supplement to the CoA's signal retiming prioritization decision-making process. The tool presented here serves as an initial version which will be updated as more feedback is collected from the CoA and further improvements are made to the ranking methodology.

There are numerous opportunities to extend this work in the future. The probe vehicle data utilized in this study did not include any measure of traffic volume or vehicle throughput, both of which are key components of roadway performance. At the time of the study, the CoA did not have access to comprehensive vehicle volume data across all study corridors. Simply reviewing travel speeds (or travel times) cannot fully depict how effectively a corridor is operating. For instance, the travel time on a cross-street might suffer if the signal is timed to favor a heavier vehicle volume on the mainline. In this case, even though vehicles on the side-street are accruing delay while waiting at a red light, this is outweighed by the higher volume passing through the intersection on the mainline. Ideally, future work would make it possible to include a measure of demand or vehicle volume as well as travel time.

As addressed in the discussion of data aggregation, future work might explore methods for examining the data on a more granular scale as opposed to rolling the 15-minute data into two-hour time-of-day periods. Further statistical analysis should be performed to explore the relationship between the results of the ranking methodology and key characteristics of the corridors, such as length or traffic signal density. Additionally, the methodology could be made more robust by introducing a technique for assessing the significance of speed changes between the chosen comparison periods.

Another significant realm of future study lies in validating the results of the methodology, particularly in quantifying the benefit of retiming one group of corridors over another. The method presented here serves as an initial exploration but should not be considered authoritative. Having access to vehicle volume data would assist here as well, allowing for computation of volume-weighted travel time or delay savings, and other such metrics.

This study utilized probe vehicle data due to its superb coverage over a wide area. However, future work might explore different or supplementary data sources which account for traffic volumes to more fully describe the operation of the signal corridors. Similarly, these and other metrics could be computed from different data sources, such as high-resolution detector data, to gain a different perspective on various aspects of signal and corridor performance. Alternately, measures of travel time reliability or variability could be developed and explored to augment the travel time and speed measures used here. Another factor that could affect corridor performance is seasonal variation, which was not addressed here but should be studied further.

Additionally, this study was limited to assessing signal performance from a corridor-based perspective. Organizing signals into length-wise corridors is effective for limited-access or isolated roads, or arterials that clearly take precedence over the surrounding local streets. However, this doesn't translate cleanly to all signalized roadways within a city. There are often roads, such as in downtown grids, which operate more as elements in a network area than as separate corridors. Devising area-wide metrics could increase understanding of the performance of such signals.

A data-driven, needs-based methodology for prioritizing traffic signal retiming, such as the one presented here, represents an improvement from the schedule-based system that many transportation agencies use to organize retiming operations. Implementing a process that utilizes this corridor ranking methodology such as this one would increase an agency's ability to provide the best possible transportation services to the public, by directing attention to signal corridors most in need of retiming. This then allows an agency to allocate resources in the most efficient way possible.

PART 2: CONSIDERATION OF ADAPTIVE SIGNAL CONTROL

Chapter 9: Review of Literature for Adaptive Signal Control

The final phase of this work involved conducting a review of literature to understand existing practices related to adaptive signal control, including corresponding data, software, and infrastructure needs. The CoA has been exploring the implementation of adaptive signal control to aid the performance of certain corridors, and hopes to develop a technique for identifying these candidate corridors using data. The relationship between signal retiming operations and the implementation of adaptive signal control will be considered as a possible extension of this project.

Adaptive signal control (ASC), also known as adaptive traffic control, is a technique that uses hardware and software technologies to manage traffic demand by adjusting signal timings to optimize traffic flow (Curtis, 2016). It does this by collecting current demand data, using this data to assess system performance, and then implementing modified signal timings based on the evaluation. When implemented effectively, ASC can significantly reduce delay and improve travel time and travel time reliability. The traditional method for handling variation in traffic demand across a day is to develop time-of-day plans for the signal timings during each segment of the day. This can be an effective strategy, particularly where demand is consistent day-to-day. However, ASC has a major benefit over time-of-day plans when demand varies from day-to-day. Similarly, ASC offers a significant advantage given its ability to react to traffic collisions, special events, construction, and other unexpected sources of variation. Studies have shown that ASC improves travel time, delay, and other metrics by 10 percent or more. This improvement can increase to over 50 percent in areas with particularly poor conditions (Curtis, 2016).

ASC systems have been in use abroad for thirty years, and in the US for about the last twenty years. However, they have only been installed on fewer than 1 percent of US traffic signals. Some of the barriers to widespread deployment of these technologies include the cost of the systems, their complexity, uncertainty about the benefits of ASC, and overhead costs associated with improving detection and communications (Curtis, 2016). However, it is believed that ASC can be used very effectively on corridors or closed networks that experience variability in demand, or where demand regularly exceeds capacity.

9.1 SOFTWARE NEEDS FOR ADAPTIVE SIGNAL CONTROL

The substance of any ASC system is its software. There are several different software products designed to perform adaptive signal control, and each goes about it in a different way. The purpose of this literature review is not to detail every ASC software product, but instead to give an overview of some of the available options.

While all ASC software products are essentially performing the same tasks, they do so using a wide variety of methods. A few of the areas in which different software products vary are the types of algorithms, the types of systems, and the system architectures they utilize (Fehon, 2004). Algorithms can be sequence-based, meaning they use a set cycle length (similar to coordinated systems) and have a pre-determined phase sequence. Alternately, they can be non-sequence based, in which the cycle length and sequence of phases are both variable. The systems themselves can be stand-alone products with full management capabilities (SCOOT, SCATS), or a unit within a proprietary signal management system (Synchro Green, Centracs Adaptive), or external to the signal management system (ACS Lite, Kadence, InSync). Finally, the system architecture can either be centralized, distributed, or peer-to-peer. Centralized systems process all strategic and tactical decisions at a central location, whereas distributed systems conduct the strategic portion at a central location but leave the tactical decisions to the local signals. Peer-to-peer systems conduct all operations on an entirely local basis, with no central supervisor.

One important difference between some software systems is the frequency with which they update the signal timings based on changes in demand. Most ASC software will update the signal controllers in small increments every few seconds. However, some, such as ACS Lite and Kadence, only update the timings every 3-4 cycles. According to the developers, this slower transition schedule improves the reliability, safety, and accuracy of the updates.

The software operates by implementing different operational strategies for different situations. If the network is oversaturated, the ASC system will adjust to maximize throughput and manage queues, whereas when the network is undersaturated, the system will adjust to provide smooth flow for the vehicles present. If there are many turning movements present, the system will focus on the distribution of green time.

Some of the software products that have been piloted by the CoA are Kadence (developed by Kimley-Horn as an improvement on ACS Lite) and InSync (developed by Rhythm).

Additionally, the CoA has explored the local adaptive features available through the D4 signal controller software as well as traffic responsive timing plan selection, a strategy that is somewhat similar to adaptive signal control.

9.2 Infrastructure Needs for Adaptive Signal Control

Detection is the crux of any adaptive signal control system. This is because detection is the primary method by which the system collects real-time data about traffic demand, thus enabling the rest of the adaptive signal control process. Therefore, an emphasis is put on the available forms of detection and the detection needs of a particular ASC product. Most ASC systems require stop-bar detection for all phases that are adaptively controlled, and advance detection for phases that are run in coordination. The CoA generally does not maintain stop-bar inductive loop detection on through movements, but often includes advance detection on these movements. Fortunately, ASC systems generally can accommodate any form of detection (video, inductive loop, magnetometer, or radar). This is important, as the CoA has been exploring various alternatives to loop detection, including video and radar technology. Depending on the software product, different firmware might be required in the signal cabinet. However, the necessity of consistent, effective detection infrastructure is the most pressing need for implementing an ASC system.

9.3 Conditions for Implementing Adaptive Signal Control

Adaptive signal control is designed to handle difficult traffic situations, but it is not always the best solution. This fact, combined with the cost of implementing the technology, means that an agency should carefully select candidate locations for implementing ASC to use their resources as efficiently as possible. The ideal corridor for implementing ASC would be one for which traffic demand varies significantly from day to day. Another situation in which ASC can be helpful is when demand is greater than capacity and the system is oversaturated.

To assess a given traffic signal system and explore whether or where ASC might be helpful, it is crucial to understand the current state of traffic demand. This means that a thorough, accurate source of traffic volume data is needed to fully assess the performance. This is something that the CoA is currently lacking, however investments in video detection technology will hopefully provide for easy data collection at a wide range of intersections.

9.4: Summary of Adaptive Signal Control Findings and Future Work

The CoA is exploring the benefits of implementing ASC in hopes of using it to improve system performance along with other operations management initiatives. The first step in doing so is understanding the context in which ASC can provide the most benefit. Therefore, it is important to lay out the various criteria for implementing ASC, including the software and infrastructure needs. The key to effective deployment of any given ASC system is the presence and maintenance of vehicle detection at the intersections in question. Additionally, given the number of different ASC products in the market, it is crucial to understand the differences between each one and the effects that these differences might have on implementing a given product.

This initiative for identifying key candidate corridors for ASC relates to the overarching system performance improvement goals woven into the CoA's signal retiming program. For this reason, it makes sense to examine each in terms of the other. Having a corridor performance ranking system that is also able to identify key characteristics of receptivity to ASC would be an eventual goal of this work. While it would be ideal to have accurate traffic volume counts available for assessing a given corridor's candidacy for ASC, the CoA is not currently able to collect this data. Until that point, it might be possible to assess overall performance variability, a key indicator of candidacy for ASC implementation, by examining the variability of travel time or speed, at least to a certain degree. Future work should explore this area as the CoA works to implement collection of comprehensive volume data.

This initial exploration of the applicability of adaptive signal control represents the first step in creating a united front in signal retiming and corridor performance improvement for the City of Austin. As data availability improves, expansion of this work will allow for continued improvement to the traffic signal system itself, as well as the level of efficiency at which the City of Austin Traffic Department is able to operate, enabling the City to provide an increased level of system operation to travelers of all kinds in Austin.

Appendix A – Complete Survey Results

Appendix A contains the complete responses to the informal survey conducted through the ITE All Member Forum.

HENNEPIN COUNTY, MINNESOTA
Ben Hao, PE, PTOE
Traffic Management Center, Transportation Department – Traffic Operations
Hennepin County Public Works

- *How many signals does your agency maintain, and of those how many are retimed each year?*

  Hennepin County Traffic operations maintains a total of 460 traffic signals. A total of about 80 to 100 signals are retimed each year.

- *Does your agency have any sort of guidelines or rules used to prioritize intersections or corridors to be retimed? If so, what are those?*
  1. Retime each signal and major corridor once at a minimum of every 5 years.
  2. Retime corridors with high crash rates and high volume or traffic pattern changes as needed
  3. Retime corridors with high signal timing requests

- *Does your agency measure the effectiveness of retiming operations? What metrics are preferred? What data sources (e.g., travel time runs, INRIX or other probe data) are used?*
  1. LOS at movement level for peak and off-peak periods
  2. Before and After Daily and Annual MOEs from Synchro Models: Delay, Stops, Fuel, Emissions at network level
  3. Before and After Travel Times by direction at corridor level measured by probe vehicles from the field for AM and PM peak periods.

- *Has your agency used or explored the use of Adaptive Signal Control? If so, how do you evaluate candidate corridors, and measure the effectiveness?*

  Not yet. We are currently working on implementing and assessing traffic responsive signal control strategy. The adaptive signal control (ASC) would be considered in the next phase. As to the MOEs for ASC evaluation, it is anticipated that the advanced traffic management system (ATMS) would be able to provide or generate system performance measures (SPM) to help evaluate adaptive signal control efficiency and benefits at corridor level. In addition to travel time collected in the field, the SPM provided by ATMS could be volume rate, occupancy and speed data collected by the field detectors and advanced MOEs derived by the ATMS, such as arrivals on green, throughput, volume to capacity ratio, coordination diagram, phase termination charts, split monitors and others.

CAMPBELL, CALIFORNIA

Matthew Jue, PE, PTOE, Traffic Engineer
City of Campbell

- *How many signals does your agency maintain, and of those how many are retimed each year?*

  44 (soon to be 45). Retiming occurs if grant funding becomes available.

- *Does your agency have any sort of guidelines or rules used to prioritize intersections or corridors to be retimed? If so, what are those?*

  Age of signal timing plans; whether traffic volumes or patterns on corridors have changed.

- *Does your agency measure the effectiveness of retiming operations? What metrics are preferred? What data sources (e.g., travel time runs, INRIX or other probe data) are used?*

  Travel time runs are used for measuring before/after travel times and delay.

- *Has your agency used or explored the use of Adaptive Signal Control? If so, how do you evaluate candidate corridors, and measure the effectiveness?*

  We've been approached by two vendors of adaptive signal control. Since adaptive signal control would be new to us, we pay attention to word-of-mouth from other agencies or consultants. For example, one vendor in particular specifies the use of its own detection systems rather than the City's current detectors. We have candidate corridors that are 1) challenging corridors or 2) are simple enough that it wouldn't be a complete disaster if the adaptive system didn't work well.

WASHINGTON COUNTY, OREGON

Shaun Quayle, PE, Transportation Engineer
Washington County Department of Land Use & Transportation

- *How many signals does your agency maintain, and of those how many are retimed each year?*

  We maintain approximately 300 signals. Last year we retimed approximately 50 signals.

- *Does your agency have any sort of guidelines or rules used to prioritize intersections or corridors to be retimed? If so, what are those?*

Measured or observed congestion, and citizen complaints drive our signal retiming efforts.

- *Does your agency measure the effectiveness of retiming operations? What metrics are preferred? What data sources (e.g., travel time runs, INRIX or other probe data) are used?*

  Yes, we have 125 roadside Bluetooth readers plus signal controller logs that we use to evaluate the effectiveness of signal timing, plus we spend multiple days in the field gauging before and after performance and fine-tuning parameters, then monitor in an ongoing basis with Bluetooth reports and watching via PTZ CCTV cameras. Our primary metrics for effectiveness are corridor travel time, queuing/queue spillback, and cycle/split failures . . . we strive to reduce each.

- *Has your agency used or explored the use of Adaptive Signal Control? If so, how do you evaluate candidate corridors, and measure the effectiveness?*

  Yes, we have approximately 30 intersections running on the SCATS adaptive system, another 12 running on the InSync adaptive system and are currently considering adaptive on 27 additional intersections. Candidates for adaptive are often corridors at or over capacity, and experience unpredictable traffic volume changes. We measure the effectiveness on-street of an adaptive system equivalently to our time-of-day systems. We also judge the success of the adaptive system by its ease of maintenance and operations. Some systems are much easier to work with than others.

CLARK COUNTY, WASHINGTON
Richard W. Gamble, PE, Intelligent Transportation Systems Manager
Clark County Public Works

- *How many signals does your agency maintain, and of those how many are retimed each year?*

  We have about 100 signals and we don't have a schedule on when they get retimed. We have a project we're working on to address this issue.

- *Does your agency have any sort of guidelines or rules used to prioritize intersections or corridors to be retimed? If so, what are those?*

  We do it based upon need or citizen complaint. Our signals operate quite dynamically though so they already have a lot of flexibility in their timing. We've added traffic responsive to the signals over the last couple of years.

- *Does your agency measure the effectiveness of retiming operations? What metrics are preferred? What data sources (e.g., travel time runs, INRIX or other probe data) are used?*

We will be doing a study next month to compare travel time with floating car vs. Bluetooth, vs INRIX. We hope to have some data on this by this summer. The goal of this is to try and develop some performance metrics to decide when a corridor should be retimed rather than putting corridors on a schedule. The hope is that the software algorithm or methodology we develop with this program will tell us when a corridor needs to be retimed. At this time, we are looking at several metrics and we don't know which one is going to be the preferred one.

- *Has your agency used or explored the use of Adaptive Signal Control? If so, how do you evaluate candidate corridors, and measure the effectiveness?*

  We are exploring adaptive signal control but have not implanted at this point. I believe we have a project this year or next that will deploy our first adaptive corridor.

ORANGE COUNTY, CALIFORNIA

Ronald Keith, TSOS, Project Manager III
Orange County Transportation Authority

- *How many signals does your agency maintain, and of those how many are retimed each year?*

  I am the Project Manager for the Regional Traffic Signal Synchronization Program for OCTA. It is called Project P. There are over 2000 intersections on this network. The 34 local agencies, the County of Orange, and Caltrans own and maintain these signals. The program is competitive between the agencies and the County. Caltrans is a participant but they cannot compete. Each year a call for projects is issued with a finite amount of funding to improve infrastructure and communications to the newest ATMS and ATC standards.

- *Does your agency have any sort of guidelines or rules used to prioritize intersections or corridors to be retimed? If so, what are those?*

  The corridors are awarded points based on VMT, number of intersections, number of agencies participating, and if it is on the Master Plan of Arterial Highways (MPAH), the Signal Synchronization Network, and/or if it has been designated a Priority Corridor. All projects are interjurisdictional in nature. Each project lasts 3 years, 1 for the construction and implementation, followed by a 2-year Ongoing Maintenance and Monitoring period. The project's corridor is ineligible for funding or competition during this 3-year period. OCTA does about 7-12 corridors per year, some of which, by request, are administered by me, internal staff, and my team of on-call consultants. We probably retime about 500-700 intersections per year. Some corridors are on their 3rd iteration because of previous programs or Project P Priority. The Board of Directors assigned which corridors are Priority and they are usually Primary, Major, or Principal arterials on the MPAH.

- *Does your agency measure the effectiveness of retiming operations? What metrics are preferred? What data sources (e.g., travel time runs, INRIX or other probe data) are used?*

  We measure the effectiveness by a layman-based metric called the Corridor Synchronization Performance Index (CSPI). The CSPI is a scoring of between 30 and 108 based on average speed, number of stops per mile, and ratio of greens to red or if you make it through the intersection on a green or if you get stopped. Everyone can understand these 3 items. A score of 60 or below means you are in dire straits. Above 60, you might consider retiming or taking a close look at what is going on. Above 70 you are doing well. Above 80 and into the upper reaches, you are doing fantastic. The metrics are calculated by doing before and after floating car studies using Tru Traffic. The author of Tru Traffic, Greg Bullock, thought our CSPI was so great, that he wrote an add-on application to Tru Traffic that you can download and it will automatically give you the information.

- *Has your agency used or explored the use of Adaptive Signal Control? If so, how do you evaluate candidate corridors, and measure the effectiveness?*

  Very few of our agencies have explored Adaptive. None of them, to date, even use the Traffic Responsive features of their respective ATMS to turn on or off the plans from real time traffic data. Set it and leave it doesn't work for any system. I hope those that are planning Adaptive realize this and provide the resources for operating their systems as much as is possible; 24/7. Traffic is still happening at 6pm when you turn out the lights and go home.

SALT LAKE CITY, UTAH

Mark Taylor, PE, PTOE, Traffic Signal Operations Engineer
Utah DOT

- *How many signals does your agency maintain, and of those how many are retimed each year?*

  We maintain 1220 traffic signals. My timing staff keeps track of the ones formally retimed, however, it varies each year based off of need and budget. Due to Utah's grid network, often changing the timing on one corridor will result in several other cross corridors needing to be retimed.

- *Does your agency have any sort of guidelines or rules used to prioritize intersections or corridors to be retimed? If so, what are those?*

  Yes and No. No, we use a lot of engineering judgement in deciding if full retiming is necessary (new cycle length, splits, offsets), or if simply polishing up the existing plans is best. Yes, we use Automated Traffic Signal Performance Measures (ATSPMs http://udottraffic.utah.gov/atspm) extensively in helping us decide which areas may need to be retimed and if so, we use the real measured data from the ATSPMs to help us know what the timings should be (instead of collecting TMCs and going through the full modeling experience). For example, the traditional optimization process is to collect TMCs manually (by TOD), model for cycle length, splits, offsets, optimize the model, implement and fine-tune. Using ATSPMs, we will first Review ATSPMs in detail and conduct lots of field observations, Models are primarily used for just their time-space diagrams (not cycle length or split assessments). The ATSPMs are helpful with split allocation, progression quality, identifying overcapacity movements, vehicle counts for TOD schedule and progression balance. During implementation it is extremely helpful to be able to review operation of the new plans immediately or the next day.

There are many other ways we use ATSPMs when optimizing a signal or corridor. The split monitor can tell you whether splits are allocated appropriately, negating the need for most TMCs. The Purdue Coordination Diagram can tell you how large your main street platoons are and if you have wasted time in the cycle, as well as how many vehicles arrive during the green phase. Approach volumes (collected automatically) can determine whether one-way or two-way progression is desired.

- *Does your agency measure the effectiveness of retiming operations? What metrics are preferred? What data sources (e.g., travel time runs, INRIX or other probe data) are used?*

  On major retiming projects we will write a memo that we keep so that not only explain any improvements collected with ATSPMs (i.e. # of split failures before and after, platoon ratios, etc.), but help us understand some of the reasons why we timed certain corridors the way we did so to minimize "screw-driver drift" and make future retiming projects easier. We are also starting to use probe travel time data (HERE) and will start to evaluate in more detail travel time.

- *Has your agency used or explored the use of Adaptive Signal Control? If so, how do you evaluate candidate corridors, and measure the effectiveness?*

  Yes, we have three adaptive systems in use on some of our signals. Two are off the shelf systems and one was created in-house by my staff. I believe adaptive control has some benefits in some areas but believe that TOD plans that are well maintained may outperform adaptive control in other areas. In other words, I'm not a believer in "adaptive control" everywhere. I think the decision to use "off the shelf adaptive" needs to be carefully reviewed using the systems engineering approach that also factors in the extremely high level of support maintenance that they require as well as the abundant maintenance costs. Just FYI, we spend much, much more time maintaining & babysitting our adaptive systems than we do our TOD systems.

FEDERAL WAY, WASHINGTON

Richard Perez, PE, City Traffic Engineer
City of Federal Way

- *How many signals does your agency maintain, and of those how many are retimed each year?*

  We have 77 traffic signals and coordinate with state DOT on 3 more, and the County on 2 more. Only 6 City-owned signals will not have some type of interconnect by the end of the year. Since so many of them run as pretty much one system during the evening peak, we tend to marshal our resources every 3-5 years and retime everything at once.

- *Does your agency have any sort of guidelines or rules used to prioritize intersections or corridors to be retimed? If so, what are those?*

  Other than system-wide efforts, just tweaks in response to requests.

- *Does your agency measure the effectiveness of retiming operations? What metrics are preferred? What data sources (e.g., travel time runs, INRIX or other probe data) are used?*

  Currently we only are using travel time runs.

- *Has your agency used or explored the use of Adaptive Signal Control? If so, how do you evaluate candidate corridors, and measure the effectiveness?*

  Reviewing even one week of tube counts on many of our corridors amply shows that there is enough day-to-day variation to demonstrate that time-of-day plans (we run 4-10 plans a week per intersection) can't adequately address the variation, even without considering overflow effects from the freeway system. After 20 years of planting seeds, we are finally getting into Adaptive. Our first phase will cover over half of our signals and should be operating in late 2019 or early 2020. We expect to implement automated signal performance measures as part of the project.

MEDFORD, OREGON
Karl MacNair, Transportation Manager
City of Medford

- *How many signals does your agency maintain, and of those how many are retimed each year?*

  Approximately 120.

- *Does your agency have any sort of guidelines or rules used to prioritize intersections or corridors to be retimed? If so, what are those?*

  Nothing written. It’s based on citizen input and local knowledge.

- *Does your agency measure the effectiveness of retiming operations? What metrics are preferred? What data sources (e.g., travel time runs, INRIX or other probe data) are used?*

  We are currently only able to use travel time runs and traffic volumes, but would like to get SPM's in place in the long term.

- *Has your agency used or explored the use of Adaptive Signal Control? If so, how do you evaluate candidate corridors, and measure the effectiveness?*

  We have one adaptive corridor using InSync by Rhythm Engineering. We have seen a large increase in volume in the corridor without seeing an increase in congestion.

TORONTO, CANADA
Rajnath Bissessar, PE, Manager, ITS Operations
City of Toronto

- *How many signals does your agency maintain, and of those how many are retimed each year?*

  2,350 signals. We started a signal optimization program in 2012 and have retimed an average of 260 signals per year. More info on this program is on our website (https://www.toronto.ca/services-payments/streets-parking-transportation/traffic-management/traffic-signals-street-signs/signal-optimization-coordination-program/).

- *Does your agency have any sort of guidelines or rules used to prioritize intersections or corridors to be retimed? If so, what are those?*

  When undertaking the program, our focus was to concentrate on the major arterials. Since we had undertaken only a few comprehensive studies in the years prior to 2012, we choose the more heavily trafficked major arterials as our first priority. Even though we had originally planned to complete all the major arterials by 2016, we did not meet the target; we are hoping to compete the major arterials this year. We do not see much value in doing full blown coordination studies on the minor arterials and collectors – we are using basic time space diagrams to fill in the minor arterials and collectors. When we start the next round of coordination studies in 2019, we plan to concentrate on routes where there has been changes in traffic patterns or volumes. We will be using HERE data for that exercise since we have a three-year contract with HERE.

- *Does your agency measure the effectiveness of retiming operations? What metrics are preferred? What data sources (e.g., travel time runs, INRIX or other probe data) are used?*

  We report to the public on MOEs generated by Synchro software. We use a combination of floating car method (using GPS software), portable and fixed

Bluetooth readers, and HERE data. The following MOEs are reported: vehicle delay (hr), stops (#), average speed (km/h), fuel consumed (L) and greenhouse gas emissions (kg). In addition, an overall benefit-cost analysis is developed for each individual corridor.

- *Has your agency used or explored the use of Adaptive Signal Control? If so, how do you evaluate candidate corridors, and measure the effectiveness?*

  We installed a SCOOT system about 20 years. We currently have about 300 signals on SCOOT. The routes chosen for SCOOT were generally parallel to major expressways – to accommodate the overflow of traffic during planned maintenance shutdowns or during incidents. We had SCOOT in the downtown core, but most of these signals have been converted to the conventional traffic system (TransSuite TCS) – there was not much benefit in having SCOOT in the downtown because of the need to keep cycle lengths low due to pedestrian wait time issues – hence, there was no room to optimize splits. We are piloting two “new” adaptive technologies this year - InSync and SCATS – 10 signals each. These two routes are currently on the TranSuite TCS and were optimized within the past three years. The TransSuite optimized timings will be used as the baseline. The main MOE that will be used is travel time on the main street (derived from floating car and HERE probe data), side street delay and pedestrian delay.

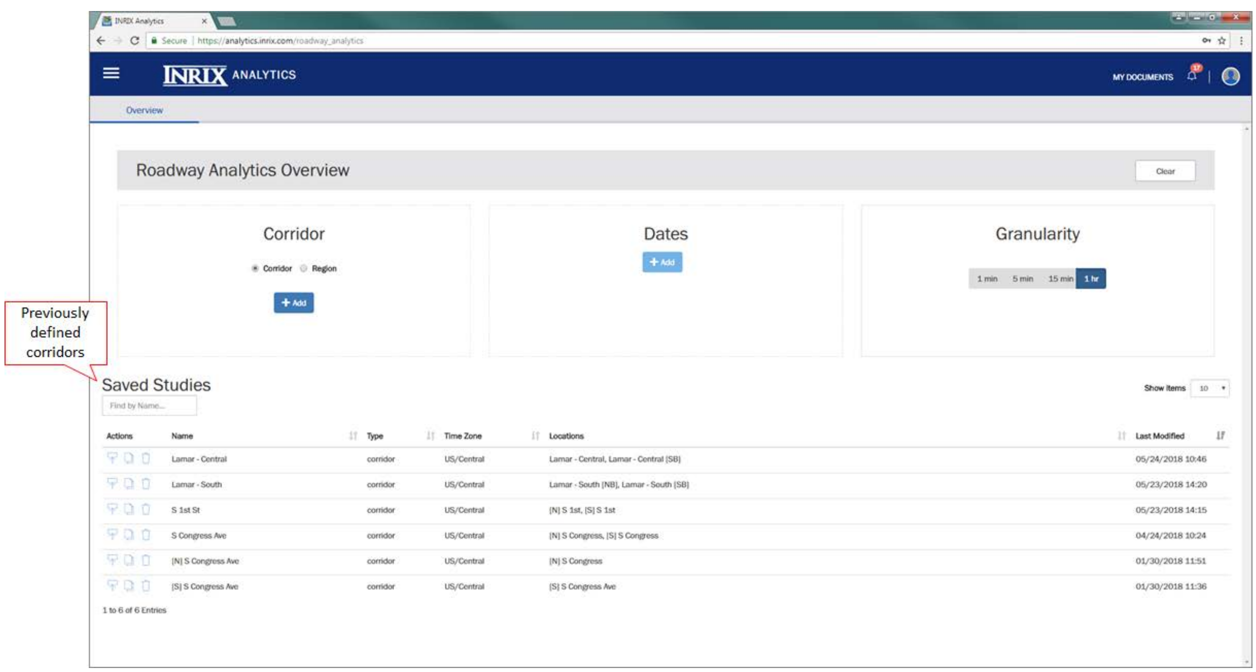
Appendix B – Data Acquisition Guide

Appendix B contains a guide detailing the workflow developed for this project. It covers navigating the INRIX interface to define corridors, downloading the data files, and ingesting the data into the Postgres database.

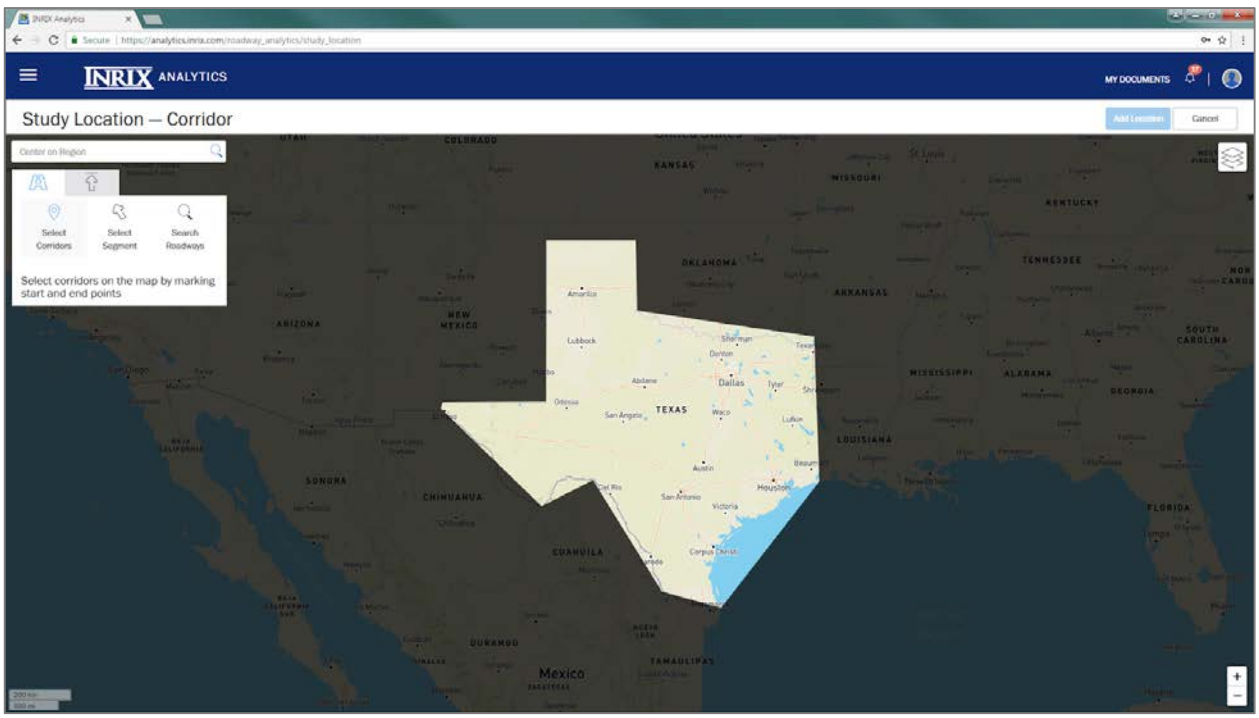
Defining Corridors

The City of Austin corridor definitions can be found at http://transportation.austintexas.io/signal-timing/. Only about one-third of all CoA corridors are retimed each year, so to view all corridors switch between the fiscal year tabs at the top. Selecting one signal on the map will highlight all the other signals in that corridor. Some corridors include signals that are on adjacent roadways. For this analysis, each corridor should be understood as the principle collection of signals in the grouping which are along the same roadway. In most cases, the adjacent signals can be disregarded for now.

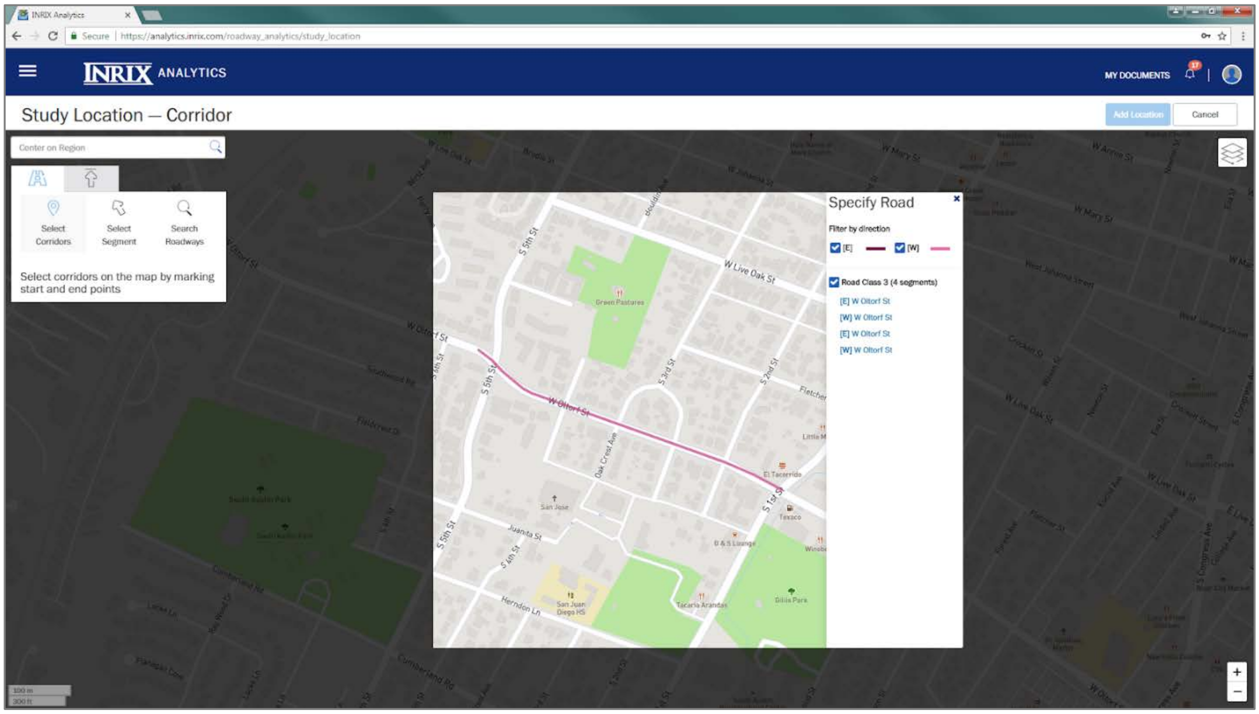
Navigate to INRIX analytics homepage (https://analytics.inrix.com/roadway_analytics) and log in.



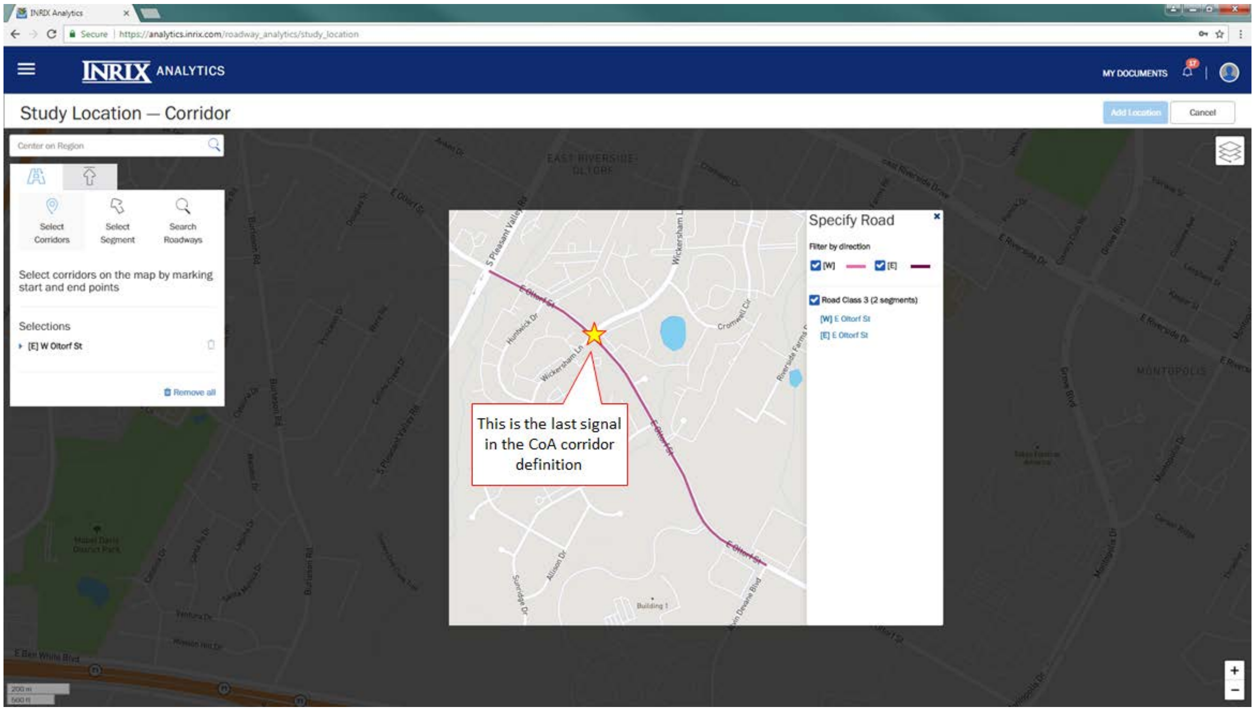
Add a corridor:



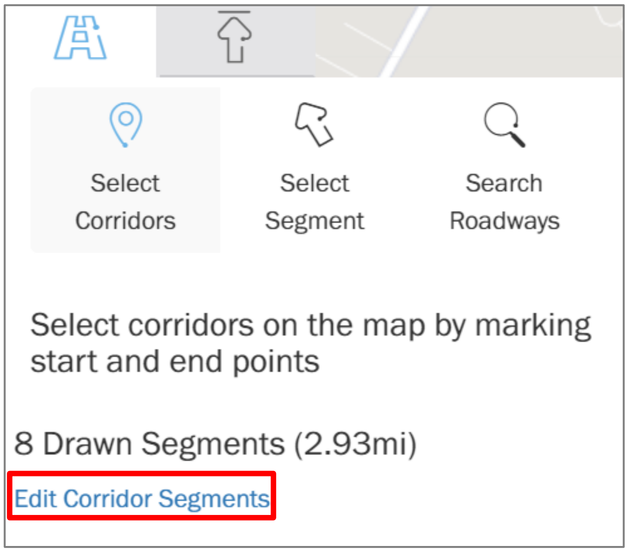
Zoom in on Austin and find the starting point of the corridor. This example will use the Oltorf corridor, which covers Oltorf Road from South 5th Street on the west to Wickersham Lane on the east. Begin by selecting the eastbound direction of travel, starting at South 5th Street. Click near the intersection of South 5th and Oltorf, which will bring up the following window:



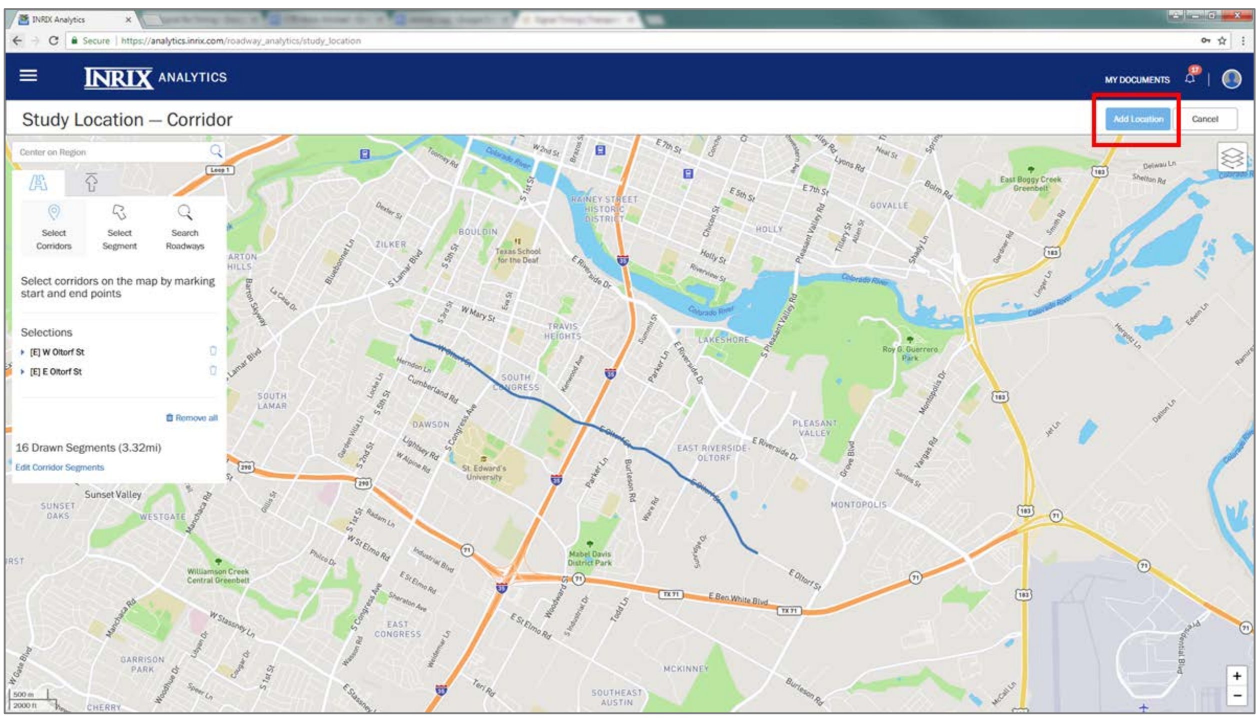
Under "Specify Road," select the correct starting segment for the desired direction. In this case, click on "[E] W Oltorf St." Then, go to the other end of the corridor and select the correct ending segment in a similar manner. In this case, the INRIX segments do not match up perfectly with the City of Austin corridor definitions, so select the segment that goes a little bit past the last intersection in the CoA corridor definition (Wickersham Lane). Make sure to select the eastbound option. Note that INRIX fills in the intermediate segments.

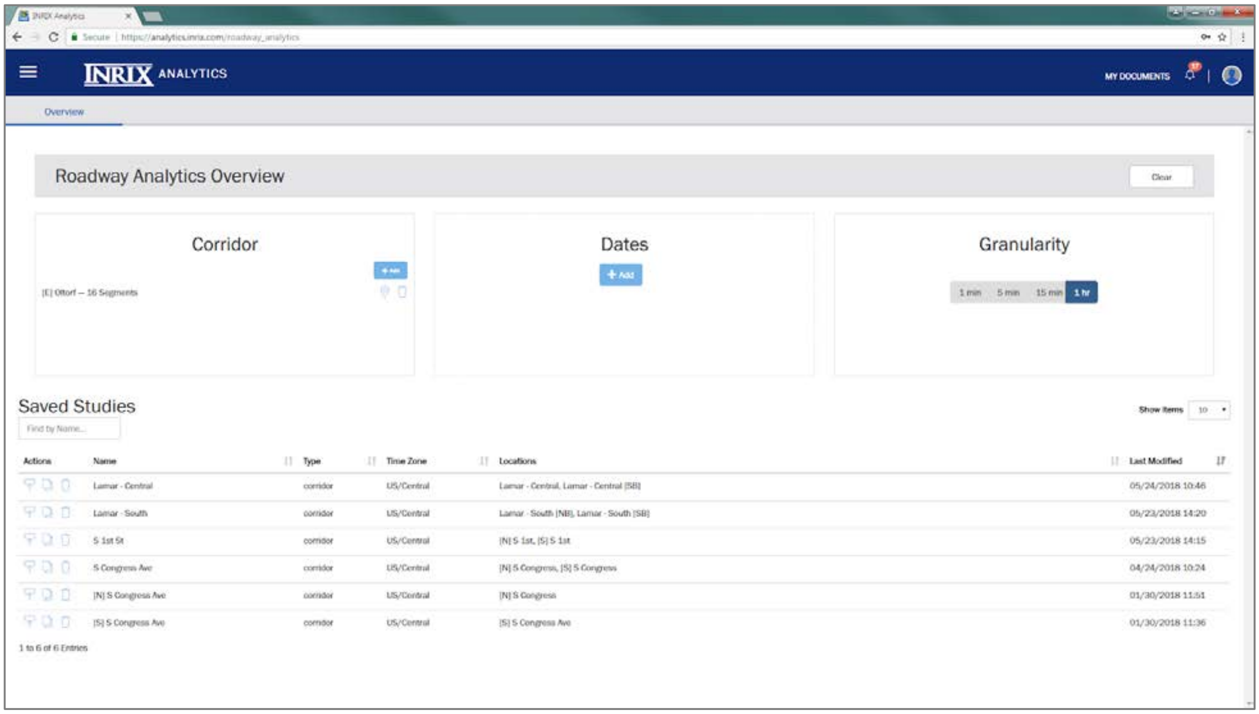


Depending on the corridor in question, there are some bugs in the INRIX interface that affect the selection of roadway segments to form a corridor. Some can be selected without any problems, while others are very difficult. For instance, sometimes if the northbound direction segments are selected for the start and end segments, INRIX will fill the intermediate segments in as southbound. For this reason, it is very important to ensure that the segments INRIX selects match the ones intended for selection. To check, click “Edit Corridor Segments” (shown below) to see a list of the individual segments selected. Pay special attention to the “direction” column and delete any incorrect segments.

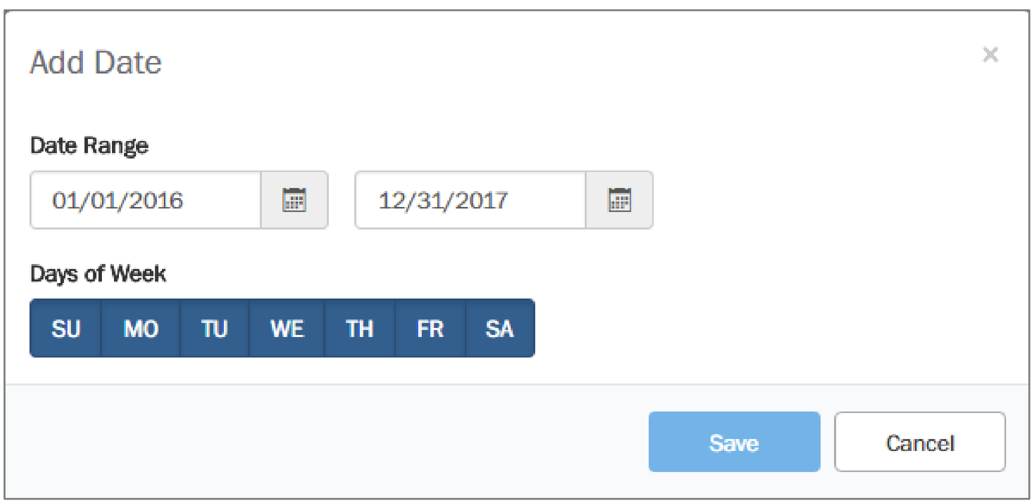


Once the corridor is selected correctly, click on “Add Location” in the upper right corner and name the location “[E] Oltorf.” Now the eastbound portion of the corridor (a total of 16 segments) is saved.

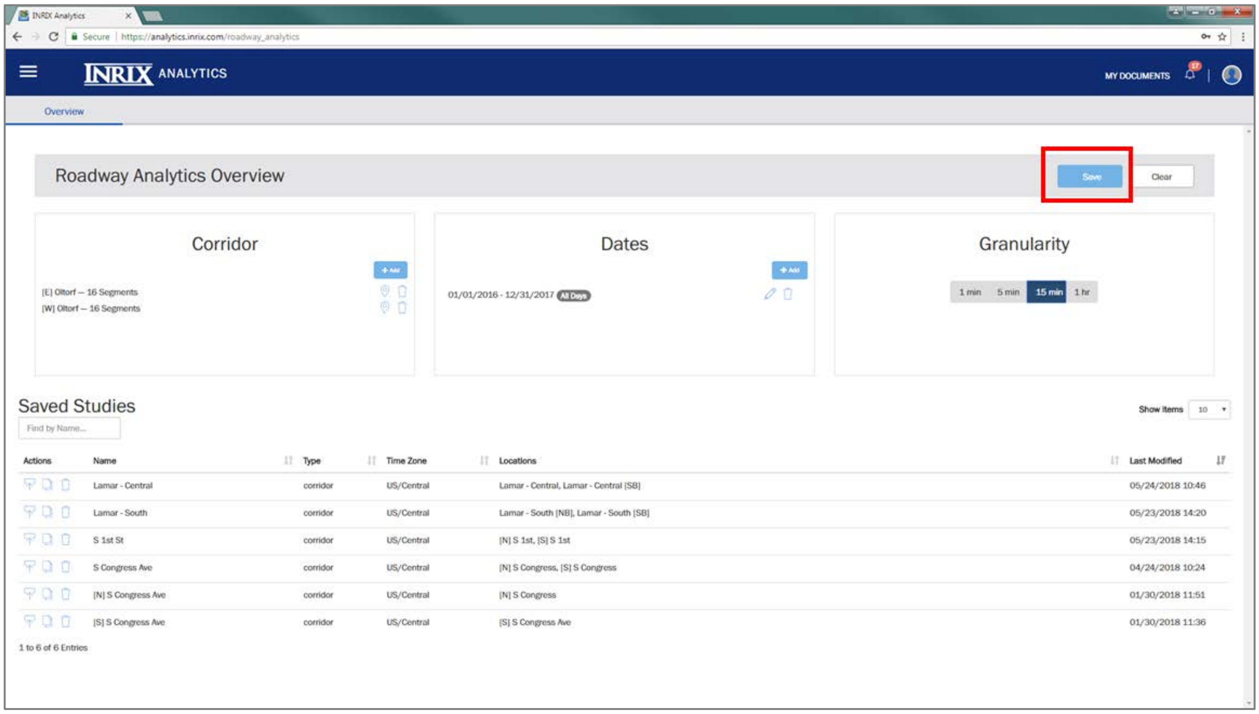




Click “+ Add” under Corridor and repeat the process to add the westbound direction. Now the full corridor has been created. Select the desired date range (in this case, 01/01/2016 through 12/31/2017 for two full years of data) and 15-minute granularity.



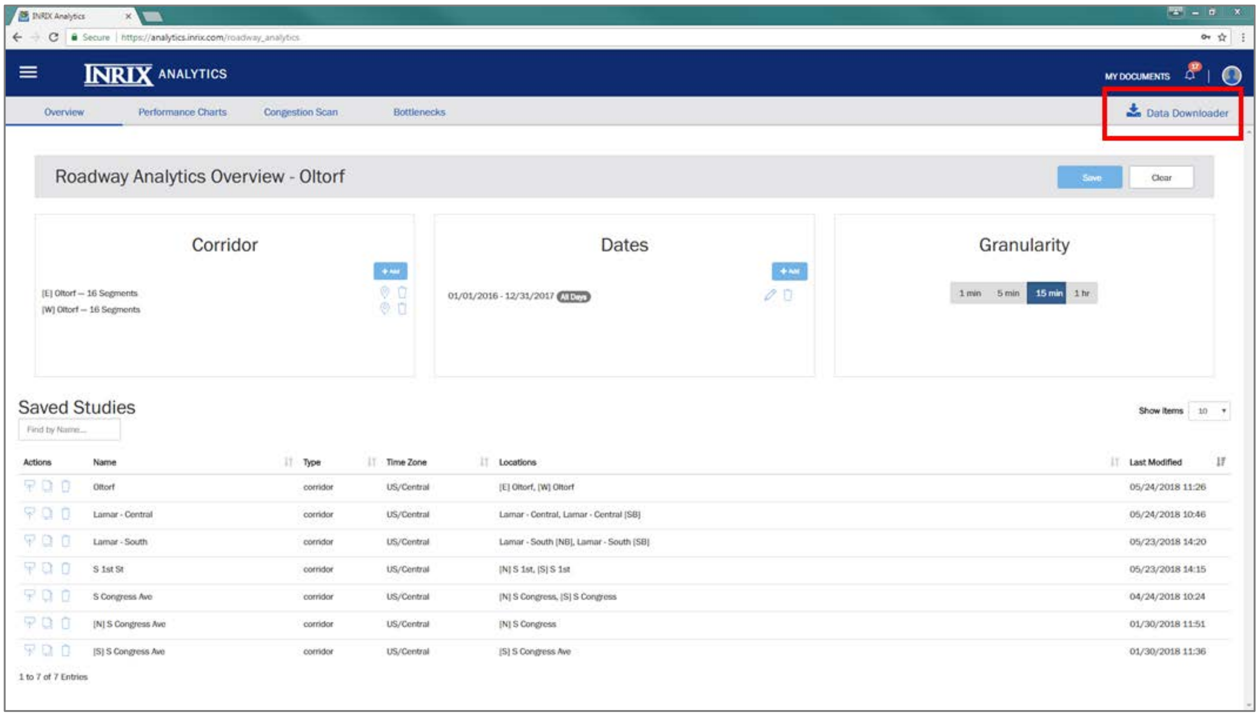
Now click “Save” in the upper right corner and name the study “Oltorf.” Make sure that the study is named to match the CoA name for the corridor.



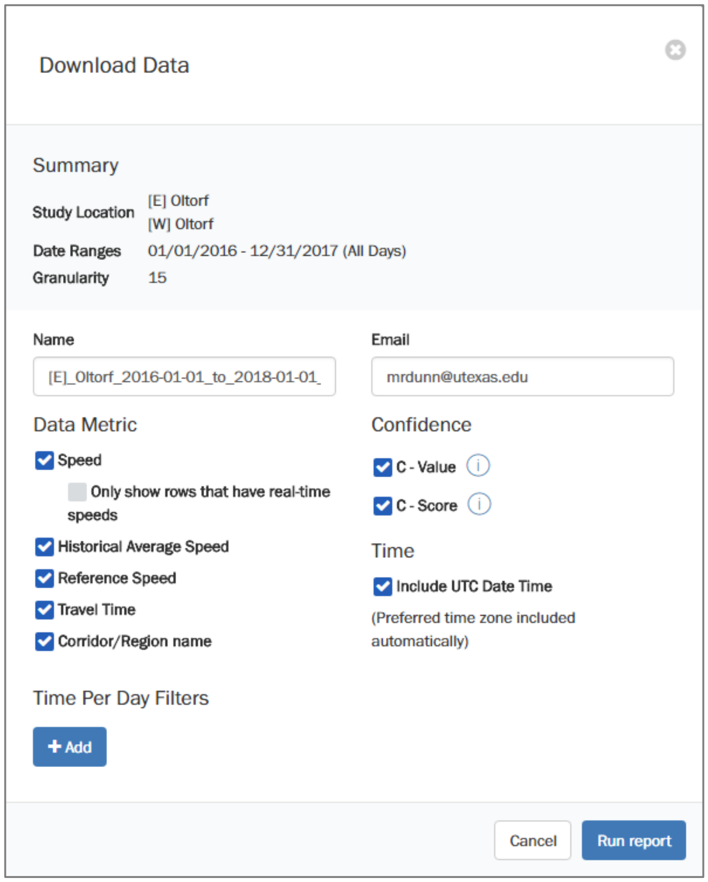
Note that now, the "Oltorf" study can be pulled up from the list of saved studies at the bottom of the home page.

USING THE DATA DOWNLOADER

Click on “Data Downloader” at the top right of the screen, shown below in the red box.



It is not necessary to change any of the data download settings. Click “Run Report” in the bottom right corner.



The data may take a couple of minutes to download. When it has downloaded (status reads "completed" or "queuedcompleted" on the "My Documents" page), you can click the download symbol under the "Actions" heading. Note that some of the larger corridors must be downloaded in multiple zip files. If this is the case, a dark gray arrow will be present to the left of the download name. Click this arrow, which expands the individual files, and click the blue download symbol next to each file.

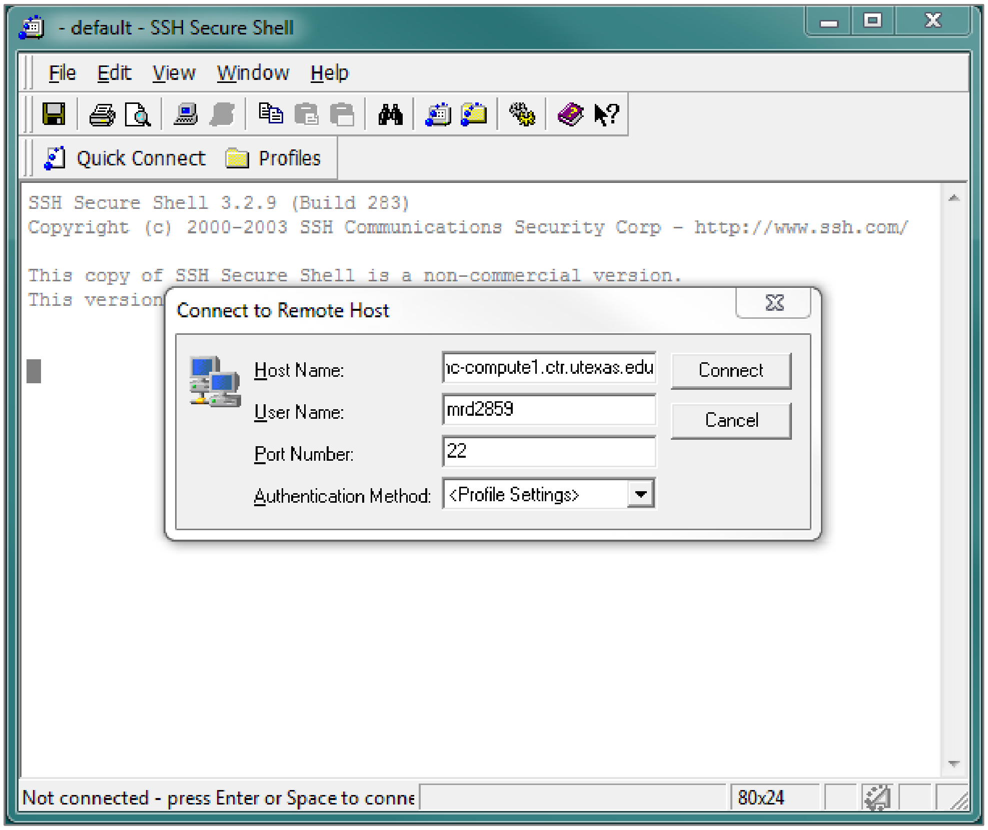
Once the file(s) are downloaded and unzipped, note that the folder contains two .csv data files. One, the "data" file, contains the individual speed records for every segment on the corridor during the study period. The other, the "metadata" file, is much smaller and contains information describing each segment. These two files are related using the unique segment ID for each segment.

Save the data in the project folder. Name the folder according to the CoA corridor definition name and add that name to the individual files. If the corridor requires multiple downloads, the metadata file will be included with each download but only needs to be saved once. Note that the file naming convention has changed since these examples were made, and adjust accordingly.

Finally, an alteration needs to be made to the metadata file. Open it and add two new columns at the end called “CoA Corridor” and “CoA Direction.” Fill “CoA Corridor” with the CoA corridor name (as seen on the CoA website with the corridor definitions). Fill “CoA Direction” with a consistent direction indicator for the whole corridor. In other words, make sure the whole corridor is either E/W or N/S in this column, as the segments can sometimes be mixed in INRIX. Also, while the metadata file is open, check to make sure that it looks correct and free from errors (correct number of segments, road names, etc.). Save the .csv and close it.

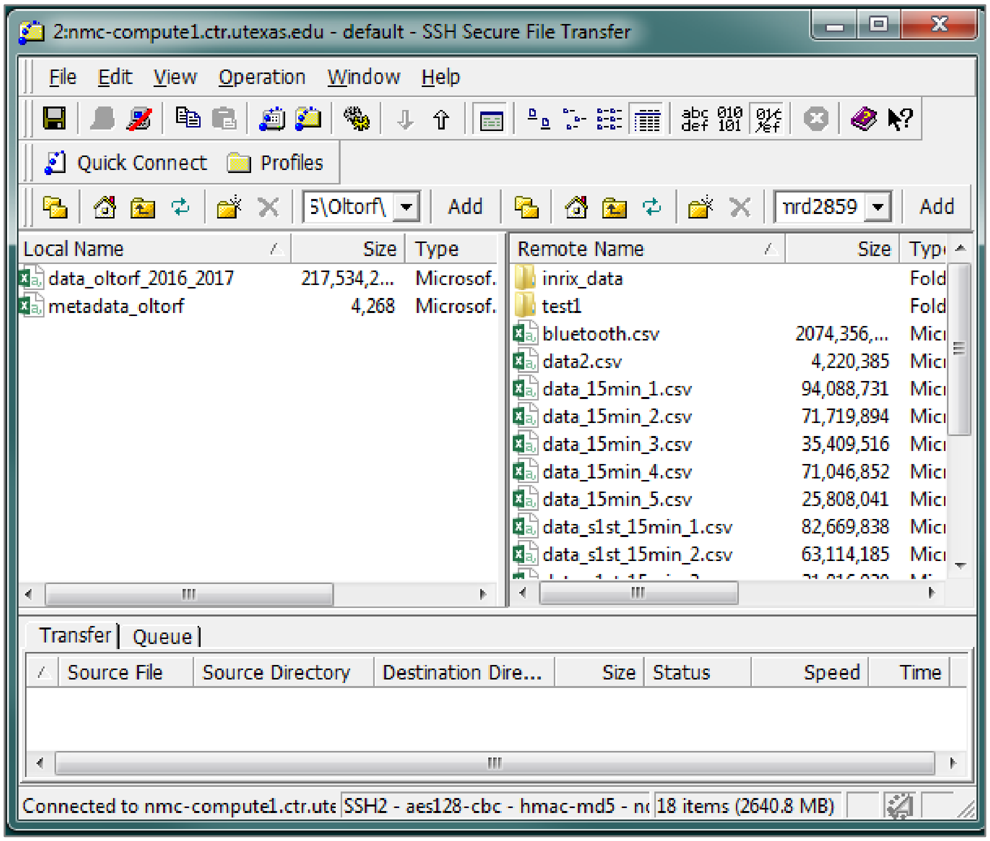
INGESTING DATA INTO POSTGRES DATABASE

Open a Secure Shell Client (SSH) session and log in to the host nmc-compute1.ctr.utexas.edu using your UT EID and password.



Open Postgres and navigate to the database using the following command: psql -U vista -d retiming

Open a new file transfer window (shortcut button or Window > New File Transfer). In the left side of the window, navigate to the location where the data was saved upon download.



Right click on each file in the left pane and select "Upload." Once the data has uploaded, ingest each file into the correct table in the database. Data files can be ingested one-by-one using the following command (note that the metadata file can be ingested similarly):

\copy inrix_15min from data_oltorf_2016_2017.csv delimiter ',' csv header

Ingesting the speed data will take a minute or two. The metadata should be fast. Alternately, a simple script can be used to automate the data ingestion process:

```
for f in . *_data.csv
do
      echo "$f"
      psql -U vista -d retiming -c "\copy inrix_15min (datetime,
segment_id, etc_datetime, speed_mph, hist_speed, ref_speed,
ttime_min, cvalue, score_30, score_20, score_10, roadclosure,
dir_corridor) FROM $f DELIMITER ',' CSV HEADER" && mv "$f"
./inrixdata2_ingested
done
```

The metadata files can be ingested by writing a similar script. Note that the script relies on the file naming convention where the data file name ends in "_data.csv" and the metadata file name ends in "_metadata.csv" (a different naming convention than the one seen in the figures in this guide). Running this script with the command `nohup sh ingest_data.sh` will start a process of ingesting the data files and will not terminate the process even if the secure shell session is ended. Once the data is ingested into the database, it is ready to be aggregated and manipulated in order to perform the corridor ranking methodology.

Appendix C – Full Corridor Ranking

Appendix C contains the full corridor ranking results, including the rank and calculated ranking metrics for all 79 corridors examined in this study. It is the full version of Table 3.

Table 5: Full Corridor Ranking Results

		Percent of Corridor Experiencing Speed Decrease			Percent of corridor Experiencing Speed Decrease > 3 mph			Maximum Speed Decrease				
Rank	**Corridor**	**AM**	**Midday**	**PM**	**AM**	**Midday**	**PM**	**AM**	**Midday**	**PM**	**Total Length (mi)**	**No. of Signals**
1	US 290 - East	95.93	85.36	96.85	21.30	22.48	25.62	-28.38	-27.31	-28.25	5.30	19
2	US 183 - Central	86.29	100.00	86.14	48.51	48.51	30.02	-19.61	-16.75	-5.17	2.79	10
3	US 183 - South	48.37	65.58	65.08	47.65	35.90	48.68	-11.35	-10.52	-11.23	3.08	15
4	51st	70.75	69.59	94.57	24.87	24.87	24.87	-3.82	-3.78	-5.79	3.26	12
5	Airport	63.07	74.65	80.88	14.66	16.87	21.64	-3.82	-5.59	-7.30	6.41	27
6	MLK - East	60.12	85.10	89.35	19.54	18.03	13.38	-3.55	-7.59	-6.04	5.42	15
7	Lamar - North	75.65	100.00	86.24	7.93	7.93	7.93	-3.69	-3.69	-5.45	5.88	15
8	Enfield	56.49	76.61	100.00	8.28	8.53	21.47	-3.21	-6.02	-4.09	1.30	9
9	Ben White - East	91.28	52.06	52.72	37.55	0.19	28.08	-5.43	-3.17	-9.35	3.61	14
10	Manor	79.88	57.12	67.69	3.55	3.55	3.55	-4.96	-6.03	-6.47	3.83	15
10	Pleasant Valley	80.22	80.22	99.05	0.00	1.67	42.95	-2.16	-3.33	-8.38	2.93	11
12	IH 35 SRVC RDS	46.65	33.61	67.96	16.66	13.12	55.77	-6.09	-5.23	-6.40	2.27	16
12	Southwest Parkway	46.57	48.05	71.24	21.57	9.33	21.57	-5.99	-3.34	-6.96	5.16	18
14	Parmer - West	44.31	52.13	74.05	11.13	5.26	14.86	-10.02	-4.44	-8.85	13.99	29
15	Loop 360 - North	26.26	54.34	49.05	3.60	19.46	31.89	-8.31	-8.12	-13.48	8.17	14
16	Brodie	100.00	78.71	70.96	0.17	0.00	8.28	-4.09	-2.65	-4.37	6.55	19
17	Slaughter	49.52	38.84	67.71	17.30	16.34	20.29	-5.20	-3.50	-5.37	9.75	31
18	7th - East	66.31	57.41	89.97	0.96	0.96	20.79	-3.28	-3.38	-3.90	2.38	12
19	Riverside	63.00	67.76	83.07	0.77	0.00	13.76	-3.35	-2.91	-5.37	3.79	24
20	Braker	59.18	89.63	63.70	0.36	2.25	0.00	-4.03	-7.14	-2.48	5.56	19
21	Lamar - Central	90.14	62.31	63.44	0.00	10.88	0.95	-2.51	-5.19	-3.35	3.78	15
22	Cameron - South	61.16	46.32	59.75	6.67	5.84	0.00	-3.98	-4.57	-2.72	2.10	14
23	Koenig/Northland	56.16	37.11	51.77	2.20	1.65	4.41	-5.67	-5.97	-4.30	3.66	21
23	Steck	99.13	99.13	100.00	0.00	0.00	0.00	-2.82	-1.50	-2.12	1.46	6
25	West Gate	47.77	47.77	47.60	47.60	47.60	0.00	-6.34	-3.72	-1.67	2.10	6
26	Barton Springs	66.09	10.87	6.67	1.40	5.87	5.87	-6.49	-5.04	-6.89	1.75	9
27	Oltorf	66.86	70.39	57.75	0.00	3.37	0.00	-2.75	-3.09	-2.87	3.32	14
27	US 183 - North	37.46	59.72	42.78	1.24	25.90	1.12	-3.16	-5.11	-4.79	2.15	15
29	Cameron - North	43.32	100.00	85.07	0.00	0.00	0.00	-2.28	-2.99	-2.76	3.24	11
30	Manchaca	55.68	30.95	75.19	14.33	0.00	0.81	-5.24	-1.72	-3.33	6.90	15

Rank	Corridor	Percent of Corridor Experiencing Speed Decrease			Percent of corridor Experiencing Speed Decrease > 3 mph			Maximum Speed Decrease			Total Length (mi)	No. of Signals
		AM	Midday	PM	AM	Midday	PM	AM	Midday	PM		
31	24th	100.00	100.00	100.00	0.00	0.00	0.00	-1.56	-0.96	-1.53	0.66	6
32	Wells Branch	51.30	47.80	68.56	0.00	0.00	17.58	-2.62	-1.79	-4.67	4.43	13
33	Loop 360 - South	48.04	19.88	19.88	34.84	19.88	0.00	-5.60	-4.46	-2.77	2.14	9
34	St Johns	39.84	32.21	97.87	0.00	1.29	1.29	-2.85	-3.47	-3.65	1.79	8
35	12th - East	100.00	90.53	96.35	0.00	0.00	0.00	-1.76	-1.11	-0.67	1.02	7
36	RM 620	20.06	6.54	41.15	4.69	2.48	1.97	-4.83	-6.43	-6.11	6.41	23
37	Far West	100.00	100.00	100.00	0.00	0.00	0.00	-0.82	-0.10	-0.58	1.12	5
38	William Cannon	59.77	49.42	56.32	0.10	0.00	0.00	-4.26	-1.88	-2.15	10.08	30
39	Guadalupe - North	42.28	72.51	62.76	4.25	0.00	0.00	-3.42	-1.37	-2.23	2.84	17
40	45th	81.76	43.46	56.58	0.00	0.00	0.00	-2.21	-2.00	-2.74	2.73	11
41	South 1st - South	99.80	64.43	56.42	0.00	0.00	0.00	-2.46	-2.00	-1.09	4.21	8
42	RM 2222 - East	20.75	20.75	100.00	0.00	0.00	20.75	-1.58	-1.67	-7.96	1.57	3
43	Dean Keeton	100.00	30.05	100.00	0.00	0.00	0.00	-0.63	-1.57	-1.83	0.92	10
44	38th	38.04	40.91	68.19	0.00	0.00	0.00	-2.93	-2.47	-2.42	2.17	12
44	MLK - West	70.22	42.91	55.37	0.00	0.00	0.00	-2.84	-1.96	-2.07	1.00	12
46	Anderson Mill	29.03	40.91	59.41	0.34	0.00	0.00	-3.89	-2.00	-2.71	3.13	10
47	McNeil/Spicewood Spgs	23.94	35.16	40.95	0.00	0.59	12.11	-2.20	-3.60	-4.88	4.74	19
48	Rundberg	96.40	72.64	56.50	0.00	0.00	0.00	-1.00	-1.30	-1.48	2.14	14
49	Congress - South	13.45	27.06	52.66	0.00	10.88	10.88	-1.32	-4.61	-3.77	6.76	24
50	Burleson	37.91	29.43	26.83	9.49	0.00	0.00	-3.37	-2.10	-2.93	4.83	11
51	South 1st - North	13.38	22.89	54.22	13.38	0.00	0.00	-3.31	-2.96	-2.58	3.03	14
52	12th - West	100.00	61.13	38.80	0.00	0.00	0.00	-2.04	-0.84	-1.38	0.52	7
53	Montopolis	21.54	57.19	60.78	0.00	0.00	0.00	-1.90	-1.94	-1.84	2.55	9
54	Exposition	0.00	27.89	100.00	0.00	0.00	23.90	0.17	-0.96	-3.86	2.09	12
55	US 290 - West	44.66	30.44	46.27	0.00	0.00	8.87	-1.70	-1.54	-3.75	1.98	9
55	Woodward	29.84	29.84	100.00	0.00	0.00	0.00	-1.14	-1.45	-2.08	0.70	9
57	8th	69.22	69.70	47.55	0.00	0.00	0.00	-1.39	-0.67	-1.48	0.71	10
58	Stassney - West	28.50	55.04	83.62	0.00	0.00	0.00	-1.33	-1.19	-1.62	2.93	8
59	Lamar - South	39.77	36.12	45.27	0.00	0.00	0.00	-1.06	-2.95	-2.91	5.12	26
60	San Jacinto	72.22	41.98	56.20	0.00	0.00	0.00	-1.76	-1.16	-0.60	0.48	8
61	RM 2222 - Central	54.01	6.23	6.23	0.00	0.00	2.76	-2.11	-2.44	-3.11	2.81	7
62	Anderson	48.21	16.71	55.31	1.24	0.00	0.00	-3.42	-1.40	-1.26	2.14	10
63	6th	56.88	33.71	49.10	0.00	0.00	0.00	-1.10	-1.42	-2.22	2.07	20
63	RM 2222 - West	2.64	2.63	100.00	0.00	0.00	0.00	-0.35	-2.10	-2.41	1.48	4
65	11th	57.34	47.78	29.12	0.00	0.00	0.00	-1.89	-1.83	-0.89	0.70	10
66	Ben White - West	17.69	56.83	45.71	0.00	0.00	0.00	-2.20	-2.06	-0.63	1.72	8
66	Trinity	66.77	49.99	49.99	0.00	0.00	0.00	-0.47	-0.54	-0.97	0.41	6

Rank	Corridor	Percent of Corridor Experiencing Speed Decrease			Percent of corridor Experiencing Speed Decrease > 3 mph			Maximum Speed Decrease			Total Length (mi)	No. of Signals
		AM	Midday	PM	AM	Midday	PM	AM	Midday	PM		
68	Congress - North	21.07	6.97	57.87	6.97	0.00	0.00	-3.20	-0.29	-1.86	0.97	20
69	Metric	30.13	13.21	30.13	0.00	0.00	0.00	-2.29	-1.51	-2.69	4.96	14
70	Stassney - East	46.09	46.09	46.09	0.00	0.00	0.00	-0.42	-1.05	-1.59	2.18	7
71	7th - West	27.87	42.86	58.81	0.00	0.00	0.00	-0.91	-0.31	-1.48	0.71	12
72	Cesar Chavez - E	44.48	28.73	43.09	0.00	0.00	0.00	-1.21	-0.45	-1.97	2.06	7
73	5th	0.00	40.85	41.19	0.00	0.00	0.00	0.02	-1.32	-2.61	1.78	18
74	Great Hills	24.30	24.30	24.30	0.00	0.00	0.00	-0.37	-2.07	-1.46	1.50	6
75	Lavaca	14.95	6.78	63.51	0.00	0.00	0.00	-0.16	-0.08	-1.69	0.98	13
76	Guadalupe - South	45.79	35.30	8.69	0.00	0.00	0.00	-0.56	-0.83	-0.51	0.76	12
77	Jollyville	22.35	0.00	22.35	0.00	0.00	0.00	-0.47	0.00	-1.69	2.60	5
78	Escarpment	0.00	0.00	0.00	0.00	0.00	0.00	1.37	0.78	0.43	4.19	7
79	Lakeline	0.00	0.00	0.00	0.00	0.00	0.00	2.59	4.31	1.95	1.28	6

Appendix D – Code for Initial Ranking Tool

The structure of the Shiny web-app tool revolves around three separate (but related) files: global.R, server.R, and ui.R. The global file contains broad information relevant to various features and processes within the app. In this case, it handles connecting to the PostgreSQL server containing the data and creating tables necessary for plotting. The server.R file contains the "back end" analysis necessary to generate results, and the ui.R file is the code that controls the layout of the user interface (UI). Each of these three pieces of code is as follows:

CODE FOR GLOBAL.R FILE

```
library(shiny)
library(DT)
library(ggplot2)
library(RPostgreSQL)
library(dplyr)
library(data.table)
library(lubridate)

server = "<server_name>"
uname = '<user_name>'
pwd = '<password>'
dbname = '<database_name>'

drv <- dbDriver("PostgreSQL")

conn <- dbConnect(drv, dbname, host = server, port = 5432, user = uname, password =
    pwd)

segments <- dbGetQuery(conn,"select * from inrix2_segments;")

################################################################################
#Use the following command to create new table "segment_order" in PSQL database
#ONLY NEED TO RUN IF DATA CHANGES
################################################################################

# ##convert to data table
# seg_seq=setDT(segments)
#
# ##E segments
# e_seg=segments[coa_dir=="E",]
# setorder(e_seg,road,start_long)
# e_seg[,dir_order:=rowid(road)]
#
# ##W segments
# w_seg=segments[coa_dir=="W",]
# setorder(w_seg,road,-start_long)
# w_seg[,dir_order:=rowid(road)]
#
# ##N segments
# n_seg=segments[coa_dir=="N",]
# setorder(n_seg,road,start_lat)
```

```
# n_seg[,dir_order:=rowid(road)]
#
# ##S segments
# s_seg=segments[coa_dir=="S",]
# setorder(s_seg,road,-start_lat)
# s_seg[,dir_order:=rowid(road)]
#
# ordered_segments=rbind(e_seg,w_seg,n_seg,s_seg)

######################################
#Write table segment_order to database
######################################

#dbWriteTable(conn,"segment_order",ordered_segments[,c("segment_id","road","dir","dir_
#order","length_mi")],overwrite=TRUE,row.names=FALSE)

################################################
#Create table segment_speed_summary2 as follows:
################################################

#select road as corridor,start_date, end_date, extract(year from datetime) as year,
#a.segment_id, dir, length_mi, c.id as date_range,avg(speed_mph) as avg_speed,
#dir_order, d.id as tod_range, start_hour, end_hour, case #when extract(dow from
#datetime) = 0 or extract(dow from datetime) = 6 then 0 else 1 end as weekday into
#segment_speed_summary2 #from inrix2_15min a, segment_order b, date_ranges c,
#tod_ranges d where a.segment_id = b.segment_id and datetime >= start_date #and
#datetime <= end_date and extract(hour from datetime) >= start_hour and extract(hour
#from datetime) <= end_hour group by #road,a.segment_id, dir, length_mi, extract(year
#from datetime), start_date, end_date, date_range, tod_range, start_hour, end_hour,
#weekday, dir_order;

#get data for plotting
speed_data <- dbGetQuery(conn, "select * from segment_speed_summary2")

#get list of corridor names for drop-down selector in UI
corridor_options <- unique(speed_data$coa_corridor)
```

Code for Server.R File

```
function(input, output, session) {

  output$ranking <- DT::renderDataTable({
    ranking_results_query = "select * from rank_results_trb;"
    ##### this query controls what shows up in the data table
    ranking_results <-dbGetQuery(conn, ranking_results_query)
    ranking_table <- DT::datatable(ranking_results, options = list(pageLength = 10),
    rownames = FALSE)
    return(ranking_table)
  })

  output$plot <- renderPlot({

    ##Adjust width so that smallest segments are visible
    width_multiplier=3

    ##Define gap between segments
    gap=0.05

    all_data = speed_data[!is.na(speed_data$coa_corridor),]
```

```
all_data_wk = all_data[as.character(all_data$weekday) == "1",]

#find data for corridor selected in UI dropdown selector
corr_data_wk=all_data_wk[all_data_wk$coa_corridor==input$selected_corridor,]

################################################################################
#####Create table dir_sign to define arrow direction, and labels for directions
################################################################################

##We're adding dummy values for date_range and length_mi because R searches for
##these when we add the segment geometry to create an arrow.
##When we define the tod_range_s value we need to pick the first range that we're
##using in the plot, because that's where the arrow appears

dir_sign=data.frame("coa_dir"=factor(c("N","S","E","W"),
    levels=c("N","S","E","W")), "sign"=c(1,-1,1,-1), "date_range" =
    factor(c(1,1,1,1), levels = c(1,2)), "length_mi"=c(1,1,1,1),
    "tod_range_s"=factor(1,levels=c("0","1","2","3","4")))

dir_text=data.frame("coa_dir"=factor(c("N","S","E","W"),
    levels=c("N","S","E","W")), "tod_range_s" = factor(1,levels =
    c("0","1","2","3","4")), lab="Flow",
    "date_range"=factor(c(1,1,1,1), levels=c(1,2)), "length_mi"=c(1,1,1,1))

labels <- c("N" = "Northbound", "S" = "Southbound", "E"="Eastbound",
    "W"="Westbound")

labels_tod<-c("0"="12 a.m.-5 a.m", "1"="6 a.m.-9 a.m", "2"="10 a.m.-3 p.m", "3"="4
    p.m.-7 p.m", "4"="8 p.m.-11 p.m")

min_speed=min(corr_data_wk$avg_speed)
max_speed=max(corr_data_wk$avg_speed)

#########################################################
#####Subset data_sign and labels for relevant directions,
#####and identify the "reverse" direction
#########################################################

dir_sign_p<-dir_sign[dir_sign$coa_dir %in% unique(corr_data_wk$coa_dir),]
dir_text_p<-dir_text[dir_text$coa_dir %in% unique(corr_data_wk$coa_dir),]
labels_p<-labels[unique(corr_data_wk$coa_dir)]
labels_tod_p<-labels_tod[as.character(unique(corr_data_wk$tod_range))]
directions=unique(corr_data_wk$coa_dir)
reverse_direction=subset(directions,directions %in% c("S","W"))

############################################################
###Make the order the same in both directions (we can adjust
###the workflow later so that it works for all corridors)
############################################################

max_sid=max(corr_data_wk$dir_order)

corr_data_wk$real_order=corr_data_wk$dir_order
corr_data_wk$real_order[corr_data_wk$dir==reverse_direction]=1 + max_sid –
    corr_data_wk$dir_order[corr_data_wk$dir==reverse_direction]

##########################################################################
####Creating a "position" Column to better accomodate cumulative widths
##########################################################################
```

```
#Grouping by daterange and direction, order by dir_order and get the cumulative
#length to the end of each segment

plot_data<-setorder(setDT(corr_data_wk), date_range, coa_dir, tod_range,
    real_order)[,cs:=cumsum(length_mi*width_multiplier) + gap*real_order,
    by=c('coa_dir','date_range','tod_range')] ##Order by direction and dir order
    and compute cumulative length

#Get the position of the beginning of the segment

plot_data<-plot_data[,css:=cs-length_mi*width_multiplier-gap]

#Set the bar at the middle point of the segment width
plot_data<-plot_data[,position:=css+length_mi*width_multiplier/2]

plot_data$tod_range_s<-paste(plot_data$tod_range)

####################
#####PLOT GENERATION
####################

##Adjust width so that smallest segments are visible
width_multiplier=3

##Define gap between segments
gap=0.05

##position of text
arrow_pos_y=0.95*max_speed
arrow_pos_x=0.3

plot <- ggplot(plot_data, aes(x=position, y=avg_speed, fill = factor(date_range),
        alpha=factor(date_range), group=factor(date_range), width=length_mi *
        width_multiplier)) +

    theme_classic()+

    geom_bar(stat = "identity", position = "identity")+

    labs(x="Segment",y="Average Speed (mph)") +

    coord_cartesian(ylim=c(min_speed,max_speed)) +
    scale_fill_discrete(name="Date Range")+
    scale_x_continuous(labels = plot_data$real_order,breaks=plot_data$position) +
    scale_alpha_manual(values = c ("1"=0.8,"2"=0.3),guide=FALSE)+

    scale_fill_discrete(name = "Year", breaks = c("1", "2"), labels = c("2016",
        "2017")) +
    theme(strip.text.x = element_text(size = 18))+
    ggtitle(paste(plot_data$coa_corridor,'\n Weekdays')) +

    theme(plot.title = element_text(hjust = 0.5,size=16)) +
    theme(legend.title = element_text(size=12), legend.text =
        element_text(size=10), legend.position=c(0.9,0.9)) +
    theme(axis.title = element_text(size=12), axis.text =
        element_text(size=10,angle=0)) +
    theme(strip.text.x = element_text(size = 9))+

    facet_grid(coa_dir~tod_range_s, labeller = labeller(dir = labels_p,
        tod_range_s = labels_tod_p))+
```

```
        ##Adding arrow. Created separate data frame so that it can change with facets.
        geom_segment(data=dir_sign_p,aes(x=arrow_pos_x-sign*0.1,
            xend=arrow_pos_x+sign*0.1, y=arrow_pos_y-2, yend=arrow_pos_y-2), size=2,
            arrow=arrow(length=unit(2.5,"mm")),show.legend=FALSE)+
        geom_text(data=dir_text_p,x=arrow_pos_x,y=arrow_pos_y,label="Flow")

        plot(plot)
  })
}
```

CODE FOR UI.R FILE

```
fluidPage(
  titlePanel("City of Austin Traffic Signal Retiming Prioritization"),
  h3("Corridor Ranking Table"),
  DT::dataTableOutput('ranking'),

  h3("Segment Speed Plot"),
  selectInput('selected_corridor', 'Select a Corridor to Plot:',
      sort(corridor_options), selectize = TRUE),
  plotOutput('plot')
)
```

Glossary

ASC	-	Adaptive Signal Control
CoA	-	City of Austin
CTR	-	Center for Transportation Research (at The University of Texas at Austin)
GOR	-	Green Occupancy Ratio
HCM	-	Highway Capacity Manual
ITE	-	Institute of Transportation Engineers
LOS	-	Level of Service
MLP	-	Multi-Layer Prioritization
PF	-	Progression Factor
ROR	-	Red Occupancy Ratio
R_p	-	Platoon Ratio
TOD	-	Time-of-Day
UI	-	User Interface
VMT	-	Vehicle Miles Traveled

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