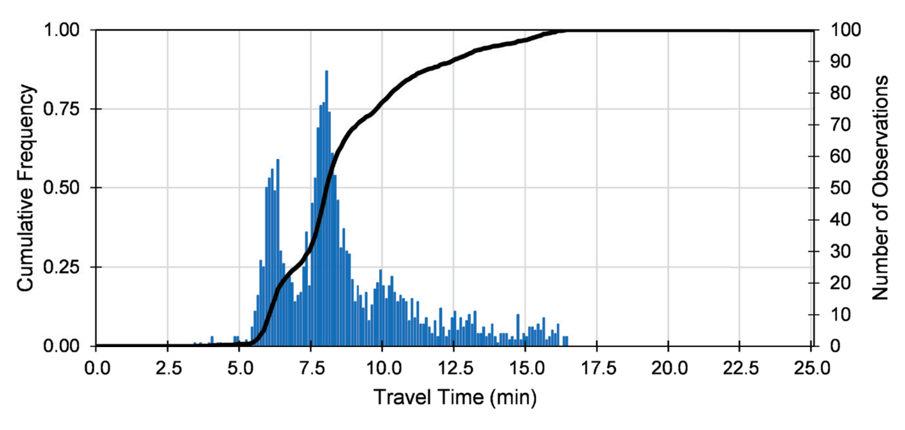
Executive Summary: Performance Measures of Interrupted-Flow Roadways Using Re-Identification and Signal Controller Data



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Introduction

Transportation agencies and metropolitan planning organizations (MPOs) have long had a need to demonstrate accountability. For example, MPOs and other agencies are often required by federal and state statutes to develop Congestion Management Programs (CMPs) to monitor and assess traffic congestion. Thus, most agencies have a method for satisfying this need, yet these historically have not always been connected to decision making processes, nor have they been part of a shared vision between planners, engineers, and other stakeholders.

The current situation is one of increasingly constrained agency budgets. Figure 1 shows the projected state of the Federal Highway Trust Fund based on data available at the time of writing that indicates a cumulative budget shortfall of over $50 billion by the year 2020, unless action is taken to maintain the fund. At the same time as budgets are becoming smaller, there is an increasing demand for more and better infrastructure. In this situation, accountability is becoming even more important.

The MAP-21 highway funding bill included many new provisions requiring the adoption of performance measurement programs by agencies in order to continue receiving federal funding. It stands to reason that the next funding bill will continue this trend toward emphasizing data-driven performance measurement.

This report presents a methodology based on two relatively new data sets that present a tremendous opportunity to change management practices in the operations of arterial highway systems. These include **vehicle re-identification data** and **high-resolution controller data**. These data sets enable agencies to measure how their systems are doing in a continuous, automated process, eliminating the need for costly manual data collection methods and enabling the development of highly informative data sets that can inform system operators, planners, and decision makers alike, on varied analysis levels.

This executive summary provides an overview of the findings of the report, with more detailed information given within the pages of the full report that follows.

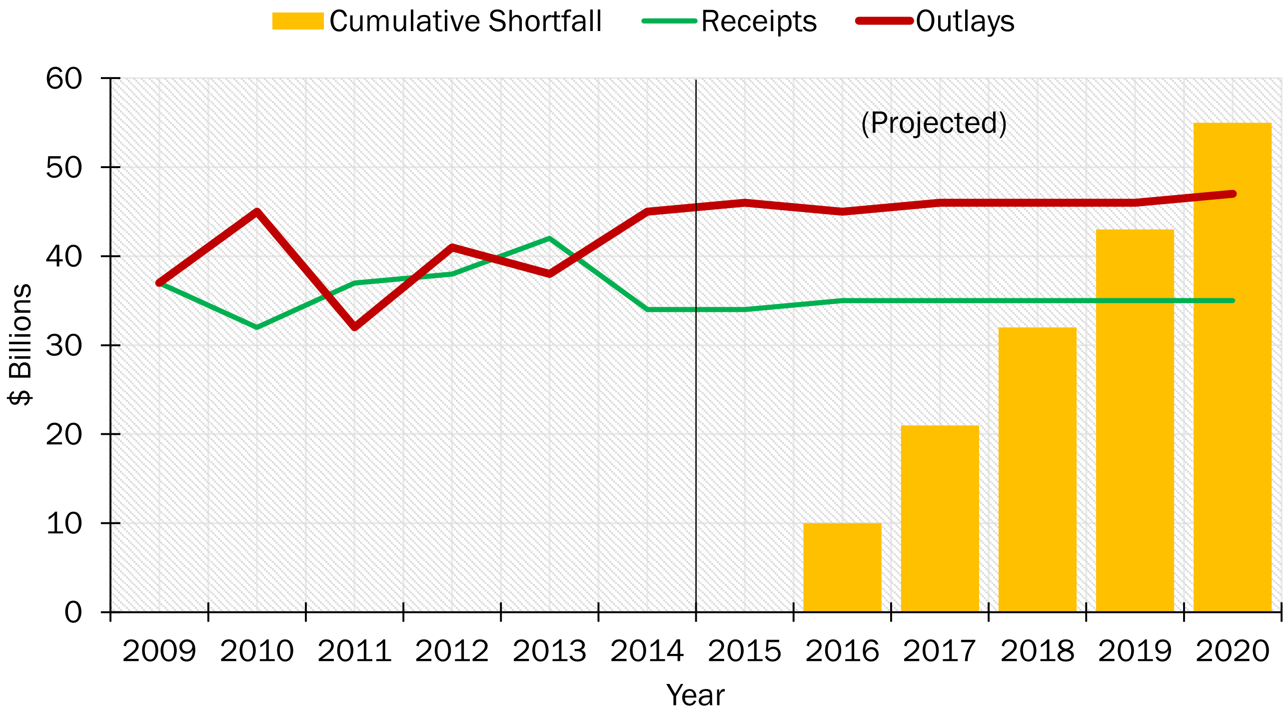


Figure 1. State of the Federal Highway Trust Fund [1].

Problem Statement

Arterials represent a major portion of the overall road network, gluing together freeways to local roads and serving as the major thoroughfares in many communities. Overall, arterials carry about 43% of the total amount of traffic, as shown in Table 1.

There are many different aspects of performance of a transportation system that can be measured. For example, the infrastructure quality can be considered. In highway systems, the "health" of pavements and bridges can be measured. Other performance categories include safety, accessibility, environmental impact, and mobility. While all of these aspects are important, mobility directly relates to the experience of system users and their perception of how the system is operating.

Historically, mobility has been challenging to analyze, especially on arterials. What sets arterials apart is the high volume of traffic with signalized intersection control. The dynamic, complex nature of traffic signal control makes it impossible to analyze arterial performance in the same manner as freeways. Today, most agencies rely on public complaints, engineering judgment, and arbitrary service schedules to maintain arterial operations, and they do not really possess an "arterial management system."

In contrast, pavement management systems are comparatively advanced and are today in widespread use in most agencies. Figure 2 shows how pavement management systems have developed. After the initial exploratory research on pavement performance measures came a period of consensus building in which certain performance measures emerged as standard measures of pavement quality. Standard methods for data collection then followed. The next step was to develop systems to manage that data and turn it into useful information.

The final stages in the development of pavement management systems involved integrating performance measures into engineering practice and the decision making processes. Although there are many factors at play when agencies decide where to invest their repaving dollars, pavement management systems play a key role in helping make an informed decision.

Arterial management systems are not at this level of development because it has historically been difficult to obtain the type of data necessary to conduct assess performance on a wide scale. Existing arterial datasets include floating-car studies and turning movement counts, which require labor intensive manual data collection. They do not allow monitoring on a day-to-day basis, which is important for managing arterials, because traffic is dynamic.

One objective of this research is to help accelerate the development so that arterial management systems can become reality sooner, as the dashed curve in Figure 2 illustrates.

Table 1. Distribution of roadways in the United States by functional class [2].

Functional Class	Percent of Total Mileage	Percent of Total Travel
Interstate	1.2	22.8
Other Freeway / Expressway	0.2	6.2
Other Principal Arterial	3.8	24.3
Minor Arterial	5.7	18.4
Major Collector	11.1	7.8
Minor Collector	7.2	2.1
Collections	2.2	5.3
Local	68.6	13.1
Total	100.0	100.0

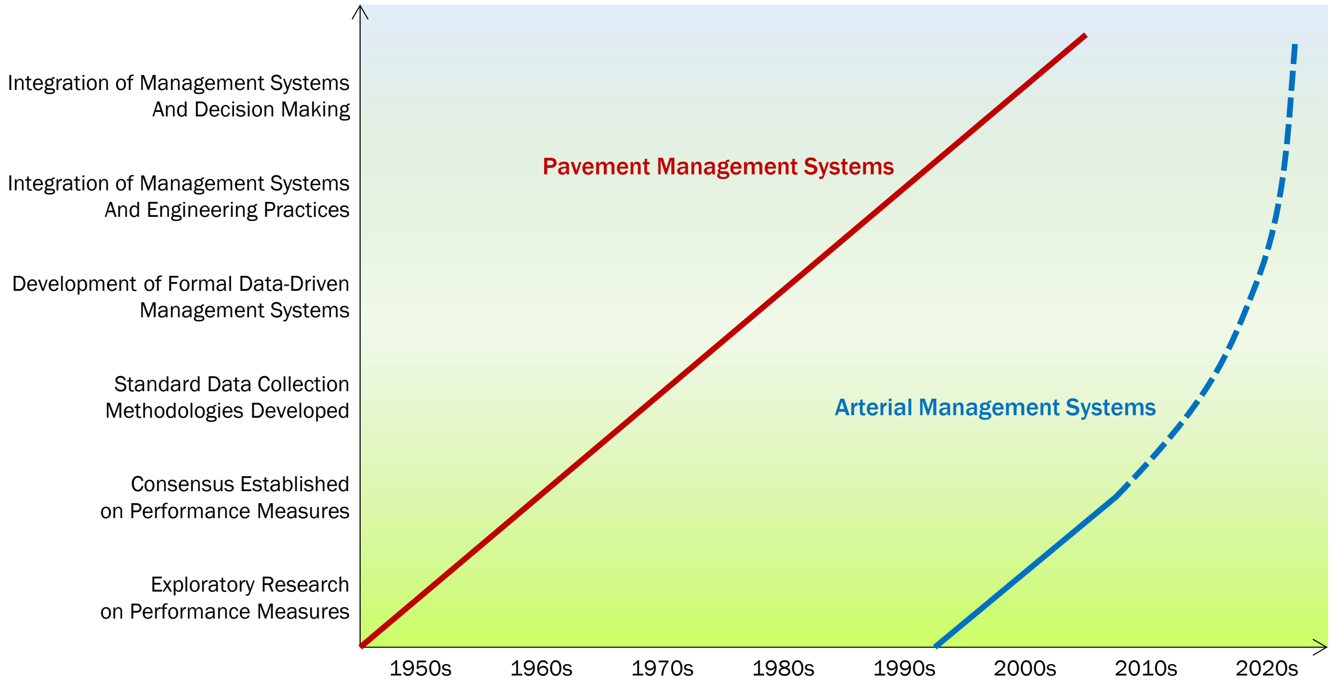


Figure 2. Conceptual evolution of arterial management systems compared to pavement management systems.

Opportunities for Improvement

Traffic control systems include a variety of computing devices that could potentially help monitor system conditions and identify deficiencies. The high cost of manual data collection has limited its coverage, while the formerly high costs of electronic communication historically limited the amount of automatically collected data that could be obtained from the field.

Today, these limitations have been eased by new technologies that bring opportunities to improve the way arterials are monitored and operated. This report focuses on two new types of technology:

- Travel times along corridors can be directly measured using automated **vehicle re-identification** sensors, replacing manual techniques.
- Detailed information about traffic events (such as vehicle arrivals and lights changing from red to green) can be logged by controllers as **high-resolution controller data**.

Automated data collection systems that provide this new data are now available to agencies, opening the door to a much more detailed level of analysis than traditional techniques, providing constant, continuous coverage of field operations.

The traffic industry has begun to adopt these technologies widely. A growing number of vendors now offer equipment capable of logging high-resolution controller data, while vehicle re-identification data sensors and/or services can also be obtained from several vendors. Agencies can now implement the technology modularly and incrementally, through routine equipment upgrades, instead of requiring large capital projects that would traditionally have been needed to outfit an arterial corridor with sophisticated monitoring capabilities.

Need to Integrate with Business Processes

These new technologies enable the **integration of performance measures into business processes**, which is critical to improving arterial management. Investments in management systems are more likely to be successful if they can:

- Speak to specific objectives of the agency
- Provide useful information that enables assessment of those objectives
- Identify opportunities for improvement
- Allow testing and comparison of solutions

In brief, the arterial management system should make the tasks easier for the personnel who use them, and deliver a return to the public in the form of improved performance. This will be the case if they are set up to specifically address agency objectives, and if they are integrated into the existing business processes of system operations, maintenance, and planning.

An Integrated Approach to the Problem

In manufacturing processes, where failures can be extremely costly, statistical process control is employed to minimize the probability of failures. While traffic control is far less predictable than the movement of widgets between stations in a factory, the basic concepts can be adopted as a vision for arterial management.

The five key strategies of statistical process control are to define, measure, analyze, improve, and control. These are sometimes referred to using the acronym DMAIC. As illustrated in Figure 3, these steps form a cyclic process. These concepts can be applied to arterial management [3] as follows.

- **Define.** Understand the objectives of the agency operating the system and state these in specific terms. Identify target levels of operation that are desirable to meet or exceed.
- **Measure.** Obtain the necessary data from the field to fully characterize the operation of the system. Historically, this has been the most difficult step in the process. This report focuses on technologies that can substantially improve the measurement process.
- **Analyze.** Distill data into useful information. Data collection alone is not enough to foster improvement or even to understand the system. Without an appropriate analysis methodology, a system becomes data rich / information poor.
- **Improve.** Use the results of the analysis to make the system work better. Identify specific aspects of the operation that need to be changed to make those improvements.
- **Control.** Proceed with improvements and use these to better inform the definitions of objectives for future operations.

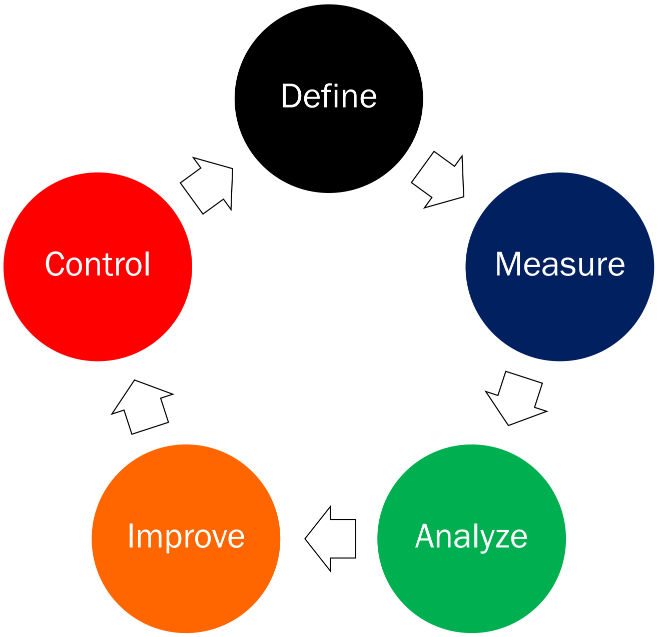


Figure 3. Basic elements of statistical process control.

Defining and Prioritizing Objectives (DMAIC)

The first stage in setting up an arterial management system is to articulate the goals of the agency's arterial program. These objectives vary in their priority among the different stakeholders involved. While objectives may evolve over time as the arterial network and the communities that it serves both change, having some idea of the focus areas to be emphasized will steer the performance measures to a purposeful end.

Defining and prioritizing those objectives is the first step in understanding what should be measured by the arterial management system. Table 2 shows an example set of objectives and their relative priority to two different stakeholders. Perhaps Stakeholder "A" represents a state transportation agency concerned with providing high quality traffic progression into and out of a major city, while perhaps stakeholder "B" is an MPO more concerned with improving pedestrian service and giving equitable green time to side streets.

It is essential to understand the relative importance of each objective to each stakeholder. Even within a single agency, there may be differing perspectives among traffic engineers, planners, and executive staff.

After identifying the objectives, the next step is to match the objectives to appropriate performance measures. This process creates a plan for the arterial management system, and identifies what to measure to quantify the extent to which objectives are satisfied.

Table 2. Example of objective prioritization.

Objective	Stakeholder A	Stakeholder B
Improve Traffic Flows	1	4
Improve Capacity Allocation	2	3
Improve Pedestrian Service	3	1
Improve Bicycle Service	4	2
Maintain Working Detection	5	8
Maintain Working Preemption	6	9
Minimize Pollution and Noise	7	5
Automate Traffic Counts	8	6
Develop Origin-Destination Data	9	7

Table 3 shows matches of the objectives from Table 2 against a candidate list of performance measures enabled by vehicle re-identification and high-resolution controller data. While the rest of this report will dig into the meaning of these performance measures in more detail, it should be noted that some objectives have more options for measurement than others. However, each objective can benefit through the use of performance measures.

Matching objectives to specific, measureable performance criteria establishes the central framework for development of an arterial management system.

Table 3. Matching performance measures to objectives.

Objective	Traffic Volumes	Green Time	V/C Ratio	Occupancy Ratio	Percent on Green	Coordination Diagram	Travel Time	Detector Error Alarms	Preemption Durations
Improve Traffic Flows					X	X	X		
Improve Capacity Allocation	X	X	X	X			X		
Improve Pedestrian Service	X	X							
Improve Bicycle Service	X	X							
Maintain Working Detection	X			X				X	
Maintain Working Preemption									X
Minimize Pollution and Noise					X	X			
Automate Traffic Counts	X								
Develop Origin-Destination Data							X		

Measuring Performance (DMAIC)

After defining the objectives and matching to performance measures, the next step is to perform the required data collection and processing. Vehicle re-identification and high-resolution controller data provide the base data to calculate a variety of performance measures. The next four figures are examples of some of the most useful graphics that can be developed from these two sources.

Vehicle re-identification data measures the amount of time for a vehicle it takes to traverse the system. This is accomplished by identifying a vehicle at two locations using a sensor, and logging the locations and exact time of observation. Such data may be used to measure how long it takes vehicles to traverse an arterial corridor by placing sensors at the two endpoints of the corridor, although that is not the only type of route in an arterial network that can be examined.

Figure 4 shows an example of the raw data collected along a signalized corridor by time of day. Each dot in this graph represents one vehicle that was matched between the entry and exit points of the arterial on Wednesdays over a 7-month period. Travel times generally fall within 5 and 15 minutes, varying by time of day. Some outliers having substantially longer travel times represent motorists who briefly left the road (for example, at a gas station) en route to their destination. The red lines show the change in the signal timing at different times of day. Note that the travel times change substantially right around these same times.

Another way of viewing travel times is to look at their distributions, as in Figure 5. In this graph, the point cloud is translated into a statistical distribution that can be shown as a histogram, with the number of observations within each category, or as a cumulative frequency diagram (CFD), that explains the percentage of the observed vehicles having travel time less than a given value. Both ways of visualizing the data have merit, but the CFD is useful for making comparisons between two or more alternative data sets.

Figure 5 also illustrates how this information can be distilled into a single number representing its essential characteristics. The median value shows a typical travel time along the corridor, while the 25th and 75th percentiles show the amount of variability in that travel time. For example, Figure 5 shows that a motorist can expect to spend about 9 minutes on the roadway, but that travel times are likely to vary anywhere from 7 to 17 minutes. Traffic signal operation is the primary influence that impacts the variation in vehicle travel time along a signalized arterial.

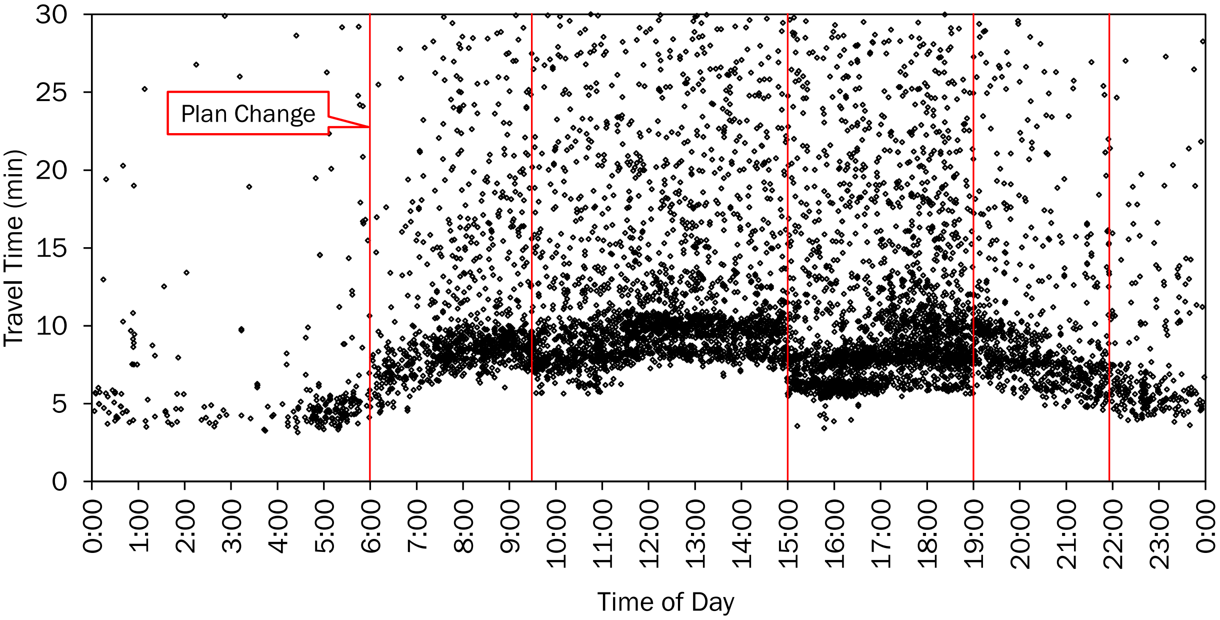


Figure 4. Travel times from vehicle re-identification displayed as a 24-hour overlay.

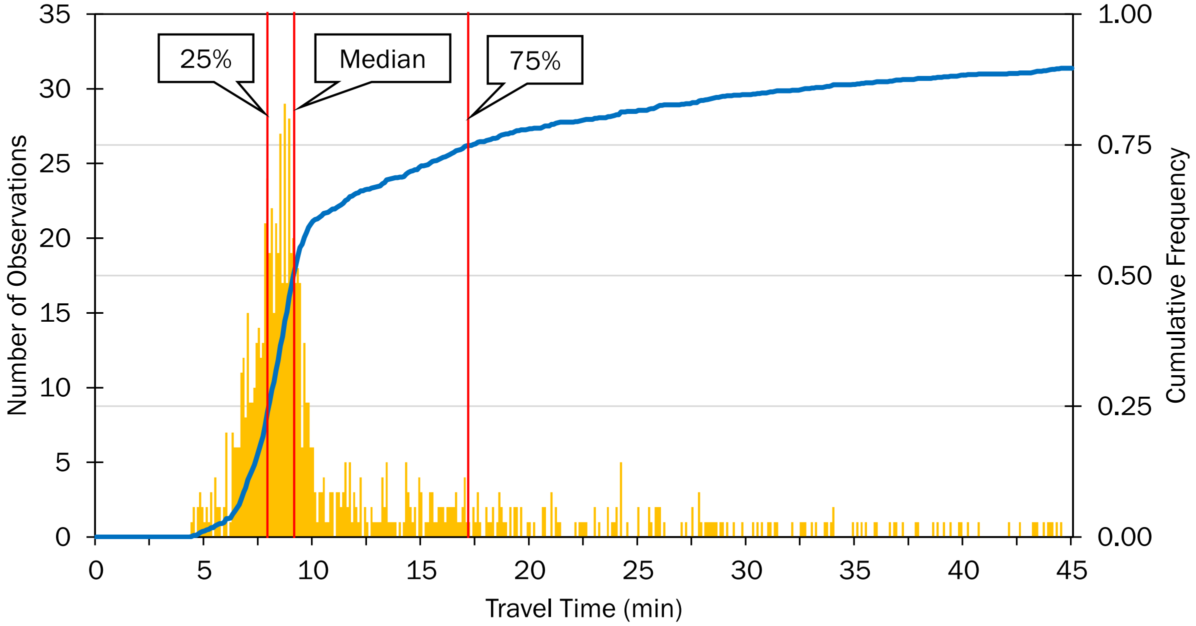


Figure 5. Visualization of travel times as a distribution (Wednesday, AM Peak, aggregated over 29 weeks).

High-resolution controller data provides insights into how traffic signals are functioning by logging the times when vehicle detectors turn on and off, and when signal indications change to red, green, and yellow. This data allows several performance measures to be tabulated that reveal the quality of service from several different perspectives.

Figure 6 presents two views of a performance measure, with the corresponding representative traffic condition shown below it. The horizontal axis in each plot represents the green occupancy ratio (GOR), which represents the amount of time during green when vehicles were present on a detector at the stop bar for a particular movement. The vertical axis shows the red occupancy ratio (ROR), the amount of time that the detector was occupied in the first five seconds of red. Each dot shows the value for an individual signal cycle. When the GOR and ROR values are high (shown by dots inside the red square), it is likely that *split failures* have occurred. A split failure happens when not all of the vehicles waiting at a signal are served during one cycle, and there are some remaining after the end of the green interval. The plot on the left hand side shows a congested situation, where many cycles have a high ROR and GOR. The right hand side shows an uncongested situation, where few cycles fall in that category.

The number or rate of split failures taking place at an intersection is one measure of the efficiency of capacity allocation. The quality of progression (the likelihood of vehicles making it through a signal on green) is another important aspect of signal operations.

Figure 7 shows an example of a performance measure called the *Purdue Coordination Diagram* (PCD). This graphic enables the quality of progression to be rapidly visualized. Each PCD presents when vehicles arrive at the traffic light, whether on greed or red. The dots represent vehicle arrivals, which are plotted by the time in the cycle on the vertical axis, and time of day on the horizontal axis. Dots above the green line are vehicles arriving when the light is green, dots below the green line are vehicles that arrive on red. Having the majority of dots above the green line indicates good progression. Conversely when there are more dots *below* the green line, it reflects poor progression at the signal.

In Figure 7, two example PCDs are shown along with a representative traffic condition for illustrative purposes. The left hand plot shows a situation where more dots fall in green than in red. This corresponds to a situation as in the image below in which vehicles arrive at the intersection while the light is green. On the right hand side, the majority of the dots are below the green line, indicating vehicles are arriving on red, which is exemplified by the image of vehicles coming to a stop at a red light.

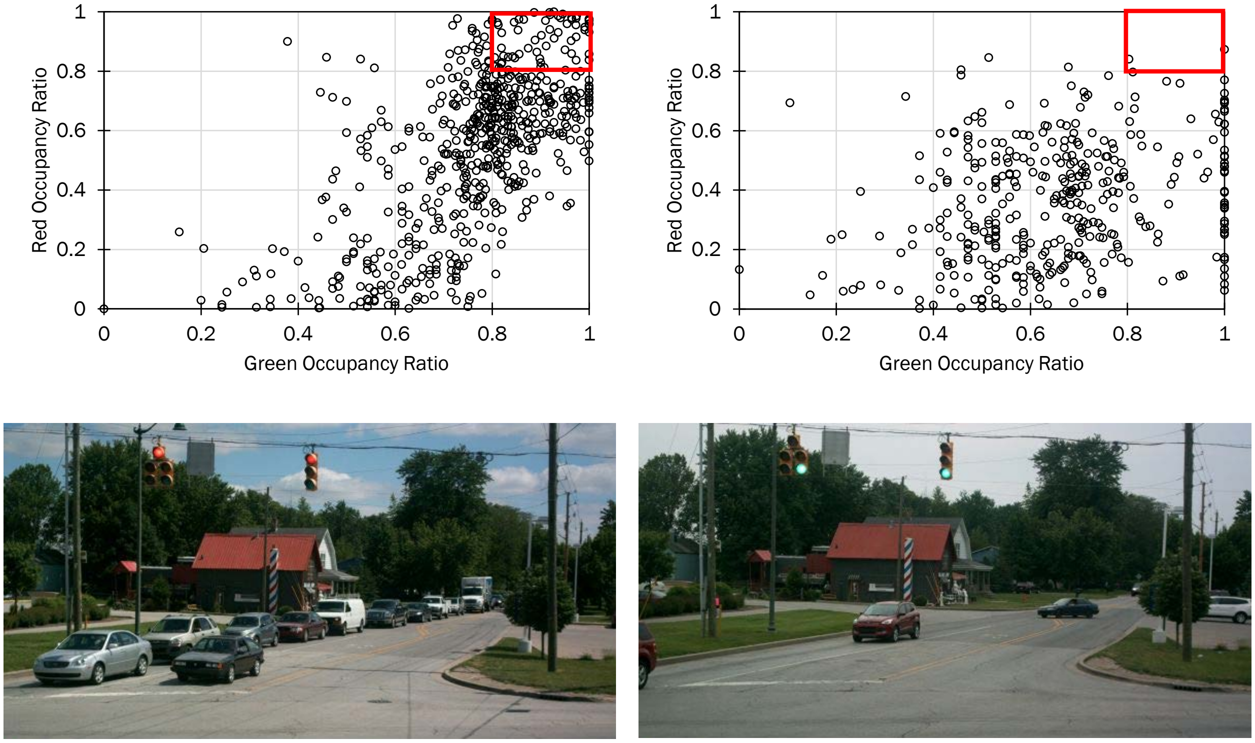


Figure 6. Movement capacity analysis using Red Occupancy Ratio and Green Occupancy Ratio.

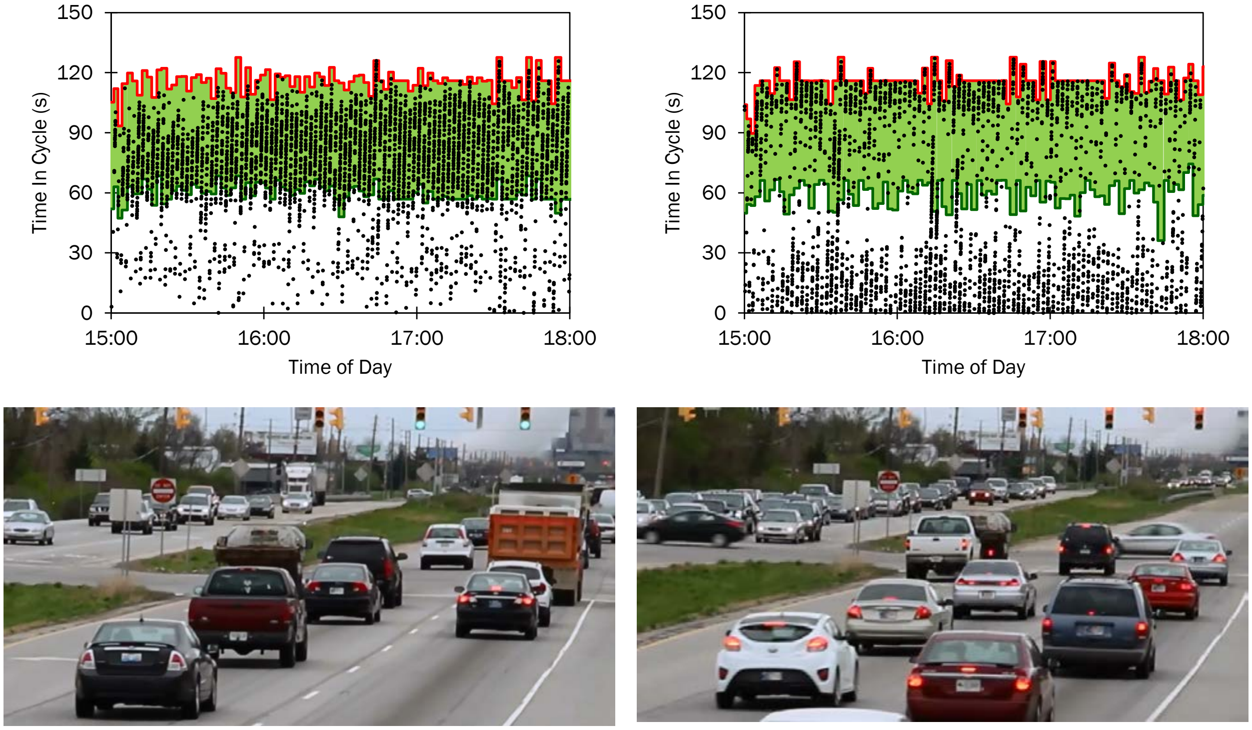


Figure 7. Coordination analysis using Purdue Coordination Diagrams (PCDs).

Combining the two data sets provides a powerful tool for understanding the impacts of signal operations on the arterial quality of service. Travel times from vehicle re-identification data can indicate the existence of a problem within a corridor, while the high-resolution controller data enables intersection-level diagnostics to pinpoint the cause of the problem in the signal timing.

Figure 8 shows a conceptual example that combines a plot of travel times with two views of system performance using PCDs. The travel time plot contains two cumulative frequency diagrams colored green and red, representing two different measurements for the same corridor. The green line lies to the left of the red line, meaning that travel times were lower under those conditions. In absence of any further information beyond the travel time, the cause of the increased travel time in the red case is indeterminate. However, *combining* travel times with high-resolution controller data provides that additional information. The green line corresponds to a situation where most vehicles are arriving in green—as shown by the PCD at the top of the figure. In contrast, the red line corresponds to a situation where most vehicles are arriving in red, as shown by the bottom PCD. In this hypothetical example, differences in the quality of progression were the root cause of the change in travel times. Another cause may be oversaturation, which would be identified by other performance measures. Although only a single intersection is implied in this example, the re-identification data could span a coordinated signal corridor, indicating a significant delay has arisen. Then the PCD could be examined at each intersection to isolate the root cause.

This simplified conceptual example demonstrates how performance measures can enable more advanced analysis of signal operations. In practice, multiple PCDs for several approaches along a corridor will need to be analyzed to see whether traffic progression is successful at each one. Additional performance measures related to capacity would reveal whether there is a shortage of green time at any of the intersections along the corridor.

Traffic progression is only one objective (albeit an important one) that can be focused on in an analysis. Other examples include efficiency of side-street green times, quality of service for pedestrians, and route choice through an arterial network, to name a few. More detailed examples are presented in the main body of the report.

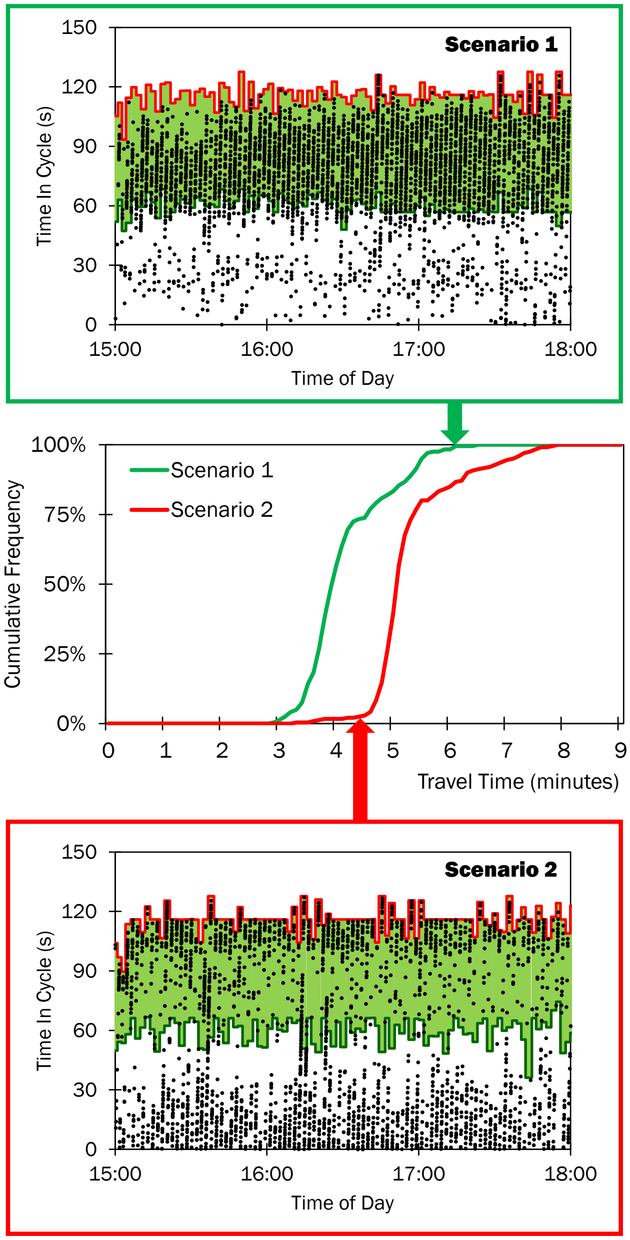


Figure 8. Combining information about travel times and arrival characteristics.

Analyzing Performance by Level (DMAIC)

The measurements of traffic performance along routes in the network and for individual corridors, intersections, and movements at the intersections, can be integrated to develop an understanding of the entire system state, at various levels of perspective.

Figure 9 shows a conceptual breakdown of three different levels at which an agency might need to assess the performance.

- **The Network Level (50,000 ft).** This perspective concerns the entire arterial program of an agency. Views of performance at this level support the coordination of agency budgets and prioritization of funding between the arterial program and other competing agency programs (such as pavements, bridges, and safety).
- **The Corridor Level (5000 ft).** This perspective concerns a particular arterial corridor or route comprising multiple intersections. Views of corridor performance are used by engineers to prioritize and select projects after the overall arterial program budget has been set.
- **The Intersection Level (500 ft).** This perspective examines an individual intersection or interchange. The performance of intersections enable engineers to scope the level of effort for a project—such as identifying the worst performing intersections within a corridor, or identifying the individual movements that have operational deficiencies.

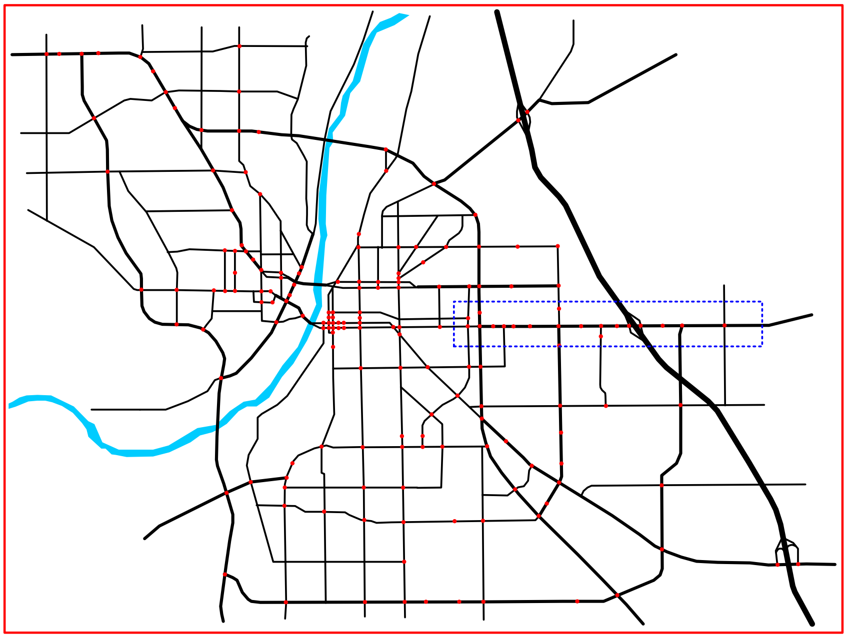
Figure 10 shows a view of an intersection with a graphical display of a performance measure for each through and right turning movement. The bars display the percent of signal cycles experiencing a *split failure*, which means that not enough green time was provided to serve all of the vehicles waiting for service on the movement. The map view shows that the northbound through movement has a rather high rate of failure while the other movements appear to be operating well.

Figure 11 shows a view of the same performance measure at the corridor level. Each intersection is labeled with an icon showing the highest failure rate of any of its individual movements. Among the six intersections comprising this corridor, it is easy to pinpoint the locations with the highest and lowest split failure rates.

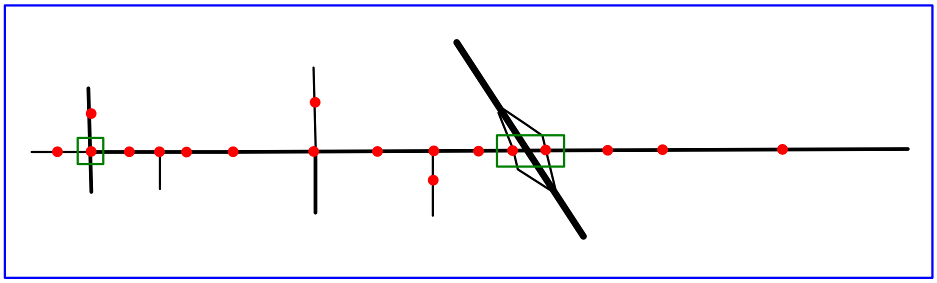
Figure 12 shows the tabulation of split failure rate across a network including six arterials in a metropolitan area. The intersections are labeled with icons separating them into split failure rates with five categories. Ag lance at the map shows that most intersections have fairly low failure rates. Most of the symbols are blue or green, indicating split failure rates less than 40%. Several intersections, however, fall in the highest category, with at least one movement having a split failure rate higher than 80%. These would consequently be likely candidates for further screening.

While operating objectives will vary according to agency objectives and the context of the arterial system (such as whether it is urban or rural), these map views illustrate the power of a data-driven analysis.

Network Level (50,000 ft)



Corridor Level (5000 ft)



Intersection Level (500 ft)

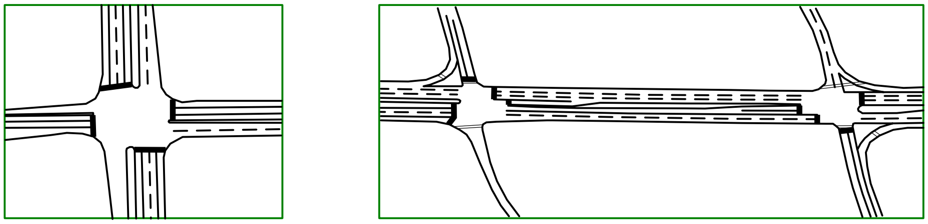


Figure 9. Network, Corridor, and Intersection levels.

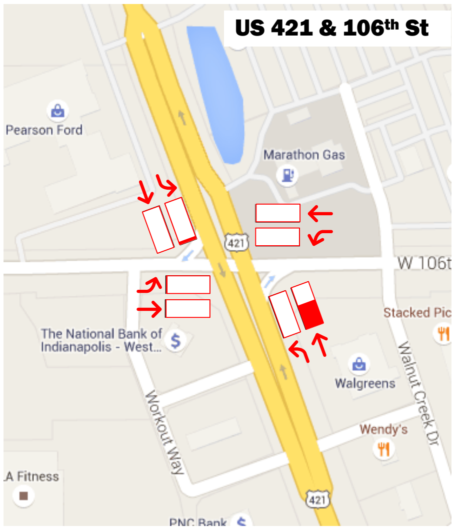


Figure 10. Intersection-level view: Percent of cycles with split failures, by movement [4].

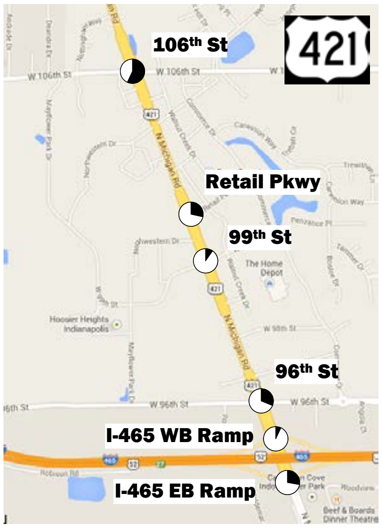


Figure 11. Corridor-level view: Percent of cycles with split failures on any movement [4].

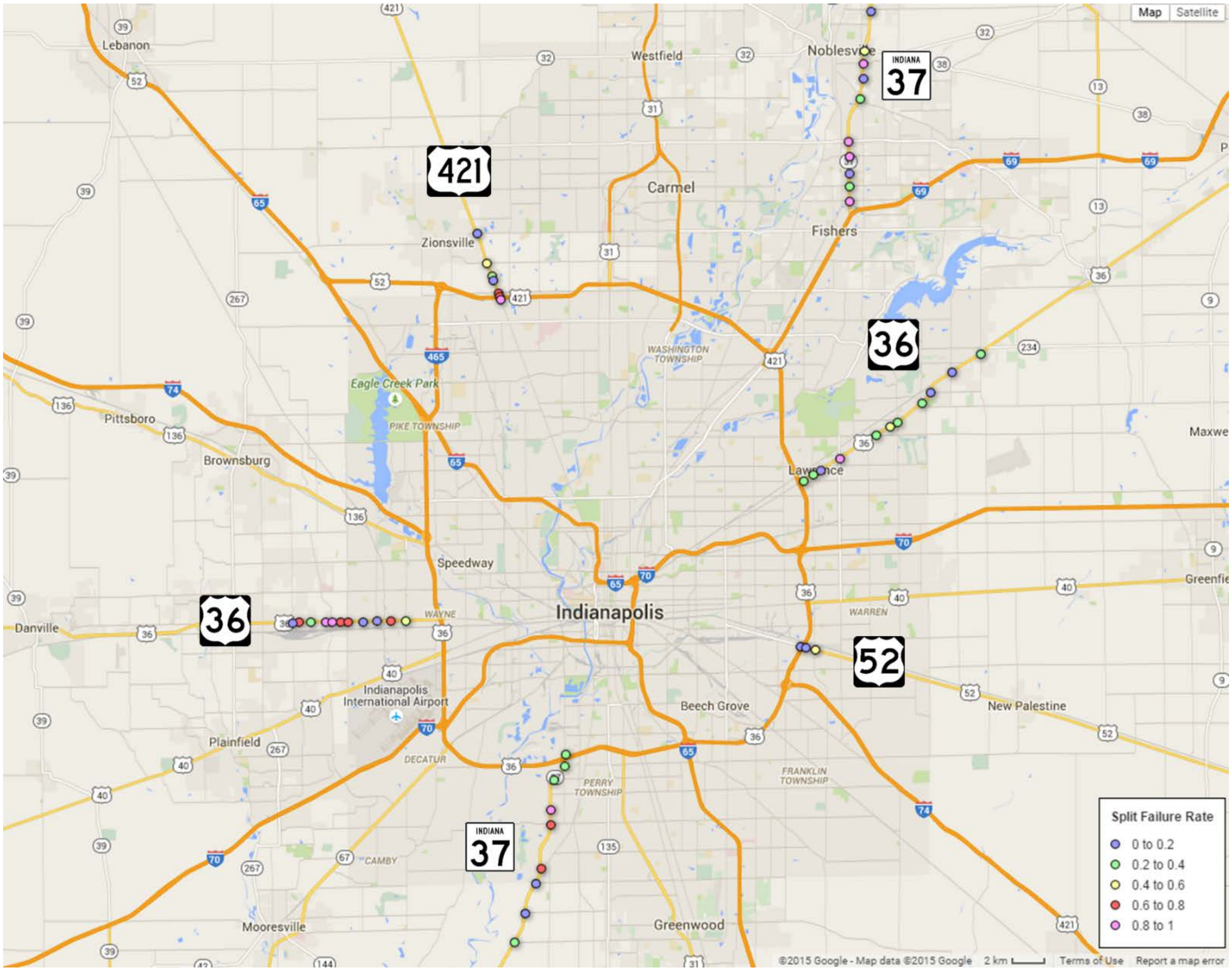


Figure 12. Network-level view: Percent of cycles with split failures on any movement.

Improving Performance (DMAIC)

The next step following defining, measuring, and analyzing is using the information gathered in that process to improve the operation of the system. By identifying locations, times, and causes of system deficiencies throughout the arterial network, it is possible to formulate solutions at the network, corridor, or intersection levels to improve them. For example, signal timing can be improved to better align the schedules of neighboring intersections for traffic progression. Where the innovation lies is in the ability to automatically measure conditions before and after improvements and to understand whether investments have paid off.

Figure 13 shows how vehicle re-identification data can be used to compare conditions before and after signal retiming. The two plots show the travel times for the northbound and southbound direction of travel on an arterial corridor before and after a timing improvement as obtained by measuring re-identification field data. The updated timing saved 1.9 minutes in the median northbound travel time and 0.5 minutes in the median southbound travel time.

The operational details are presented in Figure 14, which examines the northbound PCDs of the four signalized intersections along the corridor, before and after the timing improvement enabled by high-resolution controller data. In the PCDs, the green portion of time is shaded to help illustrate whether the vehicle arrivals (dots) are aligned with green. The numbers show the change in the percent of vehicles arriving on green before and after the timing change.

In the "before" case, arrivals at the first and third intersections mostly take place in red, which is the reason why northbound travel times were unusually long. In the "after" case, the PCDs show that the arrivals at the first and third intersections are now occurring in green rather than red. Furthermore, the percent on green substantially increased at intersections 1 and 3, yet was very little change at intersections 2 and 4. This reveals the underlying cause of the observed shift in travel times.

Importantly, before the introduction of these two enabling technologies, the "before" condition may be based purely on complaints from citizens, the analysis based on insufficient data gained from manual turning movement counts, and the "after" impact wholly dependent on a few manual floating car runs. The data-driven approach, in stark contrast, provides objective, defendable performance measures at each step.

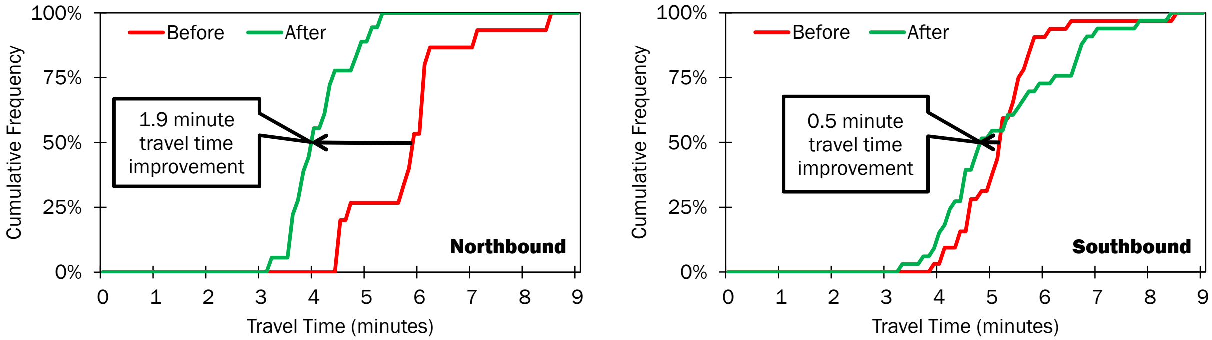


Figure 13. Assessing impact of a system improvement [5].

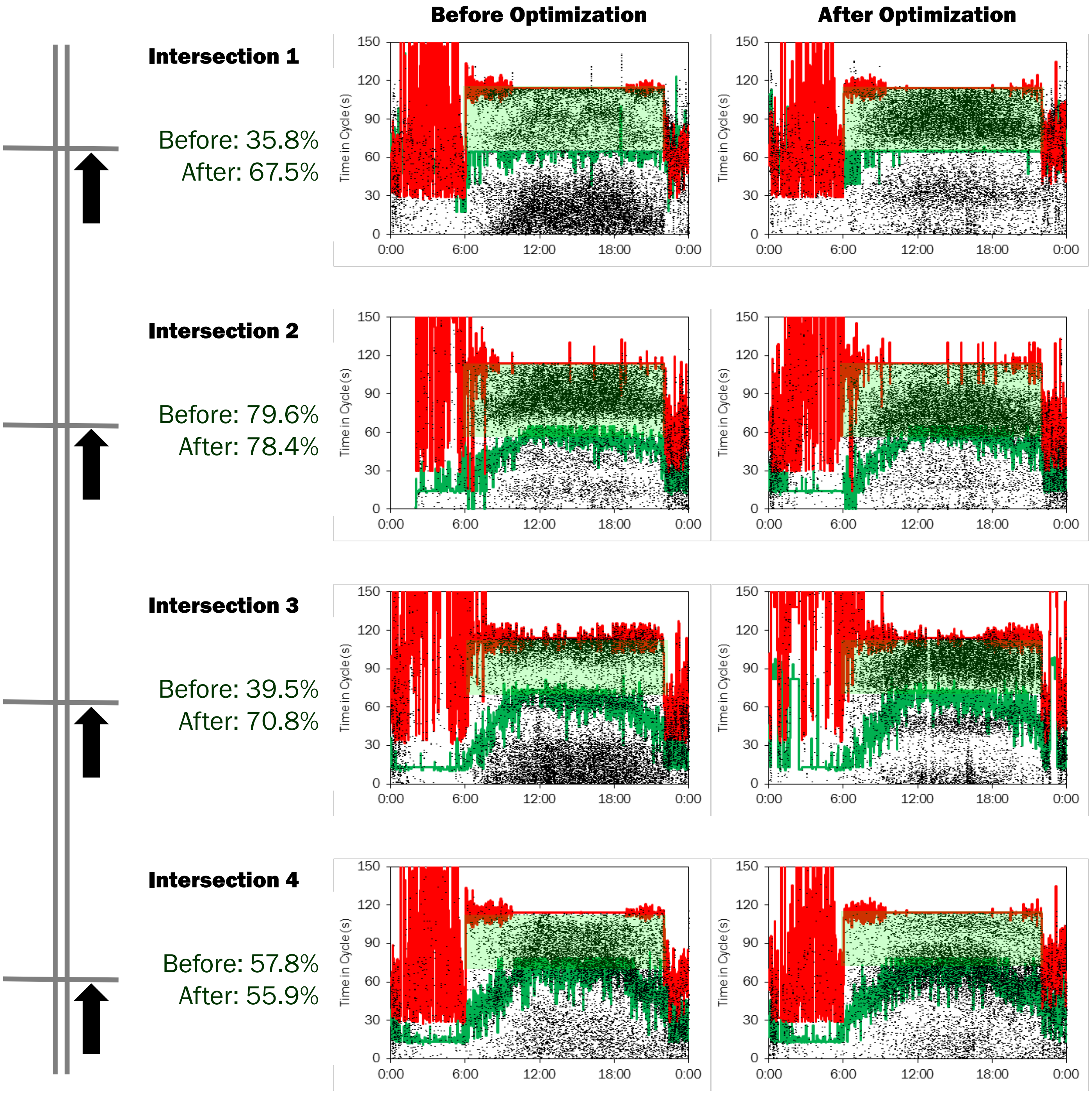


Figure 14. Assessing the operational details of the northbound progression improvement.

Controlling Performance (DMAIC)

In addition to before-and-after analyses as shown in the previous example, more powerful uses of performance measures are capable with continuous system monitoring over long time periods. Deployment of a comprehensive arterial management system incorporating performance measures would make possible the collection of data over a long enough time period to identify performance trends and take action on deficiencies before they become a problem.

The continuous monitoring of arterial performance, as in this example, provides the ability to examine new aspects of performance that historically have not been possible to analyze. The before-after comparisons that typify investments in arterial traffic control, including retiming among other options really only show a brief slice of time in which conditions have been improved. They do not show whether the improvements are stable. In the example presented here, the improvements to the timing plan yielded immediate benefits which held steady for about a year, but there was also a gradual increase in travel time over the next three years, interrupted by a few exceptional events.

The next example shows how continuous monitoring of an arterial roadway with re-identification data can reflect the long-term impacts of signal retiming, signal aging (as demand and traffic patterns change with development), and performance during a construction period.

An example of long-term performance monitoring is presented in Figure 15. This chart shows the measured travel time in one direction along a corridor over the span of about three years, from July 2011 through October 2014. Initial travel times varied between roughly 14 and 15 minutes. Then, in April 2012, traffic signals along the corridor were retimed, reducing the travel times to 13 minutes. Over the rest of 2012, travel times held at around 13 to 13.5 minutes. In 2013, road construction caused a spike in the travel times in April, but overall the travel times remained about the same. Finally, in November 2013, a bypass opened that diverted traffic to an alternative route, reducing travel times to less than 13 minutes. Later in the year, they gradually rebounded to about 14 minutes, suggesting that traffic patterns had adjusted and that it may be worth revisiting the signal timing again.

This type of information would greatly benefit an agency’s arterial program, or the congestion management program of an MPO, by assisting in the documentation of system performance. Presently, agencies must rely heavily on limited measurements and modeling techniques to derive a similar portrait of system performance over time, with far fewer interim points. A data-driven arterial management system allows that coverage to be extended over the life of the facility, facilitates better understanding of current and past conditions, and enables the agency to provide a better return on investment by the public.

It also allows the agency to quantify the return on investment for funding in arterial management in comparison to funding in other areas. Up to this point, the DMAIC process for arterial management has been presented in isolation from other management or business process functions. In reality, funding for arterial management must compete with other infrastructure preservation concerns such as road surfacing, bridges, and safety programs.

Whereas most managers are accustomed to optimizing allocated funds, the performance management program enabled by re-identification and high-resolution controller data provides the opportunity to justify additional investments in the arterial management program, enabling for the first time a quantitative response to questions such as “what improvement can be expected if the annual budget is increased 40%?” or “Can the average signal delay be reduced to less than 2 minutes at current budget levels?” Such questions can currently be addressed in other mature infrastructure management systems for pavements and bridges. The advances described in this report enable arterial management systems to begin to mature to the point where they can compete for funding based on cost/benefit analysis with other such programs.

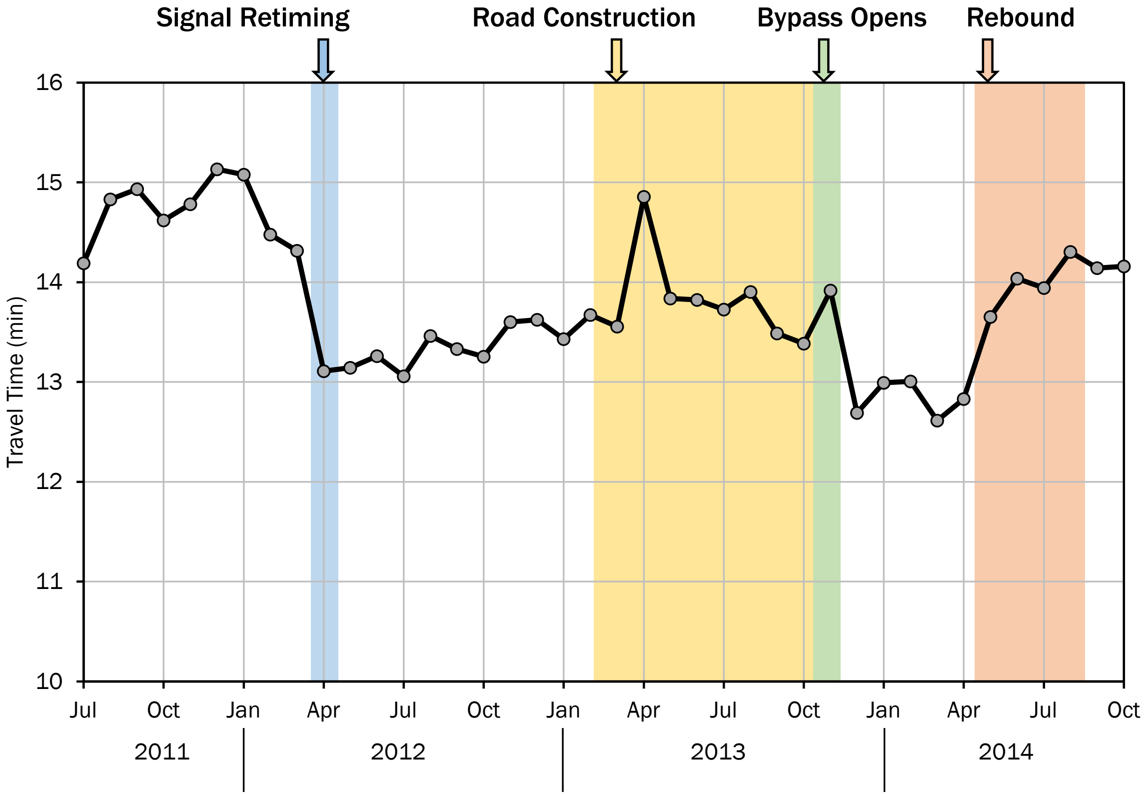


Figure 15. Monitoring of performance over a long time period.

Integration with Agency Practices

Although the report is a technically thorough document for the implementation of re-identification and high-resolution controller data, the main message is not technical in nature, but rather programmatic. These technologies enable the creation of a complete data-driven, performance-measure based Arterial Management System that can assess arterial performance in an ongoing method during the entire life cycle of an arterial roadway. In order to enable that programmatic change, personnel at each level of the organization need to understand its impact.

Successful implementation of an arterial management system will rely on successful integration into agency activities so that personnel can make the best use of the management system. Staffing and duties vary among agencies, but a synthesis of prior agency surveys [6,7] enables the development of a representative matrix, as shown in Table 4.

Table 4 explains typical personnel roles in arterial management, and identifies those tasks that would be assisted or improved with the use of an arterial management system of the type proposed in this document. The improved tasks include the following:

- **System evaluation.** Similar to the examples provided earlier, the system state can be monitored and analyzed using performance measure data.
- **Control plan development.** Data obtained by the arterial management system can be used to facilitate optimization of existing timing plans and validate new timing strategies after implementation.
- **System checking.** The duties of system monitoring that traffic management center (TMC) operators are tasked with can be augmented with the use of performance measures.
- **Complaint handling.** With a dataset to compare against, public complaints can be validated, and a new way to demonstrate their resolution is possible.
- **Maintenance requests.** The functionality or non-functionality of various system components can be identified.
- **Implementation of contingencies.** Exceptional traffic conditions such as inclement weather or special events can be particularly challenging to manage. Continuous data collection would enable development of contingency plans.
- **Detection system maintenance.** Detector errors substantially affect traffic performance, but are not easy to visually detect. Monitoring of the detection inputs will enable maintenance activities to achieve a higher level of working time of detectors.
- **Communication system maintenance.** The health of communication links will be better maintained through monitoring.
- **Traffic equipment troubleshooting and repair.** Performance measures can help engineers and traffic analysts to generate requests for maintenance as well as assist technicians validate whether components are working properly.

In addition to these potential improvements, a handful of new tasks are required to deploy a data-driven system. One of these is data system maintenance. While most agencies have some use of IT staff to maintain computers and other equipment, the need to purchase servers and software to store data will likely be a new IT use case for some.

The other task listed here is data curation. This means the activities needed to maintain data in the long term. Some agencies may not wish to maintain data beyond a certain horizon, whereas others may wish to archive it for future uses. While ultimately the means to do that will depend on decisions of traffic engineering staff and implementation by IT, as the use of the data increases, the users become stakeholders in the data curation process.

Table 4. Personnel roles in arterial management and opportunities for performance measures to assist and improve tasks, and new roles required for successful deployment of performance measures.

Task	Traffic System Engineer	Traffic Analyst / TMC Operator	Maintenance Technician	IT Specialist
Project Management	Assisted			
System Design	Assisted			
System Evaluation	Improved			
Control Plan Development	Improved			
System Checking		Improved		
Complaint Handling	Improved	Improved		
Maintenance Requests	Improved	Improved		
Implementation of Contingencies	Improved	Improved		
Data System Maintenance				Required
Data Curation	Required	Required	Required	Required
Traffic Equipment Installation			Assisted	
Detection System Maintenance			Improved	
Communication System Maintenance			Improved	Improved
Traffic Equipment Troubleshooting and Repair			Improved	
Equipment Inventorying	Assisted		Assisted	

Introduction to the Full Report

The report approaches the management of arterial performance from a series of perspectives that vary according to the "level" at which the analysis is taking place, varying from microscopic to macroscopic. The three levels defined in the report are the network, corridor, and intersection ("50,000 ft", "5000 ft", and "500 ft"). The document introduces vehicle re-identification travel time and high-resolution controller data and discusses how these can improve arterial performance management practices.

The ability to directly measure travel time efficiently and across a large geographic scale is critical because it directly measures the performance at each level based on defining the endpoints and waypoints in the vehicle re-identification process. This is complemented by the controller data that provides direct insight into individual intersection dynamics that impact travel time.

Highly detailed information about intersection operations can be developed from analysis of the high-resolution controller data, revealing intricacies about the performance of individual movements at intersections. The base data supports the formulation of performance measures that are applicable to each perspective, whether network, corridor, or intersection. This data can be integrated to evaluate the overall performance of corridors and networks.

The full report is organized into four modules that can each be independently presented to facilitate better understanding of each topic. The four modules are as follows:

- **Module 1. Arterial Management Concepts.** The first step in engaging in a performance measurement activity is to define the objectives that are to be addressed. These vary according to the priorities of the agency and the context of an arterial system. This module focuses on objectives by presenting fundamental operating concepts for arterial systems at the network, corridor, and intersection levels, and exploring what can be measured at each level.
- **Module 2. Introduction to New Technologies.** This module introduces readers to the concepts behind vehicle re-identification and high-resolution controller data. The information captured by these technologies are explained, and some example applications provide a preview of potential use cases for the data sets.
- **Module 3. Travel Time and Travel Time Reliability.** A key aspect transportation system performance is the amount of time required for users to make it through the system from an origin to a destination. This module focuses on measuring and evaluating travel times within an arterial context. Concepts related to the performance at intersections, through corridors, and across networks are explained. A series of case studies are presented in which the data is used to measure the impact of changes to the signal timing, and quantifying the resulting user benefits.
- **Module 4. Intersection Capacity and Demand.** The interaction between capacity and demand at intersections is important to many objectives in arterial operations. The efficient allocation of capacity at intersections requires balancing the distribution of green times according to demands. Beyond a certain point, however, the overall level of demand exceeds the maximum potential capacity of the intersection, and capital improvements are needed. This module presents performance measures that measure the amounts of capacity supplied and the degree to which it is utilized. Combining these concepts enables

differentiation between operational deficiencies that can be corrected through adjustment of signal timing, and those requiring larger investments. Case studies are presented where the performance measures supported investigation of different operational strategies.

While some concepts are explained in more detail in certain modules, each module can be presented independently as a source of information for training engineers and planners in using the methodology or briefing administrators and decision-makers.

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Publication

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Open Access and Collaboration with Purdue University

The Indiana legislature established the Joint Highway Research Project in 1937. In 1997, this collaborative venture between the Indiana Department of Transportation and Purdue University was renamed as the Joint Transportation Research Program (JTRP) to reflect state and national efforts to integrate the management and operation of various transportation modes. Since 1937, the JTRP program has published over 1,600 technical reports. In 2010, the JTRP partnered with the Purdue University Libraries to incorporate these technical reports in the University’s open access digital repository and to develop production processes for rapidly disseminating new research reports via this repository. Affiliated publications have also recently been added to the collection. As of 2017, the JTRP collection had over 1.5 million downloads, with some particularly popular reports having over 20,000 downloads.