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Management of signal system technology on arterial corridors produces challenges for state and local departments of transportation (DOTs). The purpose of this project was to evaluate technology deployments on three arterial study corridors in Arizona. The corridors were evaluated based on criteria relating to such aspects as operations, maintenance, performance measurement, and cost. Field visits were conducted to inventory each corridor’s system, and when available, the data obtained were used to quantify performance in terms of system functionality and system efficiency. A prototype spreadsheet was developed using multiple criteria decision analysis (MCDA) to score corridor deployments based on predefined criteria. It was found that communications technology and comprehensive Advanced Traffic Management System (ATMS) software contributed to the highest scores on the corridors evaluated. The project team recommended minimum and ideal technology configurations for signalized arterial corridors. It was also found that the Arizona Department of Transportation (ADOT) would benefit from improved ATMS software and from maintenance of a technology inventory.</td></tr>
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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

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Acronyms and Abbreviations

AADT	annual average daily traffic
ADOT	Arizona Department of Transportation
ARID	anonymous re-Identification device
ATC	Advanced Transportation Controller
ATMS	Advanced Traffic Management System
ASC/2	family of Advanced System Controllers
CCTV	closed-circuit television
DOT	department of transportation
FCC	Federal Communications Commission
FHWA	Federal Highway Administration
GHz	gigahertz
ITS	Intelligent Transportation Systems
LOS	level of service
MAC	media access control
Mbps	megabits per second
MCDA	Multiple Criteria Decision Analysis
OR	operations research
PTZ	pan-tilt-zoom
RX	received messages
SR	State Route
TOC	Traffic Operations Center
TSM&O	Transportation Systems Management and Operations
TX	transmission messages
USDOT	United States Department of Transportation
USGAO	United States Government Accountability Office
V/C	volume/capacity
vpd	vehicles per day

EXECUTIVE SUMMARY

The management of technology for traffic signal communication on arterial corridors produces challenges for state and local departments of transportation (DOTs). The purpose of this project was to evaluate technology deployments on three arterial study corridors—State Routes (SRs) 77, 189, and 347—in the state of Arizona. Each corridor has different technology and different traffic patterns, and therefore has different requirements for evaluation criteria.

The technology deployments were evaluated using criteria related to operations, maintenance, performance measurement, and cost. Field visits were conducted to inventory the technology system deployed in each corridor. The project team identified key performance measures through literature searches while also considering data availability and simplicity. The performance measures fell into two general categories:

- Maintenance of system functionality
- Improvement of operational efficiency

The performance measures were calculated using data obtained from the study corridors. It was found that the technology and communications deployed on SR 77 and SR 189 allowed the Arizona Department of Transportation (ADOT) to obtain all performance measures recommended. However, though SR 347 had the technology to obtain all the performance measures, the Advanced Traffic Management System (ATMS) software was not configured to record the data necessary.

After the evaluation of corridor capabilities, a general scoring system was developed to rate arterial corridor performance. A prototype spreadsheet was developed using Multiple Criteria Decision Analysis (MCDA) to score corridor deployments based on operations, maintenance, functionality, performance measurement, and cost. It was found that communications technology and comprehensive ATMS software contributed to the highest scores on the corridors evaluated.

The project team made three recommendations for ADOT's consideration:

- Maintain an inventory of deployed technology on arterial corridors. These systems are continually changing and can be difficult for different divisions within ADOT to keep track of. An inventory would help ADOT personnel know exactly which technology is deployed even if they were not initially involved in the deployment. An inventory also would help ADOT manage technology assets.
- Either reconfigure or update the ATMS software used on SR 347. An evaluation found that by simply improving the ATMS software being used, SR 347 would obtain all the capabilities of a state-of-the-art arterial corridor.
- Explore expanding and enhancing the prototype spreadsheet for use on all arterials in the state of Arizona.

CHAPTER 1. INTRODUCTION

Deploying technology for arterial signal systems poses complex challenges. Technology can assist agencies with the operation, maintenance, and evaluation of arterial corridors. However, agencies have little guidance to draw on to understand some of the more nuanced differences between similar technologies. This project is meant to provide a process that the Arizona Department of Transportation (ADOT) can implement to assist with decision making. The process utilizes a range of criteria that includes both site characteristics and ADOT's goals. The process was developed using three signalized arterial corridors in Arizona.

PROJECT OBJECTIVES

The project undertook the following tasks:

- Compare and evaluate the three technology systems used for the study corridors with respect to maintenance functions and ability to adjust to operational changes.
- Evaluate the flexibility, expandability, and value of the three systems.
- Recommend configurations, including communication requirements, for potential ADOT implementation under different conditions.
- Recommend equipment modifications to (1) optimize performance at intersections in terms of operations, maintenance, functionality, and cost; (2) provide for optimized intersection control and monitoring from the traffic management center; and (3) complement ADOT's Transportation Systems Management and Operations Division goals and objectives for traffic management on arterials.
- Estimate the costs connected to the proposed equipment configurations: initial outlays for the infrastructure and networking connections, plus recurring costs for data service, maintenance, and personnel.

STUDY CORRIDORS

The corridors selected for study in this project were State Route 77, in Tucson (Figure 1); State Route 189, in Nogales (Figure 2); and State Route 347, in Maricopa (Figure 3). Each route is unique in its setting, traffic demand, and technologies deployed. Intersections of interest are labeled in these figures.

- SR 77 between mileposts 73.10 and 79.48 is classified as a minor arterial, moving traffic between the city of Tucson and Oro Valley. ADOT's portion of the corridor is currently operated and maintained by the ADOT Southern Region Traffic Engineering Office in Tucson. The annual average daily traffic (AADT) ranged between 39,515 and 55,8769 vehicles per day (vpd) in 2015.
- SR 189 between mileposts 1.00 and 2.78 is a principal arterial located in southern Arizona. This corridor experiences an AADT between 10,857 and 23,512 vpd. It handles relatively heavy

volumes of truck traffic (T-factor > 12 before interstate access) crossing the US-Mexico border. The corridor is operated and maintained by the ADOT Southern Region Traffic Engineering Office in Tucson.

- SR 347 between mileposts 171.05 and 182.48, located primarily in the city of Maricopa, is considered a minor arterial. At its southern end, the corridor experiences an AADT of 12,785 vpd, but the traffic load grows to about 40,126 vpd by the time the corridor reaches the city of Maricopa's northern limit. This corridor is operated by the Traffic Management Section and maintained by the Systems Maintenance Section, both of which operate out of the ADOT Traffic Operations Center in Phoenix.

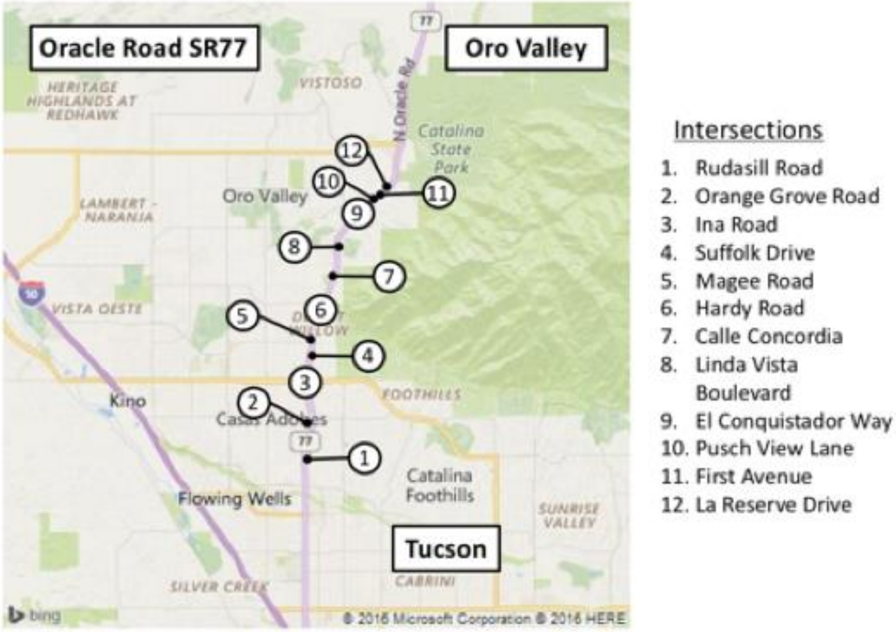


Figure 1. SR 77 Study Corridor in Tucson

(Map Source: Bing Maps, Microsoft® Corporation)

Intersections

1. La Quinta Road
2. Industrial Park Drive
3. I-19 South
4. I-19 North
5. Congress Drive
6. North Mastick Way
7. Grand Avenue

Figure 2. SR 189 Study Corridor in Nogales

(Map Source: Bing Maps, Microsoft Corporation)

Intersections

1. Farrell Road
2. Bowlin Road
3. Alterra Parkway
4. Honeycutt Avenue
5. West Maricopa Casa Grande Highway
6. West Hathaway Avenue
7. Edison Road
8. Shopping Entrance
9. West Smith Enke Road
10. Cobblestone Farms Drive
11. Lakeview Drive
12. Casa Blanca Road
13. Riggs Road

Figure 3. SR 347 Study Corridor in City of Maricopa

(Map Source: Bing Maps, Microsoft Corporation)

The three study corridors were selected primarily because ADOT took different approaches to technology deployment on each one. On SR 189, ADOT spent nearly $2 million for major overhauls, including technology deployments, to improve the corridor. Meanwhile, on SR 347, the agency took a faster approach to achieve system functionality with minimal costs. Finally, on SR 77, ADOT opted for an approach that was a compromise between the other two. While ADOT seeks to ensure that the choices it makes are thorough and well thought out, this objective can be difficult to achieve given that each site is different and there are numerous technologies and vendors to choose from. The technology choices made for each of the corridors are detailed in Chapter 3.

PROJECT FRAMEWORK

The project framework is presented in Figure 4. The framework encompasses data collection, system evaluation, and decision support leading to specific recommendations.

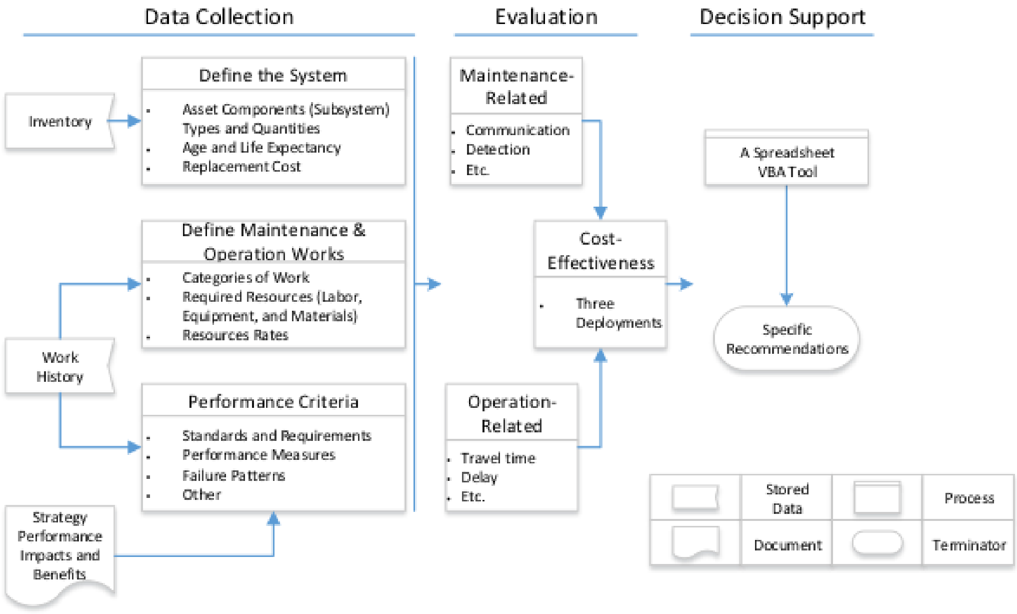


Figure 4. Project Framework

Data collection involved inventorying the components and requirements of the deployed technologies at each intersection along the study corridors. Additionally, the costs and maintenance-related qualities of the deployed products were identified, since they are relevant in the decision-making process. Finally, criteria were defined for the evaluation of system performance. Results of these efforts are documented in Chapter 4.

Upon completion of the inventorying process, the project team collected data from each technology deployed to demonstrate the types of measures that could be used to evaluate system performance.

Procedures and results are presented in Chapter 3. Also presented in Chapter 4 are the conclusions that could be drawn from the displayed measures about the operation of the sites. The results selected are meant to demonstrate the benefits of specific performance measures.

Chapter 3 addresses decision support as well. A prototype spreadsheet was developed to help ADOT decision makers configure intersections. This tool incorporates concepts from operations research on the weighting of evaluation criteria, and provides suggestions based on what was important to the ADOT engineers developing the tool. The project team used the prototype spreadsheet to evaluate the three study corridors and make recommendations for their further improvement.

CHAPTER 2. STATE OF PRACTICE

This chapter establishes the state of practice by addressing the following questions:

- What relevant performance measurement concepts inform this study?
- What relevant research informs this study?
- What practices implemented by other states can provide guidance?
- What technology is available that addresses the stated objectives of this study?

These questions were addressed to inform decisions about methodology and to better understand the research problem.

RELEVANT CONCEPTS AND TERMS

One of the primary criteria on which the technologies used in this project will be evaluated is their ability to measure performance. In this report, “performance measurement” focuses on the technologies’ ability to maintain system functionality and ensure operational efficiency. Performance-based management of transportation systems allows system managers to make informed decisions to address problems. Traffic delay, volume, travel time, signal phasing and timing metrics, and arrival metrics all affect system functionality and operational efficiency. Many of the concepts and findings discussed in this section will be used in Chapter 3.

Delay

Delay is the key metric when evaluating the impact that signal improvements have on arterial corridor mobility. Measured as time/vehicle, delay can be caused by a variety of factors. Control delay, defined as the delay due specifically to operational control, can be very difficult to measure explicitly. For signalized intersections, control delay depends on the cycle length, phase length, the way vehicles arrive, the speed at which vehicles arrive, the quality of signal progression, and the quality of signal detection systems. Control delay consists of stopped delay, start-up lost time, and vehicle deceleration, so it cannot be directly measured by roadside sensor technologies. In-vehicle technologies tracking a vehicle’s movements are the only current way to directly measure control delay (Koet al. 2008; Colyar and Rouphail 2003). To identify problems, delay can be measured for an entire intersection, by phase, or by approach.

With sensors, stopped delay and time to service can be used in place of control delay. Stopped delay is typically used to estimate control delay by measuring the total delay between the detector activations and the initiation of the green phase. Stopped delay, however, is a simplified measure that fails to account for start-up lost time, vehicle deceleration, and queue lengths exceeding the detection zone. Time to service can be used as an indicator for vehicles needing to wait exceedingly long periods of time for the green phase to activate; delayed activation indicates poor arrival types or even possible detector failures. Additionally, reviewing cycle times and phase lengths combined with time to service can indicate signals that may benefit from a sequence change (Balke et al. 2005).

Finally, level of service (LOS) is one of the most commonly used metrics to evaluate performance since it simply assigns a qualitative “grade” to how a site or intersection is performing. Intersection LOS is completely dependent on the average control delay per vehicle. It is rated on a scale of A through F, with A being the best.

Volume

Volume, throughput, and capacity are all metrics that measure a count of vehicles. Volume is a basic measure that can be used to estimate demand at an intersection. Volume is the observed count, while demand refers to the expected number of vehicles that want to use the intersection. Situational volume metrics, by time, phase, or movement, also may be used for performance measurement. With the use of high-resolution event data, volume at different points within a signal’s cycle can be examined to ensure timing plans reflect vehicle demand. Additionally, high vehicle counts in the intersection during the yellow and all-red phases can indicate a poorly timed signal or the need for additional enforcement. If there are high numbers through other movement phases, that finding can indicate a high demand for right-turn-on-red et al. 2005).

A volume-to-capacity (V/C) ratio (sometimes called the “degree of saturation”) can also be calculated. The V/C ratio is a measure of observed flow relative to a theoretical capacity. Capacity is calculated using theoretically observed values for saturation flow. Saturation flow can be calculated for each approach by multiplying the overall ideal saturation flow rate for the lanes by the ratio of effective green time to cycle length. In theory, a V/C ratio of 1 is the maximum possible value; however, since both demand and capacity are estimates, it is possible to see higher values in the field (Roesset al. 2011). Phases with high V/C ratios may indicate likely split failures. If an intersection has some phases with V/C ratios close to or exceeding 1 and other phases with lower ratios, that may indicate that capacity (green time) can be reassigned (Balke et al. 2005).

Travel Time and Travel Time Reliability

For drivers, travel time and travel time reliability are perhaps the most important measures of corridor mobility. Travel time is defined as the time it takes a driver to traverse the corridor, and travel time reliability is a general term used to describe how consistent the travel time is on the corridor from day to day. While drivers may understand that delay at an intersection contributes to poor travel times, drivers will still likely choose a route with that type of delay if they expect their travel time to be the shortest. Additionally, travel time can help quantify how an entire corridor is performing. To calculate travel time and travel time reliability, re-identification technologies like Bluetooth and Wi-Fi are frequently utilized (Haghani et al. 2010; Tsubota et al. 2011). Speed can also be used to estimate those values if re-identification technologies are not in place (Coifman 2002). Travel time reliability is simply an extension of travel time that analyzes the distribution and variance of travel time over a period of time.

Signal Phasing and Timing

Signal phasing and timing metrics are used, often in combination with other metrics such as volume, to evaluate the performance of a traffic signal. Key metrics that are tracked include cycle time and phase terminations.

Cycle time is defined as the time between the start of a green interval and the subsequent green interval of the same phase. Cycle time is important for monitoring the performance of signals that are adaptive to traffic. Long cycle times indicate light demand for a phase and can point to benefits from switching from leading to lagging lefts (Balke et al. 2005).

Phase termination occurs when the phase of a cycle ends. For pretimed signals, these are predefined by the agency operating the signal. However, for actuated and coordinated signals, phase lengths vary. Cause of phase termination is a useful metric that may indicate problems with the detection at a signal or with the signal timing plan itself. Detectors that are stuck in the ON position can cause force-offs on approaches that should generally be gapping out. Additionally, phases that frequently gap out may indicate that some green time can be reallocated (Balke et al. 2005).

Arrival Types

The way vehicles arrive at signalized intersections is important to consider when measuring performance for both individual signals and signalized arterials. A perfectly functioning signal will have all vehicles arriving at the beginning of the green phase, resulting in minimal or no control delay. However, perfect arrivals are not realistic. The *Highway Capacity Manual* defines six arrival types, with "1" being considered poor while "6" is considered exceptional (Transportation Research Board 2016). Frequent queueing may indicate that vehicles are not arriving at the correct time. Quantification of arrivals, which requires event-based data, is discussed in the following section.

Event-Based Data and Advanced Performance Measures

Event-based data (sometimes called "high-resolution" data) record an event when the signal phase changes and when a presence detector shifts between ON and OFF. Such data are collected from the detector and the signal controller and then merged. A set of performance measures has been established that require event-based data as an input to evaluate signal timing, coordination, and delay (Day et al. 2014). The guidance this work provides on detector configurations, the data storage required to implement an event-based intersection, and the uses for event-based data make a strong case for practitioners to utilize traffic signal communication systems.

Using event-based data allows for a clear analysis of signal timing and coordination plans. One suggested approach is to study the performance of signals by phase, rather than by a predefined interval (Day and Bullock 2010). Many of the previously discussed metrics, such as volume, can be evaluated by signal phase if event-based data are available.

Event-based data can be used to track split failures, green-time utilization, phase-based volume, and arrivals on green. Split failures occur when a green phase ends without clearing a queue. Frequent split failures for a specific phase mean the phase may need more green time or the signal should be retimed. Green-time utilization is a measure of how much of the green time for a phase is being used to service vehicles. If the green-time utilization for a phase is low, that phase could have its green time reallocated to another phase that may be experiencing split failures. Volumes by phase indicate the level of demand for a phase.

Arrivals on green should be used to evaluate signal coordination and actuation. Specific ranges are quantified in the *Highway Capacity Manual*, and arrivals can be estimated using event-based data and advance detectors to determine the proportion of vehicles arriving during a phase. The platoon ratio is used to denote the percentage of vehicles arriving during the green phase.

Many of the research-derived performance measures utilize event-based data since such data help relate traffic flow, indicated by the detection systems, to the signal phasing and timing plan that an engineer needs to develop. For example, event-based data were used in a clustering algorithm to classify traffic patterns observed from detectors. The results were used to select a signal timing plan in real time based on the observed patterns. The results also showed that event-based data can assist with evaluating safety and pedestrian facilities on an arterial (Muralidharan et al. 2016). Other performance measurement applications in which researchers have used event-based data include the identification of oversaturated intersections (Wu et al. 2010), the evaluation of arterial traffic flow characteristics (Wu et al. 2011), and the classification of vehicles.

Event-based data also can be integrated into visualizations such as the Purdue Coordination Diagram, which is illustrated in Figure 5. This diagram combines the visualization of arrivals with the visualization of a signal phase over time. In the diagram, the x-axis shows the time of day and the y-axis shows the time in the cycle. Each point in the diagram represents a vehicle arrival, and the lines indicate a change in the signal that the approach sees. Ideally, most points are just above the green line, indicating that vehicles are arriving early in the green phase.

RELEVANT RESEARCH

Technologies are traditionally evaluated based on two broad criteria: cost and functionality. The general research approach is to pick a metric or set of metrics by which to evaluate the technology and then report its performance. This can be done to compare two technologies that have the same function, one technology under different configurations, or both.

Three separate studies have evaluated the detection rates of microwave radar, video detectors, and wireless magnetometers under varying weather conditions. By analyzing the detection rate, the studies were able to identify conditions under which the technology was unable to reliably detect the presence of a vehicle. The studies can be used to understand how a technology may perform at a site where rain, snow, or fog, is a common issue (Medina et al. 2009; Medina et al. 2011; Medina et al. 2013).

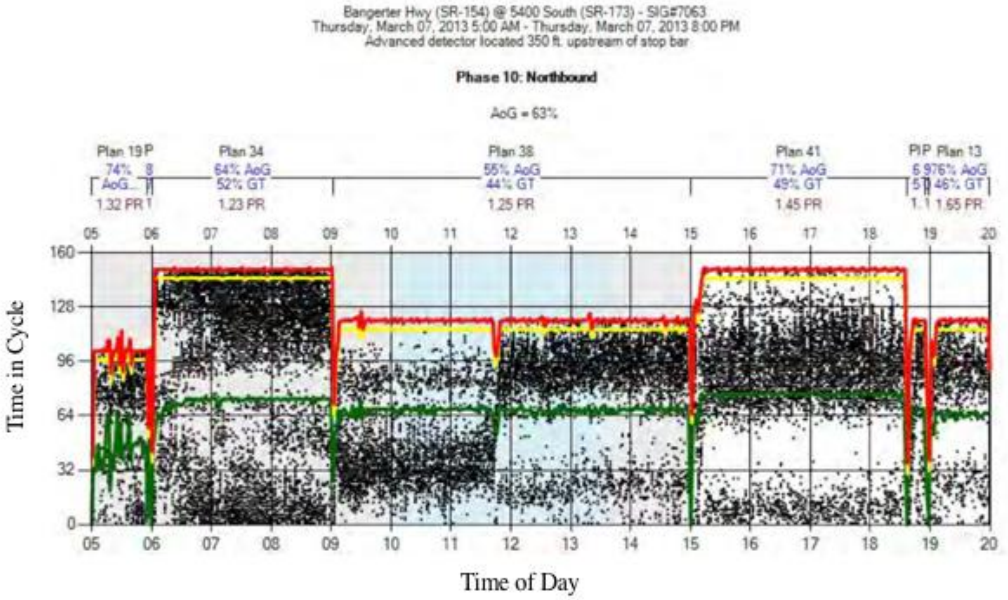


Figure 5. Purdue Coordination Diagram

(Source: Utah DOT 2018)

Benefit-cost analysis is a popular choice for evaluating Intelligent Transportation System (ITS) deployment feasibility (Bertini et al. 2005). A limitation of benefit-cost analysis is that it can be difficult to quantify and justify dollar values for nonmonetary values such as safety and delay. A study that developed a benefit-cost-analysis framework for ITS deployments concluded that little research has been done to monetize benefits of ITS (Tomecki et al. 2016).

The configuration of the technology can also impact its performance and therefore is important to consider when developing alternatives. For example, the length of detection zones for lane-by-lane loop detectors has been found to affect the operation of actuated signal controls (Smaglik et al. 2005). Meanwhile, the location and spacing of detection systems have been found to impact data sensitivity (Margulici et al. 2008). Another study has optimized loop detector configurations using a mix of safety and delay characteristics (Li et al. 2013). Texas A&M Transportation Institute has conducted a rigorous study of the detection accuracy of six detection systems and, for both stop bar and advanced detectors, provided a set of pros and cons with respect to performance, cost, operations and maintenance, and other features (Middleton et al. 2015).

The studies discussed all demonstrate that in addition to cost, a variety of other criteria can be used to compare and evaluate different technologies. These criteria include configuration (technology placement, settings, etc.), impact on traffic operations (efficiency, safety, delay, etc.), and performance under different conditions (weather, traffic flow, etc.). Many of the benefits identified through such comparisons are difficult to quantify because different users value them differently, and the perceived value may change based on the situation. For example, the performance of video detection under snow conditions will not matter to ADOT as much as it might matter to another state that regularly sees snow.

The following conclusions about research approach can be drawn from a review of the relevant studies:

1. A variety of methods and approaches may be used to evaluate technology systems for arterials. The method selected will influence the results of the evaluation.
2. The metric by which a technology is assessed depends on the value the assessor puts on various attributes, such as cost, data, and performance. The metric selected will also influence the results.
3. The technology that is appropriate for one site may not be appropriate for another site. Thus, the evaluation process should be carried out for each location. It is also critical that interoperability be maintained despite likely differences in configuration from site to site. The systems deployed must be able to communicate the same information from one intersection to the next, and to the ATMS software.

Because of the lack of related work, guidance is needed on how to plan and execute deployment of ITS on different corridors.

PUBLISHED PRACTICES AND GUIDELINES

This section is devoted to examining the published practices and guidelines that other transportation agencies are following when deploying ITS devices. Many states and regions document their plan for ITS deployment through a report or website. For example, the Oregon Department of Transportation (DOT) has done so for one of its districts in its Regional ITS Plan published in 2003 (Oregon DOT 2003). New Jersey DOT published an ITS 10-year investment strategy in 2007 (New Jersey DOT 2007).

The communications plan developed by Oregon DOT as part of its 2003 Regional ITS Plan is similar to documents developed by other state and local agencies (Stack Traffic Consulting and City of San Diego 2014; City of Laredo and Kimley-Horn and Associates 2005). Along with a set of Key Performance Indicators meant to provide guidance on ITS deployment strategies and device evaluation, a European study offers a comprehensive discussion of utility management (Payne et al. 2015).

Benefit-cost analysis is a common practice carried out by transportation agencies to make decisions on ITS and communication deployments. Florida DOT is just one agency that uses a benefit-cost-ratio threshold when deciding if an ITS project is feasible (Florida DOT 2014).

As for performance measurement, both the 2012 Moving Ahead for Progress in the 21st Century Act (MAP-21) and the 2015 Fixing America’s Surface Transportation (FAST) Act require states to report performance measures and to have at least minimal ITS infrastructure in place. Agencies that have emerged as leaders in standardizing performance measurement in their ITS operations include Indiana DOT, Utah DOT, and the City of Portland (Oregon).

Indiana DOT in collaboration with Purdue University has developed and demonstrated a variety of performance measures for signalized intersections, most of which were discussed in Chapter 1 (Day et al. 2010; Day and Bullock 2010). Utah DOT has developed an online software system by which different performance measures can be queried for many intersections in Utah (Utah DOT 2018). The City of Portland and Kittelson and Associates, Inc. have studied the performance measures that Portland can create using existing technologies and Utah DOT's software. This study provides a table showing the required technology to accurately measure data needed for performance measurement (Quayle 2013). Additionally, Report 618 from the National Cooperative Highway Research Program describes costs for the measurement of performance, recommending cost-effective measures (Cambridge Systematics et al. 2008).

TECHNOLOGY TYPES

This section describes the *types* of technology by function and the *purpose* of different technologies in terms of operations and performance measurement. It will not go into specifics on different brands. Ultimately, the choice between different brands of the same technology will come down to interoperability and interchangeability—the two characteristics that it is critical to evaluate, according to the National Transportation Communications for ITS Protocol (NTCIP 2009). In other words, are the devices able to operate with the existing signal infrastructure, and are the devices easily replaced, possibly by technology from the next generation? Besides those two characteristics, other factors that should be considered when selecting a brand is an agency's previous experiences with vendors and the price of the technology.

Traffic control technology has been shown to improve safety and to substantially improve mobility, efficiency, and energy/environmental aspects of signals (Maccubbin et al. 2008). The following technologies are frequently deployed along signalized corridors:

- Traffic signal controllers
- Vehicle detection technologies
- Radio communications
- Re-identification devices
- Traffic surveillance systems

Additionally, the type of software used to operate and communicate with devices deployed in the field can also be considered technology.

Traffic Signal Controllers

Traffic signal controllers are primarily responsible for dictating the signal phasing and timing plan, often using information from the detectors. They are required for all signalized intersections, but they are not all the same. Traffic controllers mainly consist of hardware and software and follow two different standards, one developed by the National Electrical Manufacturers Association and the second, the Model 2070 standard, developed by the California Department of Transportation. The difference in standards does not impact the functionality of the controller. The only difference between them is the way they have the controller physically sit in the cabinet. Additionally, there is little choice between controller types, since many vendors sell only one controller in two versions: one for each standard. Newer versions of controllers typically can handle larger numbers of inputs from other technology, so a set of four video detection systems (one for each approach) with many detection zones could be limited by an older controller. Since vendors typically do not sell old versions of controllers, purchasing a controller from a vendor will result in the latest available version.

Vehicle Detectors

Vehicle detectors can serve multiple functions on a signalized corridor. At an intersection, detectors can be placed at stop bars to alert the controller that a vehicle needs to be serviced, and before stop bars to alert the controller that a vehicle is approaching or that a queue is building. The main types of technologies available for detection include inductive loop detectors, image-processing systems, and radar-based sensors. Image-processing systems can use either thermal vision or regular video to track objects moving through the field of vision. Additionally, many detection technologies can be used for bicycle detection. Detection technologies are required for implementing any adaptive plan of signal phasing and timing. Such technologies are also used to collect data, particularly on volumes, arrivals, and sometimes speed.

In general, all detectors have two states: ON and OFF. If a vehicle is within the detection zone, a functioning detector will be ON. Otherwise, it will be OFF. Detector ON-OFF events are recorded in event-based data. The size of each detection zone will depend on the technology being used and the way it is configured. For example, loop detectors are embedded in the ground and only detect vehicles within the magnetic field above them. Meanwhile, a video image processor can be programmed to have multiple detection zones within the field of vision.

The arrangement of detection technology (e.g., stop bar detectors on the minor approach to an intersection and advance detectors on the major approach) tends to be more important to both operations and performance measurement than the actual type of technology. However, the type is very important for maintenance-related purposes. Image-processing systems and radar, though nonintrusive into the pavement, tend to be subject to occlusion and therefore require careful placement and setup to function properly. Image-processing systems are particularly adaptable since detection zones can be set up to capture turning movements and lane-by-lane through-movements using the same device. However, such systems are reliant on the video detection algorithms and require occasional cleaning of lenses. Loop detectors are pavement-intrusive, which can protect them from environmental factors (weather, theft, etc.). But when loop detectors do break, the maintenance is more involved, requiring lane closures, cutting, and repaving.

Radio Communications

Communications were of specific interest to ADOT in this project for many reasons. Among the benefits a robust communications system can provide are the real-time transmission of data collected by deployed technologies, the ability to remotely adjust settings of deployed technologies, and the ability to monitor overall system health. However, radio communications add one more system that needs to be maintained and monitored. One goal of this project is to establish how to objectively monitor the performance and health of the communications system itself, through ping tests and visualization.

Communications are necessary for transferring information from one signal to another, from a Traffic Operations Center (TOC) to the field, and from one TOC to another. Typically, the transfer is achieved via some combination of fiber-optic cable and radio communication, though copper wire can also be used and is often present in older networks.

A radio’s capacity is quantified in bytes and can be divided between transmission messages (TX) and received messages (RX). Some radios have fixed capacity allocations (e.g., 100 MB RX/100 MB TX) while other radios are flexible and can allocate transmissions between TX and RX based on the user’s preferences. Transmission messages are important for sending data back to the TOC or to other signals, while received messages are important for acquiring commands from the TOC for settings adjustments or from another signal for coordination purposes. For a connection to the TOC, a backhaul channel is also required. Backhaul is used to describe how the networked system connects to the TOC; it represents another radio, fiber, or Ethernet connection between one end of the networked system and the TOC. Networked radios need to have the capacity to transmit and receive their own packets between receivers while also transmitting and receiving the packets of radios deeper in the network. An example of this is shown in Figure 6. Assuming a traffic surveillance system requires 3 megabits per second (Mbps) of bandwidth, the backhaul channel to the TOC must be able to handle 3 Mbps for each of the intersections that are networked. Table 1 provides the TX and RX bandwidths required to successfully operate each type of ITS to the highest capacity. The actual number varies based on what is being transmitted, the compression algorithms being used, and the quality of the device.

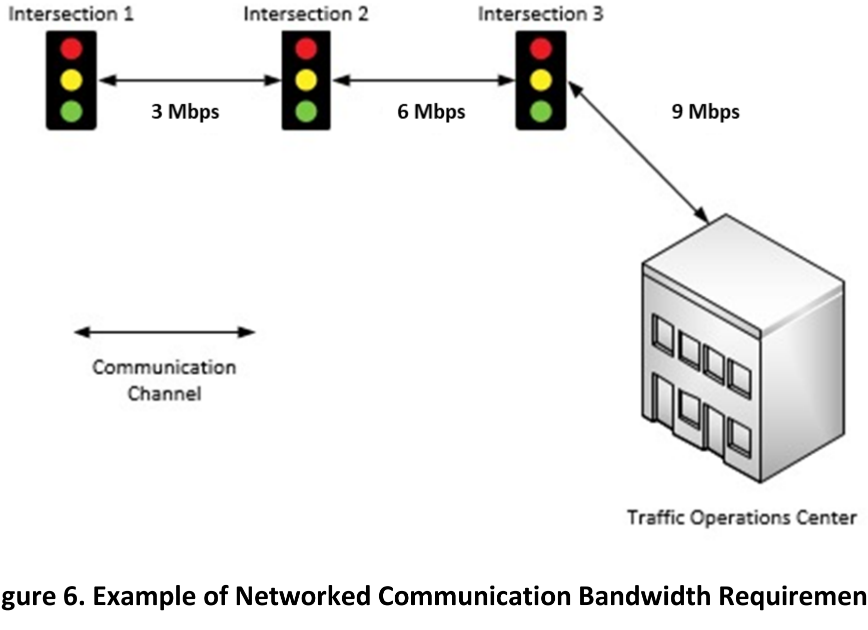


Figure 6. Example of Networked Communication Bandwidth Requirements

Table 1. Bandwidth Requirements for Different Technologies

ITS Device	TX Bandwidth Required	RX Bandwidth Required
CCTV Live Video	High	Low
Signal Controller	Medium	Low
Video Detector	High	Low
Radar Detector	Medium	Low
Bluetooth ARID	Low	None
Wi-Fi ARID	Low	None
Loop Detector	Medium	None

Antennae are responsible for projecting and receiving the messages and can be set up in a directional or omnidirectional configuration. The range in which a radio can transmit and receive messages is dictated by the radio's frequency. Frequencies are typically reported in gigahertz (GHz). A directional short-range radio (5.8 GHz) has a range of roughly 2 miles, while a directional long-range radio (11 GHz) can operate up to 4 miles. Longer-range radios are more susceptible to problems caused by weather and geomagnetic storms.

A Federal Communications Commission (FCC) license may be purchased for the radios. This helps to prevent interference by reserving a specific bandwidth for the radios. Interference can cause packet loss and network latency issues that can lead to missing data, missed commands, and other problems. Radios are typically mounted high above the intersection to avoid interference. A common maintenance activity to ensure good latency is to periodically realign the radios in the network.

Re-Identification Devices

Re-identification technology in the traffic control context refers specifically to media access control (MAC) address readers utilizing either Bluetooth or Wi-Fi, though the technology can also include other image-processing devices such as automatic license plate readers. The idea is to identify a vehicle at two different points to calculate the travel time between those points. Re-identification technology can also be used to estimate low-resolution origin-destination information. In the context of this project, re-identification systems are used primarily to collect travel times. Most re-identification systems deployed for travel time estimation read MAC addresses of discoverable devices passing a station. These MAC addresses are then transmitted anonymously via Bluetooth or Wi-Fi. Such systems will be referred to as Anonymous Re-Identification Device (ARID) systems.

Bluetooth and Wi-Fi technologies can be used to estimate control delay as well. Since delay estimation relies on signal strength, vendors recommend that multiple devices be deployed at a single intersection for improved estimates. These devices can be either mounted on poles or placed in the cabinet. The choice depends on how much flexibility of use is desired. For permanent devices, pole-mounted antennas provide the best signals but are more difficult to move and are exposed to weather.

Traffic Surveillance Systems

Traffic surveillance systems, such as Closed-Circuit Television (CCTV), are used by operators to view live feeds from a remote location, such as a traffic operation center. State-of-the-art systems have pan-tilt-zoom (PTZ) capabilities that can be controlled by an operator and provide high-quality video feeds. While these systems do not necessarily provide direct operational benefits, they allow TOC operators to quickly examine an unusual situation (such as a crash or disabled vehicle) and take appropriate actions to respond.

Video detectors can also transmit video feeds back to the TOC, but they are less flexible than the PTZ systems since they are fixed and in a position specifically for detection. All traffic surveillance technologies require maintenance for lens cleaning, which requires a team to go out with a bucket truck. Since this is not a time-consuming maintenance procedure, an entire corridor can easily be cleaned in a single trip.

Advanced Traffic Management Software

Software used by TOC operators to interface with the devices deployed in the field is also a critical component of traffic control technology. Often called Advanced Traffic Management System (ATMS) software, these programs enable signal technicians, signal managers, and supervisors to collect data, identify devices that may be malfunctioning, and remotely adjust device configurations. Interoperability with devices is critical, regardless of the technology that ends up getting deployed. Additionally, some vendors provide their own software to go along with the purchased devices, and aspects of the software such as functionality, user interface, and data collected should be considered in the decision-making process.

CHAPTER 3. SYSTEM DEFINITION

This chapter describes, for each of the three study corridors, an inventory of the technologies currently deployed, the age and life expectancy of the technologies, the costs associated with replacement, and the resources required to operate and maintain the systems.

SYSTEM INVENTORY

To fully understand the research problems, each technology deployed on the three corridors needed to be meticulously documented into a system inventory table. Each corridor was visited by the project team to determine the ITS that was already deployed. Most cabinets were opened with the assistance of ADOT personnel so that team members could examine the device configuration at each of the intersections on the corridor. SR 77 was in the process of being upgraded at the time of the site visit, SR 347 had received upgrades completed in late 2016, and SR 189 had received upgrades completed in 2015. It is worth noting that the updating process is generally ongoing, and since the field visits, minor updates have been made to each system.

SR 77 and SR 189 are both operated and maintained by ADOT's Southern Region Traffic Engineering Office based in Tucson, while SR 347 is operated and maintained by ADOT's Traffic Operations Center out of Phoenix. The offices currently use different vendors for ATMS software. To maintain privacy, the vendors will be referred to as Vendor 1 for the Southern office and Vendor 2 for the Phoenix office. Each ATMS program has different user interfaces and different customization capabilities, but generally performs the same operations by interfacing with the deployed ITS.

SR 77 primarily uses loop detection systems and video detection systems for the stop bars on the minor approaches and as advance detectors on the major approaches. Bluetooth has been installed along most of the corridor for travel time data collection. The communications system consists of 12 licensed radio pairs divided into three networked segments. Backhaul utilizes three unlicensed radios (one is 4.8 GHz, and the other two are 5.9 GHz), and each one connects to a point on Interstate 10 (I-10) from which the signals are relayed to ADOT's Southern Office. Figure 7 presents photos of a representative intersection on SR 77 showing pole-mounted communications systems and the inside of a traffic cabinet. The project team's field visit to SR 77 occurred on September 15, 2016.

Figure 7. Pole-Mounted Communications and Interior of Traffic Cabinet at Intersection of SR 77 and Hardy Road (September 15, 2016)

SR 189 uses microwave radar as the primary detection system for both stop bar and advance detection at signalized intersections. Bluetooth is used to collect travel time data. Photos of SR 189 and its intersection with Grand Avenue, taken at the site visit on November 30, 2016, are shown in Figure 8.

Figure 8. Site Visit to SR 189, and Intersection of SR 189 and Grand Avenue (November 30, 2016)

SR 347 uses thermal image-processing systems for each approach at most of the signalized intersections. The systems have several detection zones and can be configured to both collect counts by movement and serve as detectors for the signal controls. Wi-Fi is used to collect travel time throughout the corridor. Networked 4.9-GHz radios handle communications on the corridor. An 11-GHz long-range radio connects Riggs Road to I-10, where a connection is made to ADOT's Phoenix TOC. Photos of a representative intersection on SR 347 showing pole-mounted communications and the inside of a traffic cabinet are presented in Figure 9. The site visit took place on October 11, 2016.

Figure 9. Intersection of SR 347 and Bowlin Road, and Interior of Traffic Cabinet (October 11, 2016)

Tables 2, 3, and 4 provide an inventory of the detection systems, traffic control devices, and communications found at each intersection along each of the three study corridors at the time of the site visit. These configurations changed throughout the project.

Table 2. SR 77 Technology Inventory

Cross Street	Signal Controller	Stop Bar Detectors	Advance Detectors	Traffic Surveillance System	Communications	Re-Identification	Backhaul to TOC
Rudasill Road	ATC	Loops	None	None	Short Short-Range Radio	None	Radio*
Orange Grove Road	ATC	Microwave Radar	Microwave Radar	None	Short Short-Range Radio	Bluetooth	None
Ina Road	ATC	Loops	Loops	Fixed	Short Short-Range Radio	Bluetooth	Radio*
Suffolk Drive	ATC	Video	None	None	Short Short-Range Radio	Bluetooth	None
Magee Road	ATC	Loops	Loops	Fixed	Short Short-Range Radio	None	None
Hardy Road	ATC	Loops	None	Fixed	Short Short-Range Radio	Bluetooth	Radio*
Calle Concordia	ASC/2	Video and Loops	Video	Fixed	Short Short-Range Radio	Bluetooth	None
Linda Vista Boulevard	ASC/2	Video	Video	None	Short Short-Range Radio	Bluetooth	None
El Conquistador Way	ASC/2	Video	Video	None	Short Short-Range Radio	Bluetooth	None
Pusch View Lane	ATC	Video	Video	None	Short Short-Range Radio	None	None
First Avenue	ATC	Video	Video	None	Short Short-Range Radio	None	None
La Reserve Drive	ATC	Video	Video	None	Short Short-Range Radio	None	None

*Radios are Short-Range, Unlicensed

Table 3. SR 189 Technology Inventory

Cross Street	Signal Controller	Stop Bar Detectors	Advance Detectors	Traffic Surveillance System	Communications	Re-Identification	Backhaul to TOC
La Quinta Road	ATC	Microwave Radar	Microwave Radar	Fixed	Short-Range Radio	Bluetooth	None
Industrial Park Drive	ATC	Microwave Radar	Microwave Radar	Fixed	Short-Range Radio	Bluetooth	None
I-19 South	ATC	Microwave Radar	Microwave Radar	Fixed	Short-Range Radio	Bluetooth	None
I-19 North	ATC	Microwave Radar	Microwave Radar	Fixed	Short-Range Radio	Bluetooth	None
Congress Drive	ATC	Microwave Radar	Microwave Radar	Fixed	Short-Range Radio	Bluetooth	None
North Mastick Way	ATC	Microwave Radar	Microwave Radar	Fixed	Short-Range Radio	Bluetooth	None
Grand Avenue	ATC	Microwave Radar and Loop	Microwave Radar and Loop	Fixed	Short-Range Radio	Bluetooth	None

Table 4. SR 347 Technology Inventory

Cross Street	Signal Controller	Stop Bar Detectors	Advance Detectors	Traffic Surveillance System	Communications	Re-Identification	Backhaul to TOC
Farrell Road	ATC	Thermal Image Processor	Thermal Image Processor	PTZ	Short Short-Range Radio	Wi-Fi	None
Bowlin Road	ATC	Thermal Image Processor	Thermal Image Processor	None	Short Short-Range Radio	Wi-Fi	None
Alterra Parkway	ATC	Thermal Image Processor	Thermal Image Processor	PTZ	Short Short-Range Radio	Wi-Fi	None
Honeycutt Avenue	ATC	Thermal Image Processor	Thermal Image Processor	None	Short Short-Range Radio	Wi-Fi	None
West Maricopa Casa Grande Highway	ATC	Thermal Image Processor	Thermal Image Processor	PTZ	Short Short-Range Radio	Wi-Fi	None
West Hathaway Avenue	ATC	Thermal Image Processor	Thermal Image Processor	None	Short Short-Range Radio	Wi-Fi	None
Edison Road	ATC	Thermal Image Processor	Thermal Image Processor	PTZ	Short Short-Range Radio	Wi-Fi	None
Shopping Entrance	ATC	Thermal Image Processor	Thermal Image Processor	None	Short Short-Range Radio	Wi-Fi	None
West Smith Enke Road	ATC	Thermal Image Processor	Thermal Image Processor	PTZ	Short Short-Range Radio	Wi-Fi	None
Cobblestone Farms Drive	ATC	Thermal Image Processor	Thermal Image Processor	PTZ	Short Short-Range Radio	Wi-Fi	None
Lakeview Drive	ATC	Thermal Image Processor	Thermal Image Processor	PTZ	Short Short-Range Radio	Wi-Fi	None
Casa Blanca Road	ATC	Thermal Image Processor	Thermal Image Processor	None	Long Long-Range Radio	Wi-Fi	None
Riggs Road	ATC	Thermal Image Processor	Thermal Image Processor	PTZ	Long Long-Range Radio	Wi-Fi	Fiber

TECHNOLOGY LIFE EXPECTANCY

The life expectancy of ITS devices varies. However, the rapid rate at which ITS technology is developed and changes is likely to drive an infrastructure provider to replace system components before the devices stop working. Thus, a cap has been placed on the life expectancies reported in this study based on the assumption that the technology will become outdated within 10 years, and that even if a device is still physically working, it will not be doing so to the standard that will be desired in 10 years. At that point, the technology will be replaced with an improved system. While 10 years is believed to be a conservative number given the rate at which technology has progressed in recent history, further study is warranted.

At the rate cellular, wireless, and vehicular technologies are changing, it is reasonable to assume the landscape will be significantly different in 5–10 years. For example, connected/autonomous vehicles have been undergoing pilot tests for the last five years and will require additional infrastructure to be deployed at intersections. With this development, a variety of sensor technologies will be obsolete, either because the new technologies can accomplish the same tasks with better accuracy, or because they do not interface properly with the old technologies.

Table 5 presents the assumed life expectancies of traffic technologies used in this study, with the 10-year cap.

Table 5. Assumed Technology Life Expectancies

System	Life Expectancy (Years)
Signal Controller	10 years
Detector – Loop	5 years
Detector – Radar	10 years
Detector – Video/Thermal	10 years
ARID – Bluetooth	10 years
ARID – Wi-Fi	10 years
Long-Range Radio + Antenna	7 years
Short-Range Radio + Antenna	7 years
Traffic Surveillance System – Fixed	10 years
Traffic Surveillance System – PTZ	10 years

COST OF TECHNOLOGY

Technology costs were acquired through a variety of sources within ADOT. When available, the exact costs were used; when exact numbers were unavailable, estimates were used, either from ADOT engineers or, in the worst case, from literature. Table 6 provides a rough cost estimate for each technology over the technology's expected life. It is assumed that the capital costs are paid again after the assumed life of the technology has passed, though it is possible in some cases that the operational and maintenance costs will just increase (since the device will require more frequent maintenance). The reason for the rough estimate is twofold. First, prices change over time as the value of money changes over time, technology production becomes more streamlined, and competitors arise in the industry. Second, prices are often negotiated with vendors, especially when large quantities of a product are purchased at once. The rough values are used as defaults in the spreadsheet, but it is recommended that users adjust the costs manually if they are able. Finally, it is important to remember that the presence of communications impacts the operational and maintenance costs of technologies, since communications systems allow certain functions to be carried out remotely. Entries with asterisks indicate that some vendors offer a subscription service to use the technology, which will also impact the operational cost of the system. The values shown were collected from the staff of ADOT's Transportation Systems Management and Operations (TSM&O) Division and from the database of the Federal Highway Administration's (FHWA's) ITS Joint Program Office. All cost information was collected at the end of 2016.

Table 6. Assumed Technology Costs

System	Capital Cost (US Dollars)	Operational and Maintenance Costs (US Dollars/Year)
Signal Controller – ATC	$3,500 per controller	None
Detector – Loop	$12,000 per intersection	$1,000 per intersection
Detector – Radar	$6,000 per device	$200 per device*
Detector – Video/Thermal	$15,000 per intersection	$600 per intersection*
ARID – Bluetooth	$4,000 per device	None*
ARID – Wi-Fi	$4,500 per device	None*
Long-Range Radio	$8,000 per pair (450 Mbps)	$1,000 per pair
Short-Range Radio	$3,000 per pair (450 Mbps)	$1,000 per pair
Fiber-Optic Cable + Conduit	$15 per foot	None
Traffic Surveillance System – PTZ	$4,500 per system	$1,000 per system

Additionally, the costs presented depend on the availability of the infrastructure required for the system to operate properly. For example, traffic surveillance systems require access to a power source and also a high location where they can be mounted to provide a good range of visibility. These aspects must be accounted for by the design engineer, since the price of installing a mount just for a PTZ system makes that system less cost-effective. However, that same mount and power source can potentially be used for the radar detection systems. Thus, many aspects of the cost must be examined from a holistic view of the intersection, rather than from just a view of the individual device. Table 7 presents the costs of the extra equipment commonly required to make the technology function.

Table 7. Additional Costs Assumed in the Spreadsheet

Item	Cost (US Dollars)
Engineering Services and Customer Support	Varies by vendor
Traffic Control Cabinet	$6,700 per cabinet
FCC License	$465 per radio pair
Mount	$1,000 each
Switch	$2,500 per cabinet

OPERATIONAL AND MAINTENANCE PROCEDURES

The operational and maintenance costs associated with each technology were presented in the previous section. However, the cost burden is only one aspect of operations and maintenance. There are additional issues that must be considered. A staff of technicians are responsible for maintaining the systems deployed. They are often required to use ADOT resources to perform on-site maintenance, which can take an entire day, depending on the work required and the proximity of the site to the technicians' office. It would clearly be desirable to reduce the frequency with which technicians need to go to the field to fix problems that sometimes just involve restarting or adjusting a device. Reducing the frequency of field visits can be addressed in two ways—first, by using devices that are reliable and rarely require maintenance, and second, by using devices that a technician can troubleshoot remotely and take some basic actions on to address problems. The opportunity for monitoring and repair is one of the primary benefits of remote communications.

Maintenance falls into two categories—planned and unplanned. Planned maintenance involves regularly recommended activities, some of which are summarized in Table 8. These can be scheduled as needed and done for an entire corridor at once, usually in an afternoon. Addressing the whole corridor in a single trip makes it possible to save money.

Unplanned maintenance is more difficult, since it generally involves isolated incidents of technology breakdowns. Some devices are harder and more costly to replace than others. Loop detectors, for example, require a lane closure and are difficult to extract from the pavement. Anything attached to a mount requires a bucket truck to replace. Meanwhile, other devices or specific problems just require a technician to access the cabinet and replace something, such as a switch in the cabinet or a card for the loop detector. There is value to being able to remotely identify the likely problems so that the right resources can be applied. The costs associated with operating and maintaining a signalized intersection are presented in Table 9.

Table 8. Maintenance Activities

Device	Regular Planned Maintenance
Image-Processing Systems	**Regular Detector** – Lens cleaning recommended every six-months, realignment **Thermal Detector** – Lens cleaning recommended every year, realignment **PTZ Traffic Surveillance System** – Lens cleaning recommended every six months, realignment
Radios	Realignment of radios recommended as needed
Radar Detectors	Realignment
Loop Detectors	Loop card resets recommended as needed
ARID	None

Table 9. Additional Maintenance-Related Costs

Item	Cost (US Dollars)
Technician	$30 per hour
Bucket Truck	$30 per hour
Mileage	Varies

CHAPTER 4. EVALUATION OF EXISTING SYSTEMS

This chapter details a new approach to evaluating arterial systems. The approach will be demonstrated on the three study corridors, and findings will be discussed.

MULTIPLE CRITERIA DECISION ANALYSIS (MCDA)

Decision support is a relatively established topic of operations research (OR). However, despite clear relevance, many OR methods are rarely used to solve transportation problems in practice unless those methods have already been incorporated into a standard practice. An expert FHWA panel reported that trade-offs in decision making and asset valuation methodologies were both areas of research needs (USDOT 2007). The US Government Accountability Office (USGAO), in a report to the US House of Representatives Committee on Transportation and Infrastructure, noted the difficulty of quantifying the benefits of ITS in transit applications (USGAO 2016). This could arguably become even more of an issue for arterial ITS systems, where the larger variety of technologies available could result in more and more ways to estimate different performance measures.

In the current project, a weighted-sum Multiple Criteria Decision Analysis (MCDA) approach was taken to evaluate each of the study corridors. A variant of an MCDA approach known as analytic hierarchy process has been used to evaluate signal controller software options (Mladenovic et al. 2017). And a different variant of MCDA has been used to assess corridor performance based on high-level regional priorities such as safety, mobility, and growth (Boadi et al. 2017). These studies indicate that the potential for MCDA in asset management problems is known to an extent. Still, it is evident that use of this approach has not become standard practice for the vast majority of state and local DOTs.

A variety of techniques, including some of the aforementioned ones, can be used to conduct MCDA. The approach used here, referred to as the weighted-sum model, or WSM, has previously been employed to demonstrate the value of the technique in solving a complex problem faced by many agencies (Fishburn 1967). Its purpose in the present study is to demonstrate the benefit of using MCDA for technology deployments on arterial corridors and to showcase the tool developed. This method can be explored further in future research.

MCDA is a technique that allows multiple alternatives to be put side by side and directly compared based on criteria of particular interest to the investigator. The process assigns weights to criteria based on the user’s preferences and reports a score for each alternative that takes those preferences into account. Thus this method provides user-specific results while still employing a mathematical process to analyze results.

Equation 1 shows the definition of an alternative's score ($A_{WSM\text{-}Score}$) using the WSM approach:

$$A_{WSM-Score} = \sum_{j=1}^{n} a_{ij} w_j \ \ for\ i = 1,2,3 \ldots m \qquad \text{(Eq. 1)}$$

where n is the number of decision criteria
m is the number of alternatives
a_{ij} is the value of alternative i for the j^{th} criterion
w_j is the weight assigned to the j^{th} criterion

The best alternative is the one that satisfies Equation 2:

$$A^*_{WSM-Score} = \max_i \sum_{j=1}^{n} a_{ij} w_j \ \ for\ i = 1,2,3 \ldots m \qquad \text{(Eq. 2)}$$

where $A^*_{WSM\text{-}Score}$ is the best alternative (the one that maximizes the score)

In the WSM, the value of an alternative's score, $A_{WSM\text{-}Score}$, is additive, which means the units of each a_{ij} must match. To solve this, unitless scores were developed to define values of a_{ij} to ensure that the comparisons could be made. This allows the tool to compare dollar values to performance measurement capabilities with ease. Development of these scores will be discussed at a later point in the chapter.

The WSM method was selected because it is simple and has been widely used in research and practice. Thus, it can be safely used to demonstrate the value of the MCDA approach to solving this problem. A complete discussion of the WSM method and numerous other methods can be found in *Multi-Criteria Decision Making Methods: A Comparative Study* (Triantaphyllou 2000); the authors plan to rigorously compare methods for MCDA implementation in a future study.

EVALUATION CRITERIA

The first step in using the MCDA approach is to select the evaluation criteria. There are two primary groups criteria can be placed into—performance measures and technology characteristics. Performance measures will be selected from among those previously discussed in Chapter 2 based on the value of the information they provide to ADOT about operations and maintenance. Technology characteristics will be selected based on the features that are relevant to the operation and management of a system. Ultimately, the criteria selected will depend on factors related to the site and the user implementing the method.

Performance Measures

Chapter 2 presented a list of performance measures, categorized by purpose, that could be used to evaluate performance. The present section discusses the performance measure that has been selected for each purpose. The selection was carried out after the site visits to each study corridor, so that it was clear what technology was in place in the corridor. While some of the measures selected were introduced in Chapter 2, others were developed and customized by the project team to be usable with and helpful to ADOT's existing systems.

Performance measures have been divided into two groups defined by function. The first function is the maintenance of system health. These measures do not inherently help traffic progress smoothly, but they do allow ADOT engineers to monitor the technology and communication systems deployed and ensure they are operating fully and as intended. The second function is the improvement of operational efficiency. The metrics in this group are meant to help ADOT engineers adjust operations on the corridors and improve traffic flow.

Table 10 shows the performance measures selected to evaluate each corridor. Each performance measure in the table can either be mapped to one of the major purposes of performance measurement as set forth in Chapter 2, or be used to help ADOT sustain functionality of the system.

Each of the measures were selected because they are not overly complex but still provide substantial utility to ADOT engineers. Other measures presented in Chapter 2, such as the Purdue Coordination Diagram, are feasible to use if a deployed system allows for the measures presented in the table. However, the post-processing of such data requires numerous additional steps that should be automated in the future. Table 11 provides information on the data requirements and sources for each of the selected performance measures.

Table 10. Performance Measures Selected for Corridor Evaluation

Objective	Category	Performance Measure	
		Name	**Purpose**
Sustain System Health	**Communication**	Percentage of communication loss	Health index of communication
		Data completeness	
	Detection	Frequency of detector failure alerts	Health index of detection
Improve Operational Efficiency	**Capacity Allocation**	Traffic throughput/volume	Opportunity index for capacity reallocation
		Frequency of split failures	
		Degree of saturation/green-time utilization	
	Traffic Progression	Vehicle delay	Level of service Progression quality index
		Queue length	
		Percent arrival on green	
		Travel time	

Table 11. Primary Data Requirements for Performance Measures

Performance Measure	Description	Primary Data Requirements	Source of Data
Percentage of communication loss	Percentage of successful ping responses in all ping attempts	Ping attempt log	High-resolution-signal event-based data
Data completeness	Ratio of time gaps with missing data to analysis time period	Phase on and off events Detector on and off events (optional)	High-resolution-signal event-based data
Frequency of detector failure alerts	Numbers of detector-failure alerts within a period of time	Detector-failure events	High-resolution-signal event-based data
Traffic throughput/volume	Total vehicles serviced by a phase or cycle	Traffic counts Signal timing	Aggregated traffic counts
Frequency of split failures	Numbers of split failures within a period of time	Phase-termination events (max-out, force-off and gap-out)	High-resolution-signal event-based data
Degree of saturation/ green-time utilization	Ratio of fully used green time to total green time	Traffic counts OR phase on and off events Detector on and off events	Aggregated traffic counts OR high-resolution-signal event-based data
Vehicle delay	Control delay, measured as time lost due to operational systems	Traffic counts OR phase on and off events Detector on and off events	Aggregated traffic counts OR high-resolution-signal event-based data
Queue length	Length of vehicle queue by phase	Traffic counts OR phase on and off events Detector on and off events	Aggregated traffic counts OR high-resolution-signal event-based data
Percent arrival on green	Number of vehicles arriving within the green phase	Phase on and off events Advance detector on and off events by lanes	High-resolution-signal event-based data
Travel time	Average time to drive from one point to another	Bluetooth or Wi-Fi MAC address	Bluetooth or Wi-Fi MAC address

To produce the data needed to measure performance, a signal system should have the following capabilities throughout:

- High-resolution-signal data
- Lane-by-lane traffic counts from advance detectors and presence detectors
- Bluetooth or Wi-Fi MAC address readers
- Communication capabilities

However, the MCDA approach allows for examination of a corridor that has only partial coverage of those capabilities, and for examination of the impact of partial coverage on each of the performance measures. MCDA allows the engineer to weigh trade-offs between capabilities and cost. When a performance measure cannot be directly calculated, it can often be estimated using a variety of methods, each producing a different result. These estimates are typically considered less robust but can still be used if needed. One goal of this project is to examine and quantify different estimation techniques to help with the decision-making process. Table 12 provides an overview of the requirements for obtaining each performance measure through different techniques.

Table 12. Methods to Obtain Data for Each Performance Measure

Performance Measure	Direct Measurement Data Requirements	Estimation Methods
Percentage of communication loss	Ping attempt log	–
Data completeness	Presence detector ON-OFF events	–
Frequency of detector-alarm failures	ATMS software + loop detectors	–
Traffic throughput/volume	Count detectors	Presence detector ON-OFF events
Frequency of split failures	Phase-termination events	Presence detector ON-OFF events
Degree of saturation/green-time utilization	Phase-termination events + presence detector ON-OFF events	Presence detector ON-OFF events
Vehicle delay	–	Presence detector ON-OFF events Wi-Fi or Bluetooth signal strength
Queue length	–	Advance detector ON-OFF events by lane Traffic counts
Percent of arrival on green	Phase-termination events + advance detector ON-OFF events	Phase-termination events + Presence detector ON-OFF events
Travel time	Bluetooth or Wi-Fi MAC addresses	Point-based speed

Performance Measure Examples

This section presents select examples of performance measures using data from the three study corridors. Percentage of communication loss is a way to quantify stability of communication between an arterial and a TOC using ping tests. Corridors experiencing frequent outages likely have unstable communications with the TOC. The problem could stem from the corridor's radios or from the backhaul communications. Figure 10 shows an example where communications on Oracle Road went completely down over multiple days in mid-October 2016.

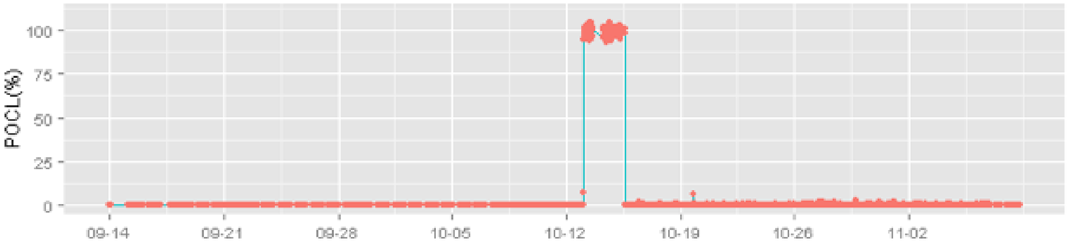


Figure 10. Percentage of Communication Loss on Oracle Road from Mid-September to November 2016 (Outage Occurred in Mid-October)

Figure 11 displays travel times on SR 347 collected using Wi-Fi-based sensors over the course of a day. Also shown are the distribution of travel times during that day and the number of sample sizes used to estimate each travel time.

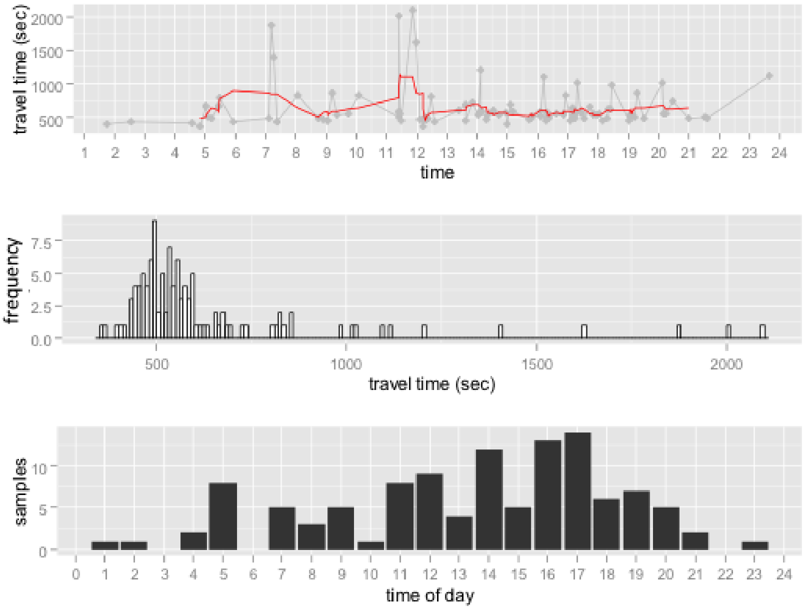


Figure 11. Travel Time, Travel Time Distribution, and Sample Sizes on October 10, 2016, on SR 347

Figure 12 illustrates split failures over a day for the left-turn phase at an intersection on SR 189. Red lines indicate the phase was terminated with vehicles remaining in the queue.

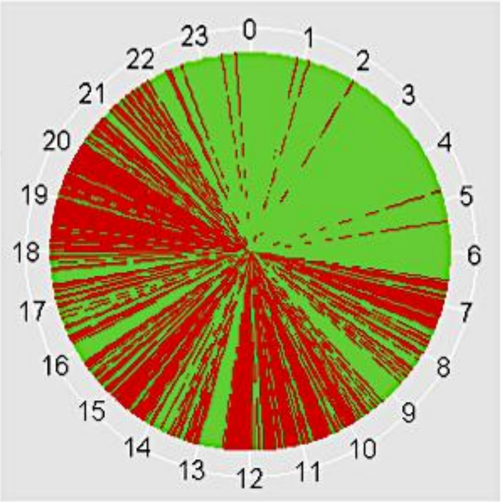


Figure 12. Split Failures on September 12, 2016, on SR 189

Figure 13 portrays queue lengths for each approach to an SR 189 intersection over an entire day. These were obtained using the detection technology deployed on the corridor. Event-based data make it possible to identify when split failures have occurred and how long the associated queue lengths have been.

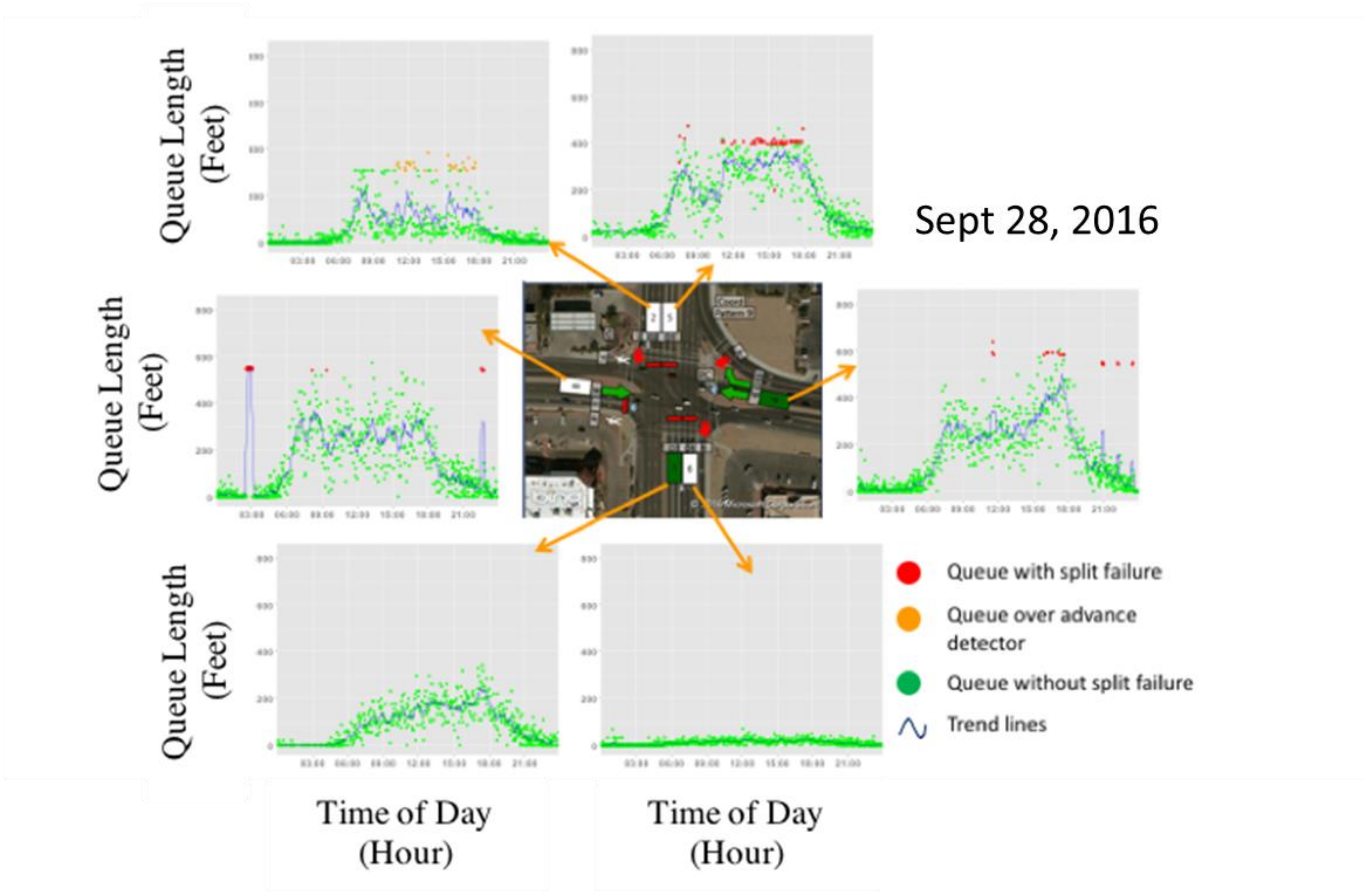


Figure 13. Queue-Length Estimation on Sept 28, 2016, at an Intersection on SR 189

Figure 14 graphs the estimated total daily hours of delay at an intersection on SR 77. Weekdays (September 26–30) averaged almost 56 hours of total delay during the week depicted. This constituted 56 hours of time lost due to intersection controls.

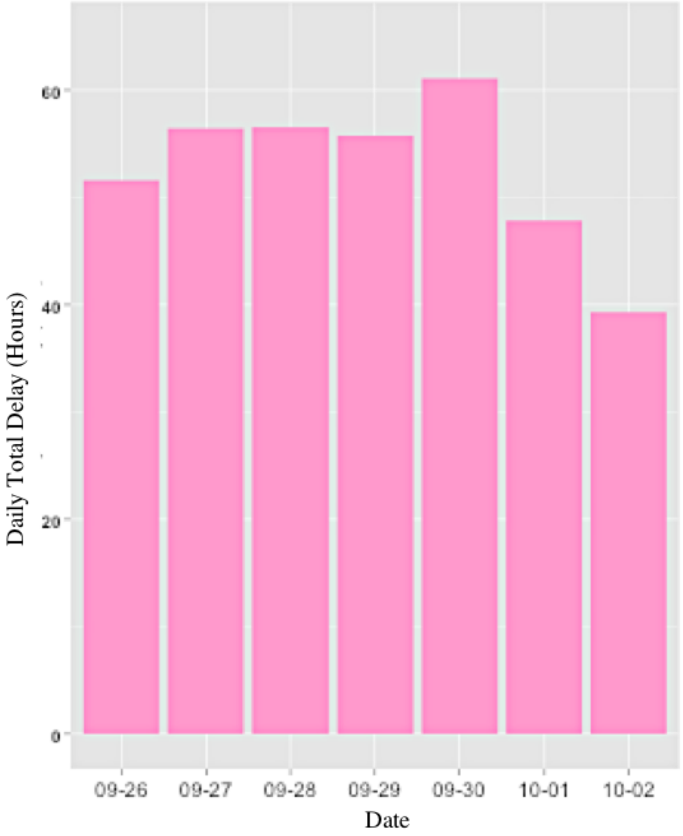


Figure 14. Estimated Daily Delay (in Hours) Over a Week at an Intersection on SR 77

Cost Criteria

Cost is an important factor in nearly every decision that can be made, and thus must be included as a criterion when implementing MCDA. For this project, two primary costs are included in the MCDA approach—the implementation cost, and the cost to operate and maintain the system. The implementation cost is the cost to acquire the technology or system and to install it. The implementation cost criterion for an alternative is inversely related to the alternative’s total cost (the sum of the costs of all the technology deployed on the corridor). Hence, corridors with higher total costs will have lower cost criterion scores. Similarly, the operations and maintenance (O&M) cost is the cost to operate and maintain the system. This cost reflects the required man-hours to maintain the functionality of the system, the cost of conducting minor repairs and routine maintenance, and the cost of powering and keeping the system online. Like the implementation cost criterion, the O&M cost criterion for an alternative is inversely related to the alternative's total costs.

In evaluating costs, certain assumptions have had to be made regarding infrastructure and other aspects of the corridor. This is because costs depend on many factors, which themselves could easily lead to a single technology's having different costs in different situations. These assumptions will be addressed further in the discussion of the prototype spreadsheet.

Other Criteria

Three other major groups of criteria have been used in this MCDA implementation—installation, maintenance, and communications and other operational criteria. These were intended to capture additional factors that an engineer would consider when deploying technology along the corridor.

Installation comprises two subcriteria, complexity and invasiveness. Complexity rates technologies based on simplicity to configure. Technologies that are likely to require expert support and substantial technician time for proper configurations will receive lower scores in this area. Invasiveness is meant to capture interruptions of existing infrastructure and traffic conditions. For example, loop detectors require cuts into pavement, which cause extended lane closures. In contrast, a Bluetooth device can simply be placed in a cabinet and will not require any interruption of traffic.

Maintenance also consists of two subcriteria, frequency and complexity. Frequency captures how often, on average, the technology requires maintenance, including routine maintenance and nonroutine maintenance. Routine maintenance was recommended by technology vendors, while the frequency of nonroutine maintenance was determined through discussions with ADOT. The complexity subcriteria grade technologies based on their maintenance simplicity. Maintenance simplicity reflects the required number of technicians to conduct maintenance, the required equipment to conduct maintenance, and the necessity of outside support. It also considers the availability of communications, since some routine diagnostic maintenance activities can be performed remotely if communications are present.

The final major category includes communications and other operational criteria. This category evaluates the functions and operational benefits of the technologies. The subcriteria include backhaul, communications reliability, real-time communications status, adaptive signal coordination, and surveillance systems. Backhaul is a rating that checks that sufficient backhaul bandwidth is present on the corridor to support the alternative. Communications reliability rates the selected radios based on the use of a radio with the appropriate range and the presence of an FCC license. Real-time communications status rates a user's ability to get information on the status in real time. This depends primarily on the ATMS software installed. Adaptive signal coordination considers the traffic controllers and communications coverage on the corridor. Finally, the surveillance systems rating checks for the presence of CCTV cameras for traffic-monitoring purposes.

Use of Criteria

While describing the meaning of the subcriteria in these categories is straightforward, providing a rating for each technology alternative is not as simple. Since there are three study corridors with technology deployments, there are a huge number of possible alternatives, each of which needs to have a value of a_{ij}. This means that the value of a_{ij} must be determined through some function or heuristic check rather than through the use of expert opinions. To accomplish this, a scoring system was developed to automatically rate each alternative.

The scoring system accounts for the percentage of the corridor that is covered by the relevant technologies (e.g., percentage of intersections or approaches covered, or percentage of corridor length covered) and considers other basic information about the alternative in question. Table 13 presents the criteria and specifications used in developing the corridor-scoring system.

Table 13. Criteria and Specifications Used in the Corridor-Scoring System

Major Criteria	Scoring Specifications
Performance Measurement	• Score considers the range within which the performance measure can be calculated along the corridor • Score considers the quality of estimates being made • Score has a value between 0 and 1, with 0 indicating no capabilities and 1 indicating high-quality estimates of the measure throughout the corridor
Cost	• Score has a value between 0 and 1, with 0 indicating the most-expensive alternative and 1 indicating the cheapest alternative • Alternative cost score is relative • Existing systems on the corridor are not accounted for in installation costs
Installation	• Score has a value between 0 and 1, with 0 being poor and 1 being exceptional • Score represents an average of all the technology characteristics
Maintenance	• Score has a value between 0 and 1, with 0 being poor and 1 being exceptional • Score represents an average of all the technology characteristics
Other	• Score has a value between 0 and 1, with 0 being poor and 1 being exceptional • Score considers the coverage of the relevant technology along the corridor

The scores assume the technology is configured properly and therefore only reflect a best-case scenario. For each criterion, an equation was formulated that reflects the specifications in Table 13. With this scoring system, every possible alternative on any corridor will have a score associated with it.

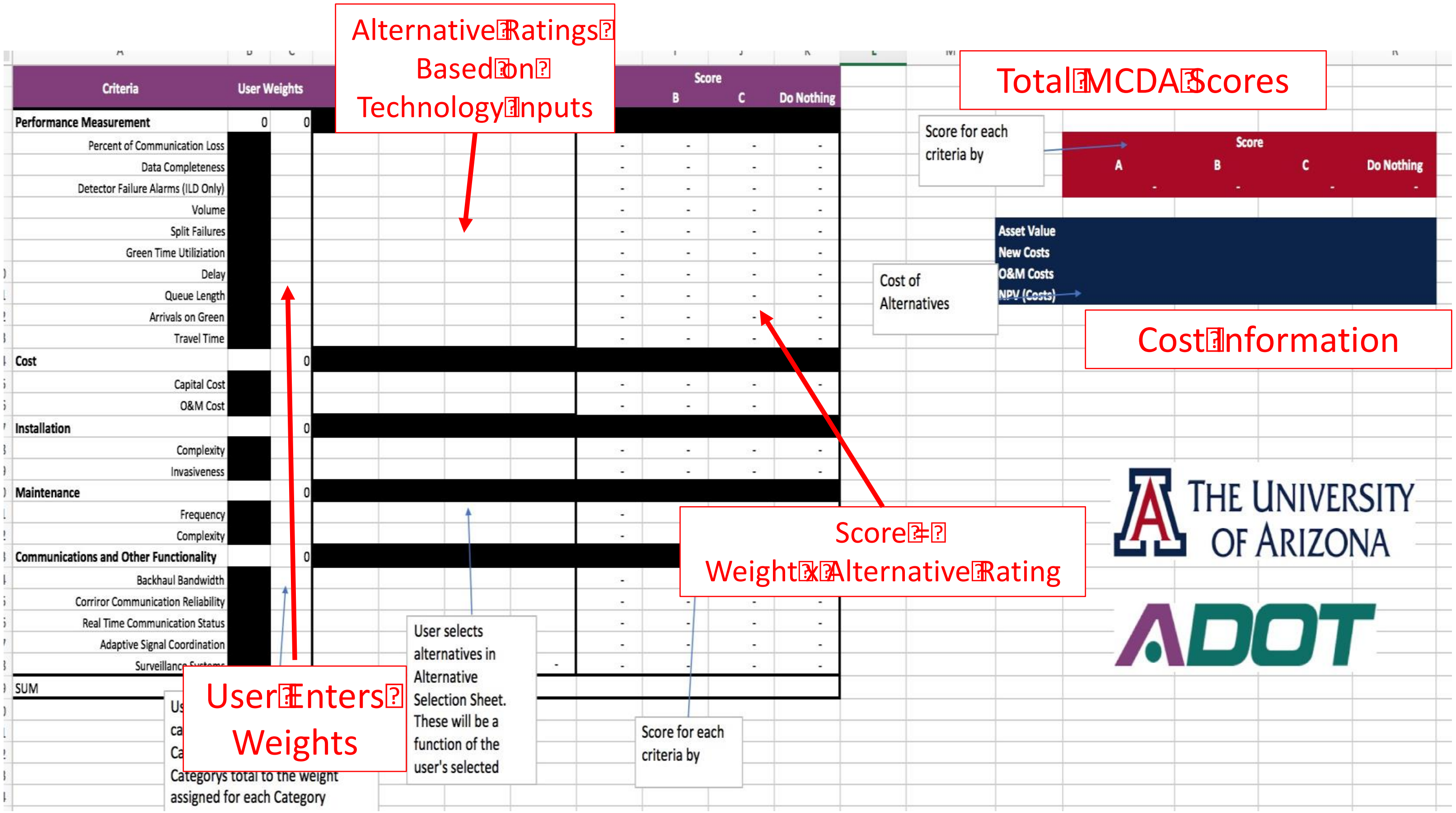
The score measuring a performance criterion indicates only that the measure can be applied using the systems deployed on the corridor. The score does not indicate anything about actual performance of the intersection. For example, if the corridor score for travel time is 0.9, that means travel times can be estimated accurately for most of the corridor, not that the corridor has low travel times.

Most scores depend on the presence of communications, the number of intersections on the corridor, and the method used to obtain the performance measure at each intersection or approach. The method scores have been predetermined based on a finite combination of technologies. They are implemented for an alternative by checking the technologies present at an intersection and selecting the combination of technologies that has the maximum method score among those present.

Implementation of Prototype Spreadsheet

A prototype spreadsheet was designed using Microsoft® Excel to implement the methodology and evaluate the three study corridors. The goal of the prototype spreadsheet is to provide a user-friendly tool that can consider as many criteria as possible when evaluating and comparing technology deployments on one or multiple arterials. Three main modules require user's input.

The first module, shown in Figure 15, displays key aspects of the MCDA approach including the user weights, the results, and the costs. It displays each criterion and allows the user to enter its weight, w_i in a box next to the criterion. Directly to the right of the weights is each value of a_{ij} calculated on the basis of the technology deployed (input later by the user) in each alternative. To the right of the a_{ij} values appears each criterion's score (the product of w_i and a_{ij}) for each alternative. Further to the right are two tables showing results. The upper table, Total MCDA Scores, shows each alternative's total score, $A_{WSM\text{-}Score}$, and the lower table, Cost Information, shows cost data including net present values, asset values, new costs, and operation and maintenance costs. The alternative with the highest score is the tool's recommended alternative, based on the user's inputs. The only input in this interface is the user's weights for each criterion. It is recommended that these weights sum to 100 for consistency, but based on the way the scores have been designed, the sum of the weights indicates the highest possible score for each alternative.



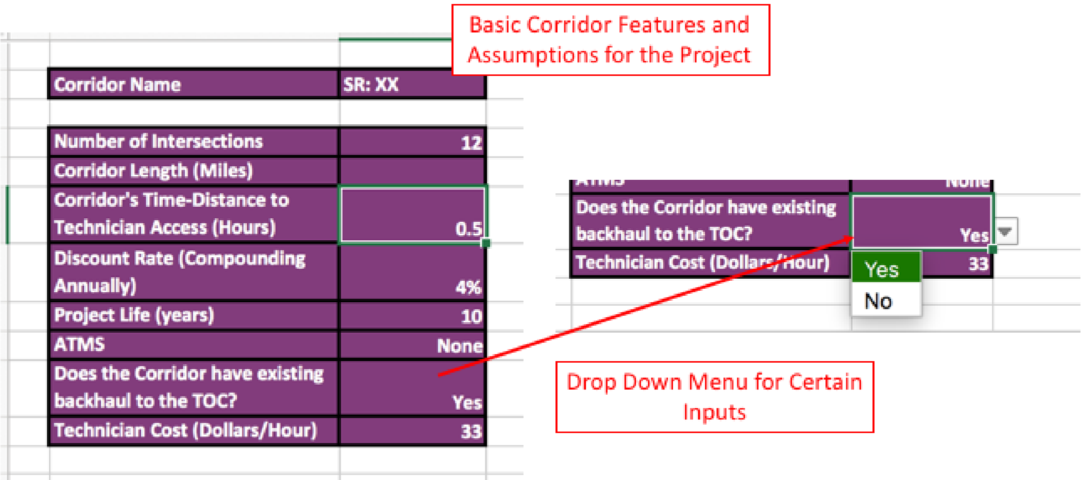
Criteria	User Weights			Score B	C	Do Nothing
Performance Measurement	0	0				
Percent of Communication Loss			-	-	-	-
Data Completeness			-	-	-	-
Detector Failure Alarms (ILD Only)			-	-	-	-
Volume			-	-	-	-
Split Failures			-	-	-	-
Green Time Utiliziation			-	-	-	-
Delay			-	-	-	-
Queue Length			-	-	-	-
Arrivals on Green			-	-	-	-
Travel Time			-	-	-	-
Cost		0				
Capital Cost			-	-	-	-
O&M Cost			-	-	-	
Installation		0				
Complexity			-	-	-	-
Invasiveness			-	-	-	-
Maintenance		0				
Frequency			-			
Complexity			-			
Communications and Other Functionality		0				
Backhaul Bandwidth			-			
Corriror Communication Reliability			-	-	-	-
Real Time Communication Status			-	-	-	-
Adaptive Signal Coordination			-	-	-	-
Surveillance Systems			-	-	-	-
SUM						

Score			
A	B	C	Do Nothing
-	-	-	-

Asset Value
New Costs
O&M Costs
NPV (Costs)

Figure 15. Prototype Spreadsheet, Module 1, Primary Interface

The second module, shown in Figure 16, is where the user begins to design the technology for the corridor. The user inputs basic information about features of the corridor likely to be consistent across all alternatives. Questions can be answered via direct input or a drop-down menu where the user can select from preset options. Some of these inputs can be changed later in an alternative's tab to reflect a user's preferences or prior knowledge.



Basic Corridor Features and Assumptions for the Project

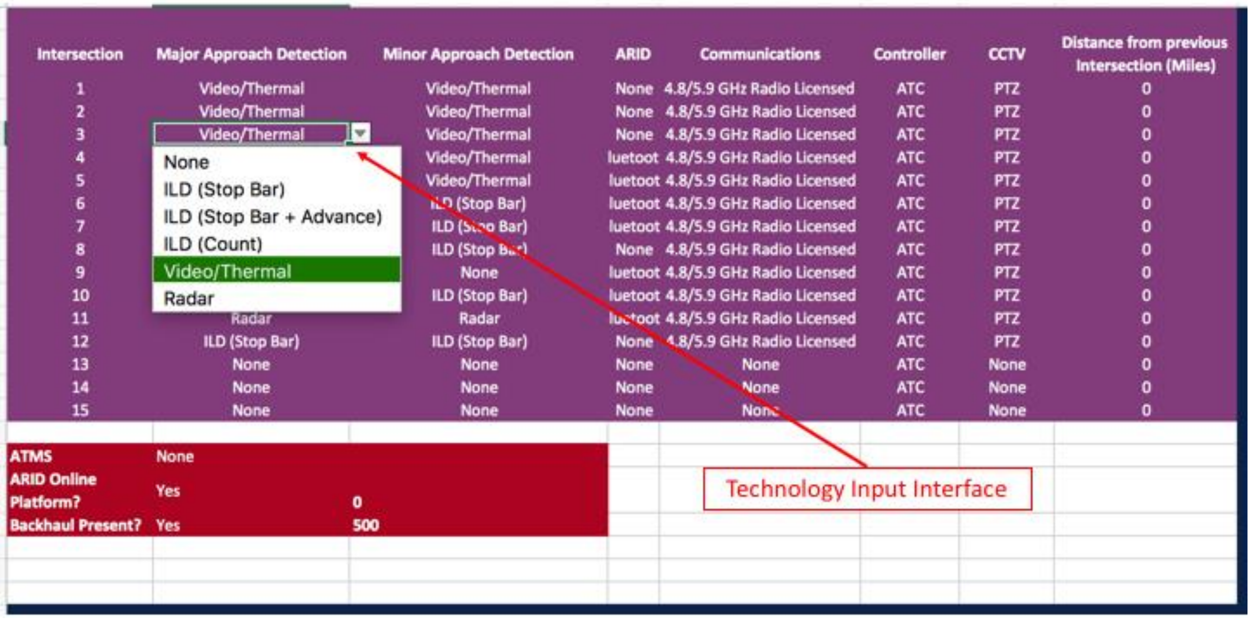
Corridor Name	SR: XX
Number of Intersections	12
Corridor Length (Miles)	
Corridor's Time-Distance to Technician Access (Hours)	0.5
Discount Rate (Compounding Annually)	4%
Project Life (years)	10
ATMS	None
Does the Corridor have existing backhaul to the TOC?	Yes
Technician Cost (Dollars/Hour)	33

Drop Down Menu for Certain Inputs

Figure 16. Prototype Spreadsheet, Module 2, Basic Corridor Information

The third module consists of four Excel tabs where the user designs alternatives. The first one is for the "Do Nothing" alternative. In this tab, the user should enter the existing technology. By creating a "Do Nothing" scenario, the user can see how well the corridor meets the input criteria without implementing any changes. The next three tabs are for alternatives "A", "B", and "C." These tabs are where the user can input three different hypothetical alternatives and see how they score relative to the "Do Nothing" scenario. Figure 17 shows an example of an alternative designed by the project team for SR 77.

A drop-down menu is used to select technology for each of the alternatives. Technology can be selected for detection systems on the major and minor approaches, communications, anonymous re-identification devices (ARIDs), signal controllers, and surveillance technology. The "Do Nothing" scenario is entered first, and each of the other alternatives defaults to the values input in the "Do Nothing" scenario. Table 14 shows the user interface for the corridor technology design. In Figure 17, each cell in the purple area has a drop-down menu to select the technology and configuration. The red area asks the user additional questions about the corridor, defaulting to values from the "Corridor Basic Information" tab in Module 2.



Intersection	Major Approach Detection	Minor Approach Detection	ARID	Communications	Controller	CCTV	Distance from previous Intersection (Miles)
1	Video/Thermal	Video/Thermal	None	4.8/5.9 GHz Radio Licensed	ATC	PTZ	0
2	Video/Thermal	Video/Thermal	None	4.8/5.9 GHz Radio Licensed	ATC	PTZ	0
3	Video/Thermal	Video/Thermal	None	4.8/5.9 GHz Radio Licensed	ATC	PTZ	0
4		Video/Thermal	luetoot	4.8/5.9 GHz Radio Licensed	ATC	PTZ	0
5		Video/Thermal	luetoot	4.8/5.9 GHz Radio Licensed	ATC	PTZ	0
6		ILD (Stop Bar)	luetoot	4.8/5.9 GHz Radio Licensed	ATC	PTZ	0
7		ILD (Stop Bar)	luetoot	4.8/5.9 GHz Radio Licensed	ATC	PTZ	0
8		ILD (Stop Bar)	None	4.8/5.9 GHz Radio Licensed	ATC	PTZ	0
9		None	luetoot	4.8/5.9 GHz Radio Licensed	ATC	PTZ	0
10		ILD (Stop Bar)	luetoot	4.8/5.9 GHz Radio Licensed	ATC	PTZ	0
11	Radar	Radar	luetoot	4.8/5.9 GHz Radio Licensed	ATC	PTZ	0
12	ILD (Stop Bar)	ILD (Stop Bar)	None	4.8/5.9 GHz Radio Licensed	ATC	PTZ	0
13	None	None	None	None	ATC	None	0
14	None	None	None	None	ATC	None	0
15	None	None	None	None	ATC	None	0

ATMS	None	
ARID Online Platform?	Yes	0
Backhaul Present?	Yes	500

Figure 17. Prototype Spreadsheet, Module 3, Alternative Design (Drop-Down Menus Are Used for Technology Inputs)

Table 14. Technology Drop-Down-Menu Options for User Interface

System Type	Options
Detection	• Inductive Loop Detector (presence) • Inductive Loop Detector (count) • Inductive Loop Detector (presence + advance) • Radar • Video • None
ARID	• Bluetooth • Wi-Fi • None
Communications	• Short-Range Radio (licensed) • Short-Range Radio (unlicensed) • Long-Range Radio (licensed) • Long-Range Radio (unlicensed) • Fiber-Optic Cable • None
Controller	• ATC
CCTV	• Pan-Tilt-Zoom • Fixed • None
ATMS software	• Vendor 1 • Vendor 2

Other sheets are used for reference tables and similar information. The spreadsheet tool dynamically looks up values from reference tables as different technologies and combinations are input into the tool. If the user wants to change any of the calculation inputs, he or she can go to the "Reference Tables" sheet and adjust technology ratings for cost, performance measurement scores, installation and maintenance scores, and other features. This is recommended for costs especially if the user has received an exact quote.

CORRIDOR EVALUATION

All three corridors were compared to one another as part of the project. The prototype spreadsheet was filled out for each corridor and evaluated under three different scenarios. These representative scenarios are cost-aggressive, balanced, and performance-aggressive.

In the performance-aggressive scenario, weights were placed heavily on criteria related to performance measures and communications. The resulting MCDA scores calculated using the WSM approach are shown in Figure 18. At first glance, SR 347 is performing the worst with a performance-aggressive approach. However, the technology infrastructure is in place. If ADOT simply improves the ATMS software, SR 347 can match the performance of the other two study corridors. The version of the ATMS software from Vendor 1 that ADOT is currently using does not meet the requirements to support a performance-aggressive approach to traffic management on the corridor. Should ADOT like to implement this approach, the research team recommends either upgrading the version of ATMS software from Vendor 1 or changing to software from Vendor 2.

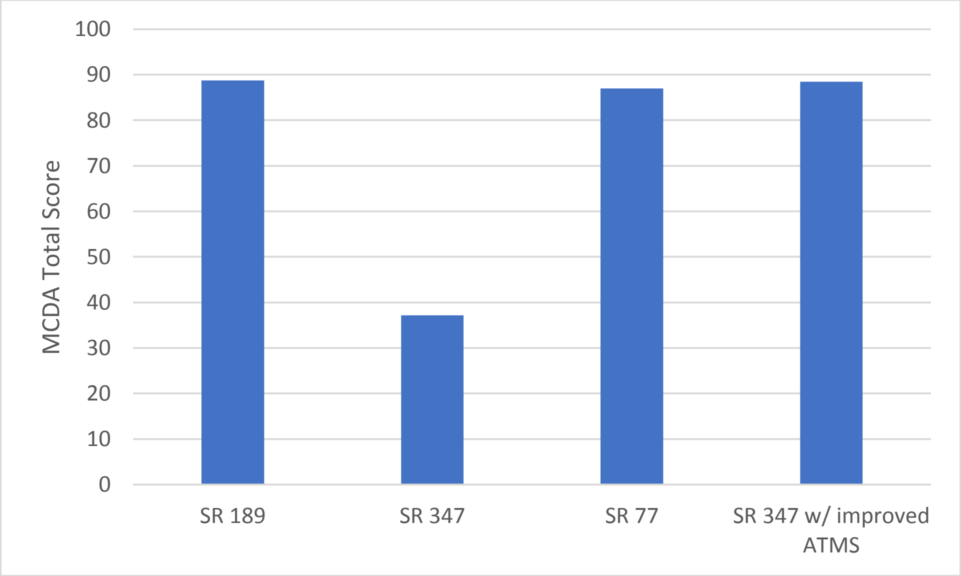


Figure 18. Performance-Aggressive Evaluation of Study Corridors

In the balanced scenario, weights were spread evenly between costs, performance, and operations. The results of the comparison are shown in Figure 19. Including cost in the direct comparison is difficult because the study corridors have different numbers of intersections. Naturally, the corridors with fewer intersections performed better in cost metrics, since their total costs were lower, as the costs are driven more by the number of intersections than by the type of technology. As a result, the scores were similar to those obtained in the performance-aggressive scenario, because the scores were proportional to other scenarios. Again, SR 347 was performing poorly with the current ATMS software, but would be much more comparable to the other two corridors with improvement of the ATMS software.

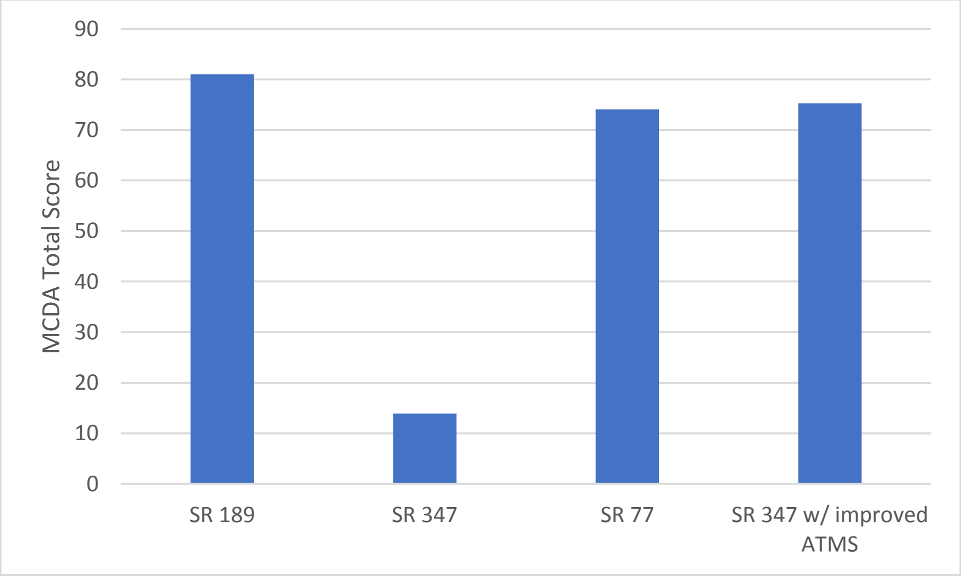


Figure 19. Balanced Evaluation of Study Corridors

Finally, in the cost-aggressive scenario, the scores for all the alternatives were almost 25 percent lower than those in the performance-aggressive scenario. The reason for the reduction is that ADOT did not take a particularly cost-aggressive approach when deploying ITS technologies on the three corridors. Despite the lower scores, performance measurement capabilities and operational capabilities improved substantially on every corridor as a result of the upgrades that were done before or at the time of the site visits.

Discussion

With the recent improvements that have been made, each of the corridors is nearly completely covered by quality communications, detection systems, and ARID devices. Scores can be increased by ensuring that ARID devices are present at every intersection and advance detection is present on the major cross streets at every intersection. The biggest changes in total score are likely to stem from technologies or characteristics that affect the scores for many of the individual criteria. For example, ATMS software and backhaul communications are both critical for all the performance measures and all the operational capability scores, so for a corridor's overall scores to be high, those two technologies must be present. The MCDA analysis provides insight into the performance of the study corridors. Overall, the scores were nearly identical for SR 189 and SR 77, while SR 347 had a much lower score. Further exploration determined that the problem was SR 347's current ATMS software. The version of the software from Vendor 1 that ADOT's Traffic Operations Center in Phoenix is using to operate SR 347 is not sufficient for collecting high-quality performance measures. Vendor 1 is able to meet this need, so it is a matter of the Phoenix TOC's expanding the capabilities of its ATMS software to match the capabilities of the corridor. The other option is to switch to the version of ATMS software from Vendor 2 that is being used by ADOT's Southern Region Traffic Engineering Office. Either change would improve the score for SR 347, and in making the decision, the Phoenix TOC should consider the cost and the interoperability of the software with other ADOT offices and adjacent jurisdictions.

When the ATMS used on SR 347 is adjusted to that used on the corridors operated by ADOT's Southern Region office, a chain reaction can be observed. By having insufficient ATMS software to take full advantage of the performance measurement, SR 347 receives a poor overall score despite having quality technology. Effectively, the technology in place on SR 347 is capable of collecting the data required to measure performance. However, the data either are not being recorded or are being aggregated in low resolution. Meanwhile, not having a detector or ARID device at an individual intersection has a relatively negligible impact on the overall score, since it does not impact the performance measurement capabilities of the rest of the corridor.

The benefits of integrating MCDA into a spreadsheet are clear when one considers that the corridors received upgrades multiple times throughout the study. Minor changes to the corridor can be entered into the spreadsheet and quickly rated without the need for additional site visits and large-scale studies.

CHAPTER 5. CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

The primary goal of this project was to study, compare and evaluate technologies, especially remote communication technologies, deployed on three dissimilar traffic signal networks installed on SR 77, SR 347, and SR 189 in Arizona. The purpose of the recent technology deployments on SR 77, SR 189, and SR 347 was to improve the communications and performance measurement capabilities of the study corridors. The conclusions are as follows:

- The ability to obtain critical performance measures was one criterion for evaluating each corridor, since such measures can assist with technology maintenance and traffic operations. The performance measures used focused on two key areas: maintaining system health and improving operational efficiency. Effective measures can enable practitioners to identify and mitigate problems at intersections. It was found through a literature search that the most effective performance measures were quantified by approach or signal phase. Obtaining effective performance measures requires event-based signal data, which record second-by-second vehicle arrivals by approach relative to the phasing and timing of signals.
- Technologies were inventoried for the intersections in each study corridor, and information about the products was collected. It was found that ADOT would benefit from a systemwide inventory of traffic signal system technology for two reasons. First, an inventory would enable a large organization like ADOT to effectively monitor its investments. Second, it would improve the evaluation capabilities of the different corridor technologies.
- Multiple Criteria Decision Analysis integrated into a prototype spreadsheet was found to be an effective method for evaluating and comparing each corridor. With this method, the project team was even able to evaluate potential modifications to the corridor. The results of the study show that the technology systems on SRs 77 and 189 have positive measurement capabilities in their current form, and that a simple upgrade of the ATMS software on SR 347 would address the poorer capabilities found for that corridor.
- Minimum and ideal configurations of technology can be identified for future corridor deployments. The minimum configuration will consist of the minimum technology required to operate a signal, while the ideal version will assume remote capabilities for operational changes and performance measurement.
    - Presence detection on minor roads and advance detection on major roads are the minimum required technology for operation of semiactuated signal controls. The minimum configuration can also permit rudimentary performance measurement if the detectors store data locally, but that arrangement would require a technician to go on-site and download the data. An ideal system will have lane-by-lane presence and advance detection for all approaches, along with communication systems and properly configured ATMS data collection procedures in place.

- Communications are recommended for all corridors. At a minimum, communications enable ADOT traffic engineers to monitor their systems in real time and identify problems with traffic operations. Ideally, data will be sent to the engineers for performance measurement, and video feeds from cameras will be in place for TOC operators to monitor traffic conditions.

- ARID devices can help provide data for travel-time-related performance measures, but are not necessary if an ideal detection system is in place. However, while travel time can be estimated using the ideal detection system, it is often easier to use ARID devices. Additionally, ARID devices can be used to obtain travel times if funds are lacking to install the ideal detection systems.

- ATMS software is also recommended for all corridor systems. Paired with communications, it enables ADOT engineers to monitor their systems in real time and identify problems with traffic operations. Ideal ATMS software will record event-based data so that engineers can measure performance on the corridor.

- Surveillance cameras are optional. The benefits are subjective and the communication burden is much higher; however, they can be used to observe traffic and identify possible problems.

RECOMMENDATIONS

Based on the conclusions, the following recommendations are made:

1. As noted in Chapter 2, numerous different performance measures were identified in the literature. In this project, the measures were all calculated as numerical values to quantify various aspects of the corridor's performance. Many visual measures, such as the Purdue Coordination Diagram, can further improve an engineer's understanding of the corridor. Visual measures are more difficult to create since they require either specific software or data skills; however, they may be worth exploring if ADOT would like to further improve performance measurement and evaluation. The scoring process has been developed so that even visual measures can be included in the prototype spreadsheet.

2. During the inventory process, it was found that ADOT would benefit greatly from maintaining a technology inventory. The traffic control system is constantly changing and evolving, so a central database—where anyone in ADOT could easily see what is deployed where—could expedite the planning process as well as enhance understanding of the capabilities at an intersection or on a corridor. Additionally, a central database would enable ADOT to track the value of its assets if cost information were recorded as well.

3. Further exploration of technology capabilities should be considered by ADOT. It is recommended that each technology undergo standardized testing for different qualities so that the marginal benefits of each technology in different scenarios are understood.

    a. Comparisons need to be made between supplementary technologies. For example, data loss due to the occlusion of cameras could be a concern in corridors with high truck volumes. However, numerous factors—including the rate of data loss, truck volume on the corridor, and the impact of data loss on performance measurement quality—would all need to be evaluated before an educated decision could be made whether to use cameras or a technology like radar.

    b. Comparisons need to be made between the same technologies from different vendors. For example, different vendors of radar devices require different configurations, use a different number of devices to achieve full coverage of an intersection, and may require different maintenance routines. Additionally, their products will likely provide different levels of data completeness and quality, and may come with different additional features.

4. It is recommended that ADOT consider further developing the prototype spreadsheet for use in evaluating newly installed technologies on the three study corridors and other future ITS corridors.

    a. The prototype MCDA tool should include geometric design features to differentiate between similar alternatives. For example, an engineer would need to know about the existence of a sufficient pole-mount for a camera at an intersection when designing an alternative.

    b. Traffic-flow characteristics should be included in the prototype spreadsheet. For example, the percentage of trucks could impact the quality of a detection technology because of potential camera occlusion. The extent to which different traffic-flow characteristics affect the data and the resulting performance measures may not even be known, further highlighting the need for additional testing and access to information.

    c. A way to score cost while accounting for the number of intersections should lead to more accurate cost comparisons. Additionally, including more technologies and accounting for more factors in the MCDA spreadsheet may allow for corridor evaluations that are more specific. Finally, software can be developed to replace the prototype spreadsheet, to provide a more user-friendly interface and give the user additional options, such as a variety of different MCDA methods or the ability to select criteria.

5. The analysis results using the prototype spreadsheet revealed that SR 347 was the only corridor whose traffic control system did not demonstrate the ability to deliver quality performance measurement in its current state. However, the technology in place is already capable of achieving advanced performance measures. All that is needed is an upgrade of the current ATMS software, or a change to new ATMS software.

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