NDOT Research Report

Report No. 607-17-803

# Developing a Quality of Signal Timing Performance Measure Methodology for Arterial Operations

November 2020

Nevada Department of Transportation
1263 South Stewart Street
Carson City, NV 89712

# Disclaimer

# TECHNICAL REPORT DOCUMENTATION PAGE

| 1. Report No.<br>607-17-803 | 2. Government Accession No. | 3. Recipient's Catalog No. |
|---|---|---|
| 4. Title and Subtitle<br>Developing a Quality of Signal Timing Performance Measure Methodology for Arterial Operations | | 5. Report Date<br>August 2020<br>6. Performing Organization Code |
| 7. Author(s) Zong Tian, Aobo Wang, Hao Xu | | 8. Performing Organization Report No. |
| 9. Performing Organization Name and Address<br>University of Nevada, Reno<br>1664 N Virginia Street, Reno, NV 89557 | | 10. Work Unit No.<br>11. Contract or Grant No. |
| 12. Sponsoring Agency Name and Address<br>Nevada Department of Transportation<br>1263 South Stewart Street<br>Carson City, NV 89712 | | 13. Type of Report and Period Covered<br>Final Report<br>14. Sponsoring Agency Code |

15. Supplementary Notes


16. Abstract

The report covers the work performed under NDOT's research contract #607-17-803, which involved the development of a quality of signal timing performance measure methodology for arterial operations.

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Two performance measures were then defined based on speed and stop characteristics: the attainability of ideal progression (AIP) and the attainability of user satisfaction (AUS). In order to determine AIP and AUS, a series of investigations and surveys were conducted to characterize the effects of non-signal-timing-related factors (e.g., arterial congestion level) on average travel speed as well as how stops may affect travelers' perceived quality of signal timing. Considering the effects of non-signal-timing-related factors, an AIP metric can be computed based on an arterial's operating speed and ideal progressive speed. The AUS metric accounted for the changes in the perceived quality of signal timing due to various stop circumstances. Based upon AIP and AUS, a grade-based performance measurement methodology was developed. The methodology included AIP scoring, AUS scoring, and two scoring adjustments. The two types of scoring adjustments further improved the performance measurement results by considering factors such as cross-street delays, pedestrian delays, and arterial geometric conditions.

The process for implementing the proposed methodology was outline in this report, including data collection and preliminary examination of applicable conditions. Case studies based on real-world signal re-timing projects were presented to demonstrate the applicability of the proposed methodology in practice. This research may have a great potential for enhancing agencies' capabilities of cost-effectively monitoring the quality of arterial signal timing, proactively addressing signal timing issues, and reporting the progress and outcomes in a timely, concise, and intuitive manner.


| 17. Key Words<br>Performance Measures, Signal Timing, Signal Coordination, Trajectory, Performance Index | 18. Distribution Statement<br>No restrictions. This document is available through the:<br>National Technical Information Service<br>Springfield, VA 22161 | | |
|---|---|---|---|
| 19. Security Classif. (of this report)<br>Unclassified | 20. Security Classif. (of this page)<br>Unclassified | 21. No. of Pages | 22. Price |

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Final Report

***Prepared for***

Nevada Department
of Transportation

***Prepared by***


Center for Advanced
Transportation
Education and Research
(CATER)
University of Nevada,
Reno


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**Final Report**

**(NDOT Research Project 607-17-803)**

Prepared for

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# ABSTRACT

The report covers the work performed under NDOT's research contract #607-17-803, which involved the development of a quality of signal timing performance measure methodology for arterial operations.

Evaluating the benefits of traffic signal re-timing is of an increasing interest to transportation policymakers, operators, and the public, as integrating performance measurements with agencies' daily signal timing management has become a top priority. The current state of practice and research was reviewed first, revealing an urgent research need for the development of a methodology that focuses on arterial-level signal timing performance assessments. Accordingly, arterial travel-run speed and stop characteristics, which can be extracted from vehicles' GPS travel trajectories, were selected to measure the quality of arterial signal timing in this research.

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# EXECUTIVE SUMMARY

## Research Objectives

Arterial operations play a crucial role in urban transportation management in Nevada, and the quality of arterial signal timing can profoundly affect arterial operational efficiency and travelers' perception of transportation services. One of the major challenges that the Nevada Department of Transportation (NDOT) is facing is the lack of a proper signal timing performance measurement methodology for arterial operations. Currently, signal timing practitioners in Nevada evaluate the quality of arterial signal timings through laborious observations conducted manually or using engineering judgements, which may lead to unsatisfactory signal operations and overdue improvements. The primary purpose of this research is to fill this gap, providing a cost-effective arterial signal timing performance measurement methodology.

The major tasks of this research are to:

- Establish effective arterial signal timing performance measures based on vehicle travel-run trajectory data to assess the quality of signal timing concerning arterial-level operations;
- Define a grade-based evaluation framework according to the proposed performance measures, describing the quality of arterial signal timing through the use of intuitive and understandable terms to better inform decision-makers and the public; and
- Provide a scheme to implement the proposed performance measurement methodology in practice.

## Research Overview

In this research, a method to measure the quality of arterial signal timing was developed, and the implementation of the proposed performance measurement was outlined. The background introduction and review of the current research and practices were presented, which identified a need for research to develop an arterial-level signal timing performance measurement methodology.

The two arterial-level performance metrics, which are: 1) attainability of ideal progression (AIP) and 2) attainability of user satisfaction (AUS), were developed based on vehicles' travel-run speed and stop characteristics. The AIP metric was defined based on travel speed while excluding the non-signal-timing factors, and the AUS metric was defined by drivers' perceived quality of arterial signal timing, which correlated to the number of stops and stopped time at intersections. In order to determine the AIP and AUS metrics, investigations were conducted to characterize the non-signal-timing factors that may influence signal timing performance measurements (e.g., arterial congestion level.) In addition, preliminary surveys were conducted to reveal several major factors that affect drivers' satisfaction with their trips along arterials.

An arterial signal performance measurement methodology was derived according to the AIP and AUS metrics. Two adjustments, the cycle length adjustment and intersection spacing adjustment, were included based on considerations of side-street and pedestrian delays as well as arterial geometric conditions. The quality of arterial signal timing can be rated at levels of A, B, C, D, and F using the proposed methodology. The implementation of the proposed method was outlined, including data collection, data processing, and a pre-implementation examination. Two case studies were documented lastly to prove the validity of the proposed performance measurement methodology. The first case study involved re-timing of five arterials as part of the regional signal re-timing project – phase 5 sponsored by the Regional Transportation Commission of Washoe County, Nevada. The second case study involved re-timing of 8 signals on Carson Street in Carson City, Nevada. Both case studies demonstrated that the proposed performance measurement methodology could reasonably gauge the quality of arterial signal timing and coordination.

**Major Findings**

1) A scalable performance measurement framework is provided, which can be implemented under a wide range of budgetary conditions and for diverse signal timing considerations. The proposed performance measurement methodology can be applied without strict preconditions and at flexible costs. For example, no specific infrastructure configurations are required, and local agencies can collect trajectories through travel-run investigations or acquire data from third-party data vendors. This allows agencies with limited budgets and staffing to conduct regular arterial signal timing performance measurements.

2) The proposed methodology can assess the quality of signal timing based on progression efficiency as well as travelers' satisfaction, which is useful for demonstrating the effectiveness of signal re-timing efforts, identifying signal re-timing needs, and reducing citizen complaints. However, the methodology can be further improved by appropriately accounting for other non-signal-timing factors such as arterial congestion level.

3) The result of the proposed methodology can be easily understood by decision-makers, practitioners, and the public, which can facilitate progress reporting, public involvement, and staff training during signal timing projects.

This research can be more valuable if vehicle trajectories can be broadly collected across road networks through emerging technologies such as connected vehicles.

**Limitations and Future Extensions**

1) The proposed methodology is not applicable for arterial segments where oversaturation exists. The causes of oversaturation are manifold, in which signal timing is one of the factors. It is worth further exploring proper metrics to describe the relationship between quality of signal timing and oversaturation in future research.

2) The proposed methodology is based on travel-run trajectories, which is a major difference from Automated Traffic Signal Performance Measures (ATPSMs) systems which rely on link-based detector and signal timing data. One current limitation of using trajectories is sample gathering, which still mainly relies on manual processes. Other automated data sources such as crowdsourcing may supplement the sampling process if they can be jointly used in the future.

3) Due to time and resource constraints, only limited traveler surveys were conducted during this research, and some key parameters have only been calibrated based on local conditions in Nevada.

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# 1. INTRODUCTION

Traffic signal control, a way to assign right-of-way to various traffic and pedestrian movements at intersections, has been in place for more than 100 years in the United States. Today, there are more than 330,000 traffic signals in the nation [1], and over two-thirds of miles driven on the road are influenced by traffic signal operations [2]. The amount of traffic delay at signalized intersections has been steadily increasing over the past 20 years [3], which contributes to an estimated 5 to 10 percent of overall travel delay, equivalent to 295 million vehicle-hours annually on major roadways [4]. Inferior traffic operations often correlate with inefficient performances of transportation systems, resulting in congestion, excess fuel consumption, and unwanted vehicular emissions. In addition, travelers perceive the transportation system operations that are of poor quality while being stopped at traffic signals. Due to the profound effects on transportation system efficiency as well as travelers' perception of transportation service quality, improving traffic signal operations has been regarded as one of the most rewarding traffic management endeavors.

Traffic signal timing is crucial for signal operations, which involves determining a variety of parameters, such as the allocation of green times among vehicular, pedestrian, and transit traffic by movement or approach, the sequential order of signal control phases, and the time relationship of timing plan operations between adjacent intersections. High-quality signal timings allow all users of transportation systems to traverse intersection(s) safely and efficiently. There has been an increased interest in improving traffic signal timing due to the remarkable payoffs in time and environmental benefits with benefit-cost ratios ranging between 20:1 and 55:1 [5], which can translate into tens of millions of dollar savings annually in the U.S.

Nevertheless, the outcomes remain far from ideal, despite considerable efforts spent on improving signal timing over recent decades. A nationwide survey evaluated the signal timing practices in the U.S. and only assigned a "C" grade, indicating that the signal operations across the country were barely performing at adequate levels [3]. The report explained how this unsatisfactory grade was determined, and is quoted in the following sentence:

*"Traffic signal timing performance is not regularly measured in connection to objectives, resulting in outdated timing patterns that do not reflect current traffic and pedestrian needs, and coordinated signals may force travelers to stop at multiple adjacent intersections"* [3].

As described above, performance measurements should be brought to the forefront of attention, which can link day-to-day practices to operational objectives. In the view of many transportation agencies who superficially consider signal timing as a process of parametric calculations, the performance of signal timing is determined after the software or model outputs have been implemented to field signal controllers; however, discrepancies can often be observed in practice as traffic patterns are versatile over time, which implies that the performance of signal timing is dynamic along with the change of traffic demands and flow profiles of movements. Consequently, regular performance measurements are necessary in order to continue operating traffic signals at their best levels.

Effective performance assessments require a decent amount of observation and study, where a high-standard set of expertise and resources is needed. As for performance evaluations of traffic signal coordination, the process still mostly relies on manual observations, which is often a costly and labor-intensive procedure conducted by a group of people either standing at intersections to observe traffic flow or driving along arterials repetitiously. In addition, manual observations may not be capable of characterizing the overall performance, but only of providing partial information on the control effects. Practitioners may have to use clear thinking and careful reasoning to deal with many varieties of data gathered from the field for identifying the cause of signal timing problems. Due to a lack of sufficient resources and competent staff, many agencies usually schedule signal re-timing based on citizen complaints. Thus, the improvements can usually be arbitrary and overdue.

Furthermore, policy-makers and elected board members may underestimate the need for future improvements while planning the budget due to inaccurate reporting, and accordingly, transportation agencies would continue evaluating the quality of signal timing with difficulty or inaccuracy due to insufficient resources allocated, therefore creating a vicious cycle.

Although most agencies across the nation realized the importance of signal timing performance measurements, performance measurements have not yet been incorporated into their daily practice because of technical, operational, and budgetary constraints. There has been an ongoing debate regarding what data collection techniques can be used and how local agencies can perform the measurements when funding and staffing are tight. A performance measurement methodology, which can assist signal timing engineers and technicians in monitoring and improving arterial signal operations through accessible data sources, is need. Most importantly, the performance measurement methodology should be able to be implemented in a convenient and affordable manner.

This report documents the development and implementation of a methodology for measuring the quality of traffic signal timing for arterial operations. The report is organized into six chapters. The research motivations and objectives are presented in Chapter 1. Chapter 2 covers a comprehensive literature review, which includes the current research and practices related to signal timing performance measurements. The existing signal timing performance measures and two major performance measurement techniques are analyzed. Chapter 3 presents the development of the methodology for measuring the quality of arterial signal timing. Two performance measures named Attainability of Ideal Progression (AIP) and Attainability of User Satisfaction (AUS) are newly defined. Based on AIP and AUS, a grade-based performance evaluation framework is established. Chapter 4 outlines the implementation process, including data gathering, data processing, and examining applicable conditions for implementation. Chapter 5 includes two case studies, which demonstrate the applicability of the proposed methodology. Finally, Chapter 6 summarizes the research findings and potential future efforts on enhancing the proposed methodology.

## 1.1 Research Motivation

This research was inspired by the significant signal timing challenges described in a report published by the Federal Highway Administration (FHWA) [ 6 ]. At present, these challenges are still unsolved, and continue to hinder signal timing practices across the country. Table 1.1 presents these significant limitations and specifies how these limitations can influence the current arterial signal timing practice. Performance-based signal management could be a solution to these challenges, and developing a signal timing performance measurement methodology is one of the key elements.

**Table 1.1: Current Signal Timing Challenges**

| Challenges | Specifics in Coordinating Signals for Arterial Operations |
|---|---|
| No Standard Established for Good Operations | The widely adopted measures, such as reductions of travel time or the number of stops, can be used to demonstrate the improvements through before-after analyses; however, whether the "best" performance has been attained is still unknown. Active management is impossible without a definition for good operations, and accordingly, citizen complaints become the de facto traction towards making signal timing improvements [7]. |
| Inadequate Performance Measurements Due to Limited Resources | Arterial-level signal timing performance measurements usually require a massive amount of work, including manual observations and floating-car studies. Many agencies either hardly or arbitrarily evaluate the performance of arterial-level signal operations due to budgetary and human-resource limitations |
| A Lack of Practical Methodologies and Applications | Very few software packages are currently available for signal coordination development [8,9,10], among which almost none are capable of measuring the quality of arterial signal timing. |
| Ineffectively Reporting the Progress and Outcomes | Practitioners face difficulties in articulating the progress of arterial signal timing practices with an intuitive language, which may mislead the decision-makers and the public who evaluate the returns on investments and decide the future funding allocation. |

With an effective performance measurement methodology, agencies across the nation may be more capable and willing to integrate performance measurements with daily practices and decision-making processes, which ultimately improve traffic signal operations. Both data-driven and problem-driven signal timing procedures can be enhanced, as exhibited in Figure 1.1, where effective, active (or even proactive), and multi-stakeholder involved signal timing management can be achieved. In this manner, the previously mentioned "vicious cycle" would terminate with the quality of signal timing continuously improving.

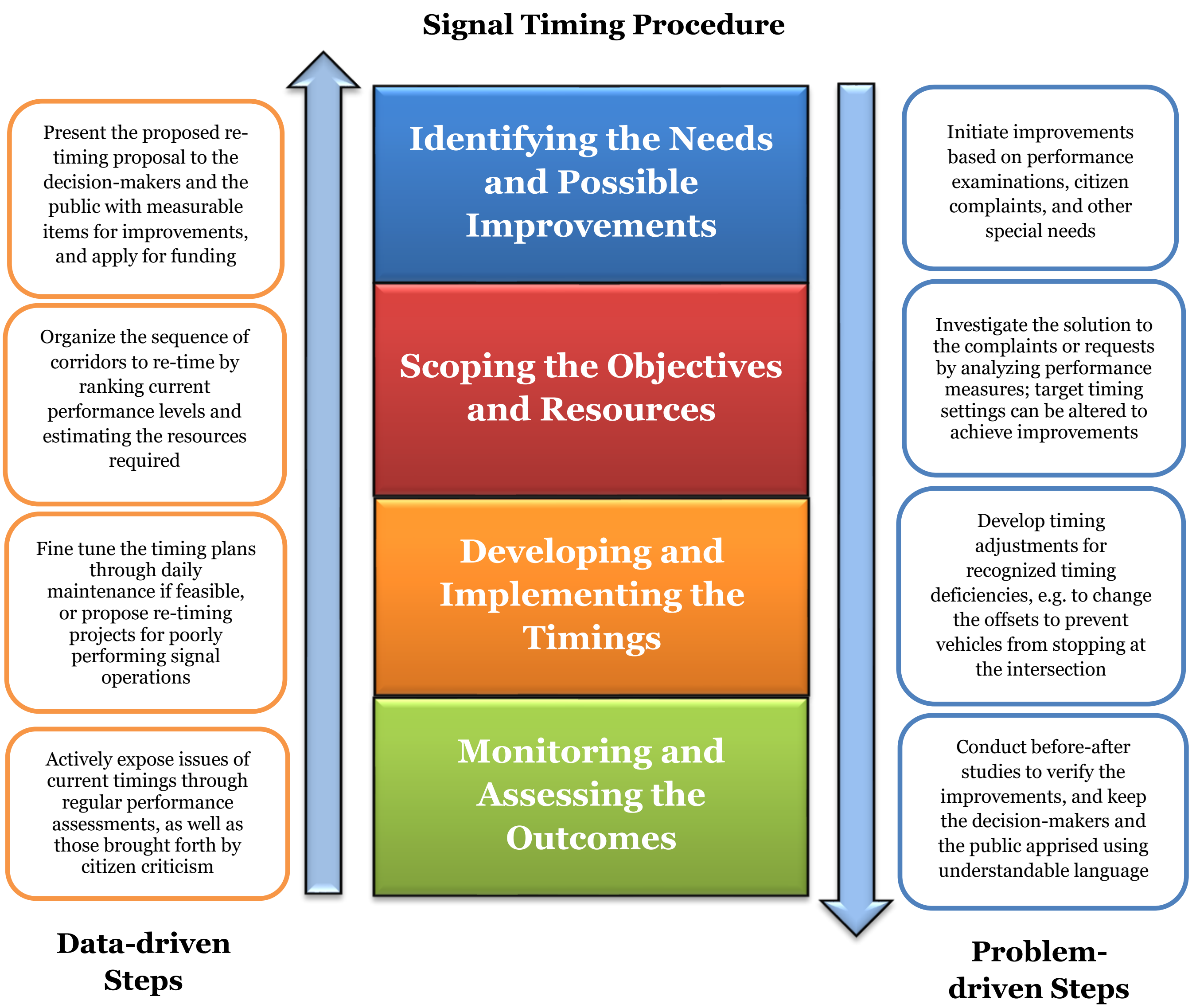



**Figure 1.1: Integrating Performance Measurements with Signal Timing Practices**

## 1.2 Research Objectives

This research aims to develop a performance measurement methodology for arterial signal timing analysis. The primary objectives of this research include:

1) Establish performance measures based on vehicle travel-run trajectory data to assess the quality of signal timing concerning arterial-level operations;

2) Define a grade-based evaluation framework according to the proposed performance measures, describing the quality of arterial signal timing through the

use of intuitive and understandable language in an effort to inform decision-makers and the public; and

3) Provide a procedure to implement the proposed performance measurement methodology in real-world operations.

Accomplishing these research objectives can help agencies across the nation in addressing the aforementioned limitations by the following ways:

1) The research proposes a methodology for measuring the quality of arterial signal timing based on various considerations, including progression quality and traveler perception. The quality of signal timing links signal timing design to arterial operations and perceived quality of service, which can guide signal timing improvement projects to reduce arterial travel delays, stops, and potential citizen complaints. For developing the proposed methodology, the effects of non-signal-timing factors (e.g., arterial congestion levels, arrival profiles, and geometry constraints) on arterial operations have been considered, which makes the resulting quality of signal timing more informative and accurate compared to the conventional signal timing performance measurements. For example, when congestion occurs, signal timing is usually considered problematic through the conventional performance measurements; however, the poor performance can be primarily due to oversaturated traffic demands. The proposed methodology addresses the signal timing aspect explicitly, yielding unbiased performance assessments to assist transportation system operators and decision-makers in properly choosing congestion relief strategies beyond signal timing, such as widening roadways to increase capacity and promoting public transit and car-free transportation modes to reduce demands.

2) The proposed methodology provides a grade-based evaluation framework, which can be easily understood by signal timing project stakeholders, elected officials, and the public who have limited signal timing knowledge. This can facilitate budgeting, progress reporting, and public involvement processes during a signal timing project. The performance grades can also promote information exchange among practitioners, including signal timing experts and trainees who can quickly share results and develop their expertise.

3) The proposed performance measurement can be conducted in a scalable and multipurpose fashion. It is feasible in the contexts of multiple signal control modes (e.g., pre-timed, actuated, or adaptive signal control), various objectives (e.g., improving progression along arterial through movements, improving transit signal

priority, or improving mobility along a specific route of interest), and various scopes (e.g., ad-hoc performance studies or daily monitoring). The proposed performance measurement is based on vehicle travel-run trajectories, which are constituted by the Global Positioning System (GPS) data. Such trajectory data can be gathered through probe vehicle investigations, acquired from third parties (e.g., INRIX and the National Performance Management Research Data Set (NPMRDS), and obtained from emerging connected-vehicle applications [11]. Using trajectory data possesses excellent flexibility in budgeting and resourcing. An agency can still perform performance measurements under tight-budget conditions by assigning a few technicians to do travel runs along arterials for generating GPS data. Alternatively, an agency can obtain abundant trajectory data from third-party data providers or by deploying connected-vehicle technologies if budget allows. In addition, based on the trajectories generated by transit buses or bicycles, the proposed methodology can be used to evaluate the quality of signal timing with respect to transit and bicycle traffic moving along arterials.

# 2. CURRENT STATE OF PRACTICE

This chapter provides a literature review of the current studies, techniques, and applications with regard to signal timing performance measurements.

For decades, the federal government has expressed a keen interest in performance measurements, and the local agencies have been required to strategically plan how they will deliver high-quality services as well as measure their programs' performance in meeting the commitments. A key feature of MAP-21 (Moving Ahead for Progress in the 21st Century Transportation Bill) is the establishment of performance- and outcome-based programs, which placed much emphasis on promoting the concept of performance measurements.

A succinct definition of performance measurements can be expressed as [12]: assessing progress toward expected program achievements, including information on the efficiency with which resources are transformed into goods and services (outputs), the quality of those outputs (how well they are delivered to users and the extent to which users are satisfied) or outcomes (the results of a program activity compared to its intended purpose), and the effectiveness of operations with regard to their specific contributions to program objectives. As stated in an NCHRP report that was also quoted by the FHWA Operations Performance Management Program [13], performance measurement is the use of statistical evidence to determine progress toward specific organizational objectives. This includes the evidence of both measurements of the quality of outcomes and user perception, which would be accomplished through a user satisfaction survey.

As transportation is regarded as a service industry, the establishment of a set of performance measures is essential for gauging the level of transportation services with regards to their strategic and operational goals. The performance measures should quantitatively reflect how the transportation services have performed in comparison with the optimal levels. The satisfaction of users who are ultimately served by transportation systems needs to be included in the performance measures, in addition to the concerns of transportation system owners or operators whose definition of the best quality is often deemed authoritative. As exhibited in Figure 2.1, effective performance measures should consist of two aspects: 1) measuring how well a service is delivered and 2) measuring how well the users feel about the service.


**Figure 2.1: Two Major Aspects of Performance Measures**

Properly selecting performance metrics is essential for signal timing performance evaluations. Hence, an analysis of the metrics used in the current signal timing performance measurements is presented in this chapter.

The current practices and techniques for measuring signal timing performance can be classified into two categories: 1) performance measurements based on high-resolution controller event data and 2) performance measurements based on travel-run data. A comprehensive review is presented regarding these two types of performance measurement techniques.

## 2.1 Performance Measures Adopted in the Current Practice

Nearly one and half centuries ago, traffic signals were first invented in order to organize traffic flow at intersections. Today, traffic signals have become more advanced and ubiquitous. There are many signal control modes, such as pre-timed, semi-/fully-actuated, responsive, and adaptive. There are also several types of traffic signal controllers and detecting sensors that have been invented. Technological advances can enhance the performance of traffic signal operations; however, studies have indicated that sophisticated traffic signal control systems do not always deliver the expected outcomes in practice [14]. There is a misconception by some practitioners when conducting performance measurements that the more resources invested in upgrading the facilities and the more cutting-edge the control systems installed, the better performance these systems can produce. Accordingly, the implementation of signal timing performance measurements still requires a focus on how well the traffic is served under the control of traffic signals, rather than by an input-oriented approach which only counts the number of investments.

Even though signal control techniques have significantly evolved and become more diverse, the ultimate objective of the field of traffic signal control is still based around one theme – assigning right-of-way within the context of safe operation while minimizing the possible delay generated. In addition, there exist several objectives taken into consideration when looking at all participants at an intersection, e.g., passenger vehicles, freight trucks, pedestrians, bicyclists, and transit buses. The *Signal Timing Manual* [15] documents several specific operational objectives that can be used individually or in combination to focus on signal timing efforts, which are listed in Table 2.1.

To achieve the highest level of every objective is impractical. There are a few inherently incompatible objectives, e.g., most means to improve the quality of arterial progression would inevitably increase the total delay on the non-progressed movements. Additionally, some objectives may mutually overlap under certain circumstances. For instance, the quality of progression not only influences the number of stops at an intersection but also closely correlates with environmental and economic impacts. Poor quality of progression results in additional stops, leading to increased idling time of vehicles at intersections, which consumes more fuel and generates more emissions than if vehicle platoons can smoothly traverse the intersections [16]. Hence, in real-world practices, it is common to see that only some critical objectives are selected and then measured in performance evaluations, in an effort to achieve the expected outcomes. For example, for a signal re-timing project that aims to develop transit signal priority, minimizing the delay time and the number of stops for transit vehicles is the core intention that the performance measurements should focus. The other objectives can be either included in the critical objectives or regarded as prerequisites for successful operations, which means that any signal timing improvements according to the critical objectives can be deemed meaningful only if a good extent of the other objectives can be fulfilled. For example, the travel time along an arterial can be reduced at the expense of the side-street traffic and pedestrians; however, the reduction will be in vain if a significant delay time increase is imposed on the side-street traffic and pedestrians, especially when travelers who frequently use the minor-street routes are aware of the increased delays and then complain to the agency.

**Table 2.1: Multi-dimensional Objectives of Signal Timing Practices [15]**

| Objectives | Definitions | |
|---|---|---|
| **Safety** | Reduce vehicle-, pedestrian-, and bicycle-related conflicts. Provide sufficient time for all traffic participants to execute movements. Ensure those signal indications would not be distractive or confusing to drivers, pedestrians, and cyclists. | |
| **Mobility** | Capacity Allocation | Serve vehicle, pedestrian, and bicycle movements as efficiently as possible while also distributing capacity as equitably as possible across movements and modes. Prioritize some movements according to need (e.g., transit priority) without excessively delaying other movements. |
| | Corridor Progression | Minimize delays on high-priority movements (typically the through movements along the arterial) for vehicles, and if possible, for transits or bicycles. |
| | Delay Control | Control delays on the secondary movements (the turning movements along the arterial or the cross-street movements) for vehicles, and if possible, for transits or bicycles. |
| **Environmental Impact Mitigation** | Minimize the amount of induced pollution by improving the efficiency of vehicle trajectories, e.g., by reducing vehicular delays or stops. Promote high-occupancy traffic modes (e.g., transit priority). | |
| **Queue Length Management** | Prevent the formation of excessive queues on critical lane groups, such as freeway exit ramps. Avoid queue spillovers, e.g., eliminating the stops as much as possible between closely spaced intersections such as interchange signals. | |
| **Operating Cost** | Minimize stops and delays in order to reduce vehicle operating costs and to save time costs for drivers, pedestrians, cyclists, and transit passengers. | |
| **Accessibility** | Provide the ability for pedestrians and transit vehicles, including special-needs groups, to execute movements. Improve the ease of reaching destinations and activities according to need (e.g., by reducing delays and stops along major commuting routes) | |

When it comes to arterial operations, the critical task of signal timing is to improve platoon progression between signals, which is achieved by signal coordination, the most iconic part of arterial-level signal operations. The remainder of this report will focus on the performance measurements for signal coordination. The concepts, methodologies, and techniques for developing signal coordination were documented in the Signal Timing Manual [15], which will not be further discussed within this report.

There have been a number of metrics adopted in the current practice pertaining to signal coordination evaluations, which are summarized in Table 2.2.

**Table 2.2: Performance Metrics Used in the Current Practice**

| Metrics | Criteria for Good Operations | Data Source | Strengths | Weaknesses |
|---|---|---|---|---|
| **Progression Bandwidth** | The greater Progression Efficiency, Progression Attainability [17], or Progression Opportunity [18], the better quality of signal coordination it performs. | Time-Space Diagram | The quality of timing plans can be estimated when the timing is initially designed through visual analysis. | Progression bandwidth only displays the length of the progressive time window, which cannot pledge good platoon progression formed in reality. |
| **Percent Arrivals on Green** | Percent arrivals on green is the proportion of vehicles that arrive during a green indication relative to those that arrive during a red-light indication. A high percentage demonstrates the signal coordination is effective. | Detection and controller events | It indicates how many vehicles actually benefit from signal coordination. | A specific set of detector installation and layout is required. The data collection can be significantly affected by queuing. |
| **The ratio of Arrival on Green to Arrival on Red** | The ratio of intersections that the vehicle arrives at on green to that the vehicle arrives at on red traversing along the arterial. Achieving less-than-two stops per five signals is Usually considered a good operation. | Floating-car studies | It provides an intuitive and corridor-level analysis of progression quality, which can be obtained through observations. | It is sensitive to the size of samples as well as the number of evaluated signals. |
| **Platoon Ratio** | It is calculated as percent arrival on green divided by the green-to-cycle ratio [19]. Platoon Ratio ranges between 0.3 and 2.0. A platoon ratio of 0.3 represents Arrival Type 1 [20], which can be caused by the inferior quality of progression. A platoon ratio of 2.0 indicates an exceptional quality of progression. | Detection and controller events | It averts inappropriate timing designs, which are mostly in favor of arterial traffic. Platoon Ratio of 1.0 is a handy baseline by which to judge whether signal coordination is beneficial or not. | Platoon Ratio is a link-based metric and requires a specified detection configuration. It is also sensitive to queuing. |

**Table 2.2: Performance Metrics Used in the Current Practice (continued)**

| | | | | |
|---|---|---|---|---|
| **Travel Time /Travel Speed** | Good quality of progression can be demonstrated by the reduced travel time or the increased travel speed. | Travel-run trajectories | Travel time or average speed can be an intuitive performance measure to the public, operators, planners, and maintenance staff. | It can be influenced by non-signal-timing factors such as congestion levels along arterials. It does not reveal travelers' perceptions. |
| **Number of Stops per Mile** | The fewer stops per mile, the smoother platoon operation achieved, which indicates a better quality of signal coordination. | Travel-run trajectories | It closely relates to fuel consumption, polluting emissions, and the underlying feelings of travelers. | It is sensitive to signal density (the metric may be less applicable for arterials where signals are closely spaced. Under such circumstances, the number of stops per mile could be unsatisfactory even if arterial signals are optimally timed already.) The number of stops is not differentiated regarding stop duration. |
| **Vehicle Delay** | Good quality of signal coordination typically can reduce the average delay of vehicles in the system. Some measures were developed based on vehicle delay, e.g., Performance Index [21], which is a combination of cumulative delay and the number of stops incurred on the trip. | Simulation studies or mathematic calculations | Average vehicle delay is a network-level metric, which covers traffic on the side streets. | It is challenging to measure vehicle delay time in the real world. |

As described in Table 2.2, the quality of progression can be mainly reflected by link-level metrics (e.g., Percent Arrivals on Green/ Platoon Ratio), and by arterial-level metrics (e.g., the number of stops per mile/ travel time or travel speed along the arterial), which are computed by using controller event data and travel-run trajectories.

Both types of metrics are useful for evaluating the quality of signal timing; however, some vital information of signal operations may be missing if only one type of metrics is adopted. Figure 2.2 illustrates the time-space diagrams of two signal timings for three intersections. While only the offset and phase sequence at Intersection 1 is different between the two timings, two forms of progression are produced. For the link-based progression case, neighboring intersections all possess very good progression bandwidths, but vehicles going through all three intersections would inevitably make one stop, such as Trajectory $\alpha$. As for the arterial-based progression, the link progression bandwidths are similar to what the link-based progression achieves, but most arterial traffic would not stop as shown in Trajectory $\beta$, which implies that only using link-level metrics may not be able to capture the complete characteristics of arterial traffic operations.

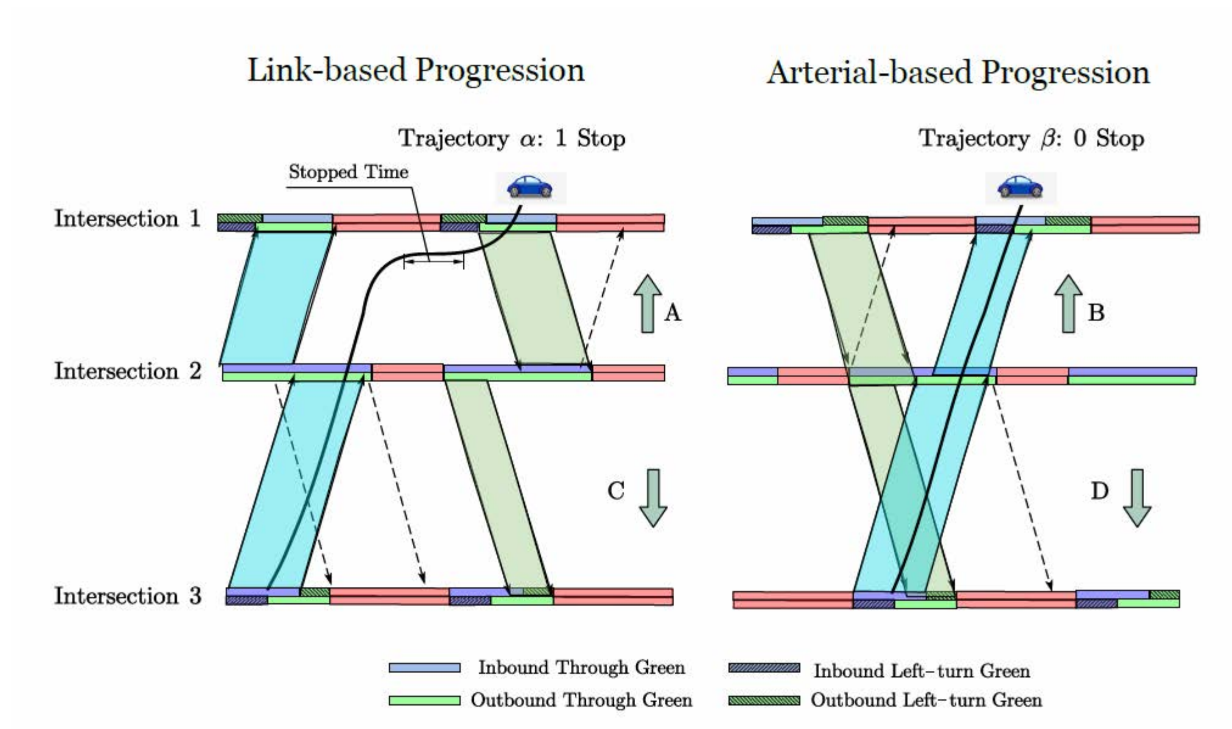



**Figure 2.2: Comparison between Link-based and Arterial-based Progression**

Compared to link-level performance metrics, arterial-level metrics is more difficult to obtain due mostly to data availability. A vast amount of data collection along different routes of interest is required before a representative sampling can be obtained. Therefore, many studies and innovations have been conducted on the basis of link-level metrics [22]. In contrast, arterial-level metrics related research is scarce [23, 24, 25]. In recent years, more and more emerging technologies, such as connected vehicle, have been developed and implemented into reality, which hold promise for ubiquitously collecting high-resolution travel-run trajectories throughout the roadway network. It is expected that such data sources would drastically promote signal timing practices, while also demonstrating that the related research is much needed. This research mainly focuses on exploring potential arterial-level performance metrics by leveraging trajectory data in order to enhance the current signal timing performance measurements.

## 2.2 Current Performance Measurement Techniques for Arterial Operations

### 2.2.1 Performance Measurements Based on Controller Event Data

Nowadays, most traffic signal controllers have the capabilities of archiving high resolution controller events, such as phases turning green, phases turning red, and detector calls received or lost with timestamps that have a resolution of up to 0.1 seconds. Therefore, data logged by controllers can be used to reproduce a control state in a combination of signal control operations (which/when/how long phase(s) turn on green) and traffic flow operations (when/how many vehicles pass over a detector), at any given moment during the time of signal operation. Some studies [26, 27, 28] have generated signal timing performance measures by leveraging these data sources, and upon which, several techniques have been developed such as Automated Traffic Signal Performance Measures (ATSPMs) [29] and SMART-SIGNAL [30].

ATSPMs is one of the most noted performance measurement systems for signal timing, and is based on high-resolution data-logging capability added to existing traffic signal infrastructure. It provides several data analysis techniques for evaluating communication, detection, timing, and coordination of traffic signal systems. Professionals can use the information provided by ATSPMs to identify and correct deficiencies in signal operations.

The U.S. Department of Transportation (USDOT) and the Federal Highway Administration (FHWA) are currently promoting ATSPMs as a means of improving traditional signal re-timing approaches by providing continuous performance monitoring capabilities [31]. According to the information published by the FHWA, approximately 26 transportation agencies at both state and local levels are involved in implementing ATSPMs. Recently, an open-source software package was developed [ 32 ], which published a framework for continued innovation in data analysis techniques regarding ATSPMs.

The ATSPMs system contains several measures, including 1) Purdue Phase Termination, 2) Split Monitor, 3) Pedestrian Delay, 4) Preemption Details, 5) Purdue

Coordination Diagram (PCD), 6) Approach Volume, 7) Approach Delay, 8) Arrivals on Red, 9) Approach Speed, and 10) Purdue Split Failure [33]. Data visualization is also enabled upon several diagram themes [7]. These automatically collected and generated measures depict the status of signal operation in real-time and help practitioners monitor whether an agency's objectives have been achieved.

Among the diagrams of ATSPMs, there is one specifically addressing arterial signal timing, which is called "Purdue Coordination Diagram (PCD)." PCD is a useful tool for offering a quick visualization of how well a signal system is coordinated. The effectiveness of signal coordination on certain movements is demonstrated through quantified and graphical indicators. As shown in Figure 2.3, detection events are shown as black dots, and each dot indicates a moment when a vehicle triggers the road detector, implying a vehicular arrival at the time. Signal phase status is shown as red/green dotted lines, and each dot represents the moment when the signal phase turns red or green, implying the duration times of the green and red intervals. Through this combination, both visual and quantitative figures of the proportion of vehicle arrivals during red and green time intervals are provided.

The PCD chart plots the time of day on the horizontal axis and the time in cycle along the vertical axis. The vertical strips represent single cycles divided by BOG (begin of green, shown as green dots on the diagram) and EOG (end of green, shown as red dots on the diagram). The region between the line of BOG and EOG dots delineates the time window when vehicles can move through the intersection without stopping. The more vehicles showing up within this time window, i.e., the higher portion of black dots located in the region, the better quality of coordination. The EOG line also portrays the fluctuation of cycle times as the cycle length would be varying during non-coordinated time periods and coordinated time periods whereas transitions happen.

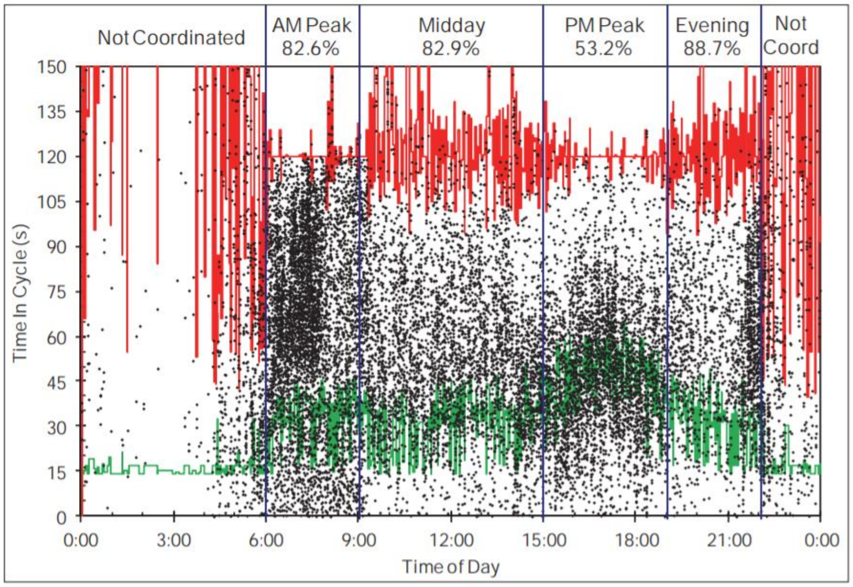



**Figure 2.3: Purdue Coordination Diagram (Source: Signal Timing Manual [15])**

A practitioner can intuitively assess the level of performance through a comparison between the dot densities above and below the green line. In addition, some numerical measures are provided based on the distribution of the dots. For example, the percentage of vehicles arriving on green for each coordination plan is shown above the PCD chart in Figure 2.3 – "AM Peak 82.6%" indicates 82.6% of the vehicles traversed the intersection without stopping during the AM-peak coordination plan.

Furthermore, the percentage of arrivals on green divided by the green-to-cycle ratio yields a new metric called the "Platoon Ratio," which accounts for the fact that the longer green time of a cycle is assigned to a phase, the more likely vehicles on that phase arrive on green. The Platoon Ratio, therefore, rewards signal coordination that is performed with shorter greens on coordinated phases, and penalizes signal coordination with unnecessarily long green times allocated to the coordinated phases regardless of the fact that those phases can certainly achieve a high percentage of vehicles arriving on green.

A Platoon Ratio of 1.0 is a threshold which indicates that the effectiveness of signal coordination is insignificant. Numbers greater than one represent that traffic signals are well coordinated, and numbers lower than one indicate that there could be detrimental signal timing settings that result in inefficient arterial operations.

With the capabilities of automated data collection, an ATSPMs system allows 24-7 surveillance, aiding both the supervisory and perceptive capabilities of the agencies, which are being tested or deployed in many states across the U.S. [34, 35, 36]. However, there are still some issues with ASTPMs that need to be addressed.

First, the implementation of ASTPMs requires a certain infrastructural configuration [37], which makes the system less appealing to those agencies with limited funding resources. The ASTPMs-enabled traffic signal controllers must be equipped with high-resolution data loggers. Most controller manufacturers such as Econolite, Peek, Siemens, Intelight, and Cubic-Trafficware have integrated controller data loggers with their up-to-date products; however, agencies may need to spend additional funds on replacing or upgrading their existing controllers. ASTPMs systems also rely on specific detection setups. For example, to produce the PCD diagrams, advance detectors (or called setback detectors) need to be deployed and well-maintained at the intersections, whereas current practices on detector configuration vary considerably from one agency to another [38]. Hence many agencies may need to convert their detection configurations. In addition, operating and maintaining the web service and database of ATSPMs require additional technical personnel.

Another limitation of ATSPMs lies in queuing. Generating PCDs requires data collected by setback detectors. But, as illustrated in Figure 2.4, when a queue spills and reaches the position of the setback detector, a false platoon may be created on the PCD chart [39], and the resulting percent arrivals on green and platoon ratio can be incorrect.

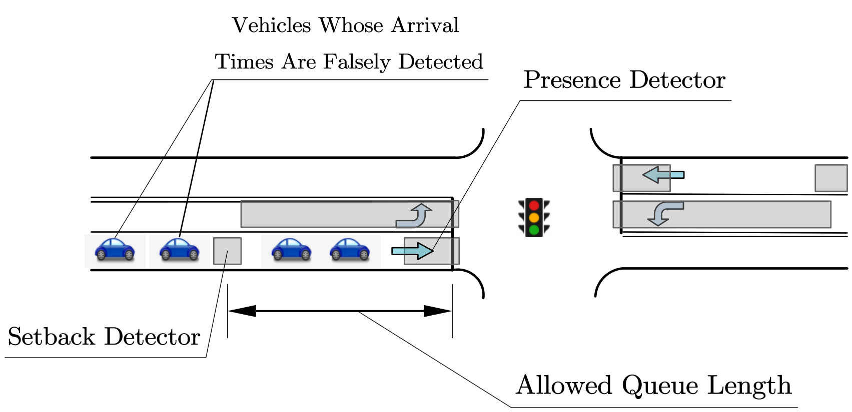



**Figure 2.4: Queuing Issue of ATSPMs**

More importantly, the ASTPMs-type performance evaluations are mostly based on link-level metrics that focus on independent traffic movements, not arterial-oriented performance measurements. Consequently, some characteristics which indicate the quality of arterial signal timing (e.g., travel speed and stops driving along an arterial) cannot be well captured by ATSPMs [40].

The use of ATSPMs is complex and obscure in daily practice sometimes. As for the PCD charts, one of the comments from the current users of ATSPMs was noted – "PCD charts show too many dots" [41]. While the PCD is generally considered an effective tool for performance measurements, practitioners often encounter challenges when attempting to quantify the signal timing performances based on the metrics provided by PCD. In order to establish a defensible standard of "good quality of timing for arterial operations", researchers have been trying to aggregate the data provided by ATSPMs into letter-grade assessments [42]. The overall grades of the quality of signal operation are categorized as "A," "B," "C," "D," and "F" in a format similar to the Level of Service (LOS) framework documented in the Highway Capacity Manual [43]. Practitioners can monitor and manage signal operations based on the grades, e.g., to recognize re-timing needs through grade ranking. In terms of arterial operations, one additional consideration, volume-to-capacity ratio, was integrated with Platoon Ratio, which is an enhancement to ATSPMs. The thresholds of grades A through F may change according to the congestion level at an intersection. For instance, when the volume-to-capacity ratio nears zero, an "A" grade is granted for Platoon Ratios greater than 1.3; however, this threshold reduces to 1.15 if the volume-to-capacity ratio increases to 0.9, as illustrated in Figure 2.5. Although the performance ranking methodology is established with the abovementioned improvement, some issues should be noted. In Figure 2.5, the scattered data points were collected on multiple approaches along an arterial. The overall grade for the arterial can be determined according to a weighted average grade across individual approaches, with the approach volume serving as the weight. Hence, some cases would not be well assessed using such a methodology. For example, if there are four intersections along an arterial, one timing achieves grades as "A-C-A-C" and the other achieves "B-B-B-B", they both are rated as "B" overall, but the arterial operations may be much different.

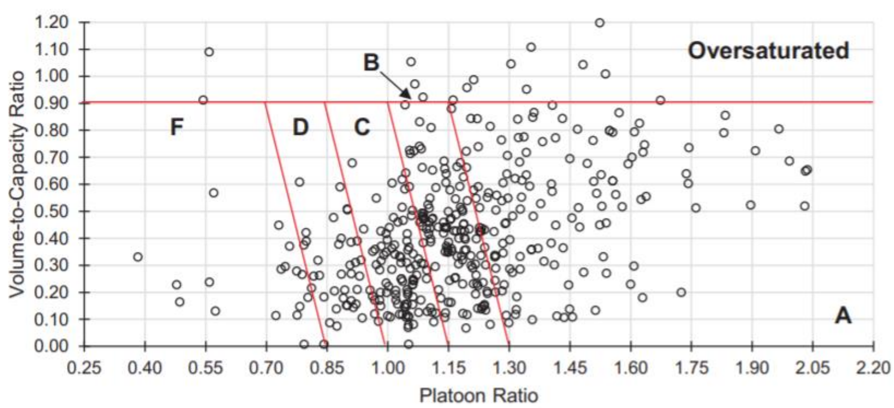



**Figure 2.5: Grading Methodology of Progression Quality Used by ATSPMs [42]**

Studies related to ATSPMs are still ongoing [44], and more information about how ATSPMs can consolidate signal timing management will be presented in the deliverables of the NCHRP Project 3-122: Performance-based Signal Management of Traffic Signals.

SMART-SIGNAL is another technique for gauging signal timing performance based on high-resolution controller event data. Different from ATSPMs, SMART-SIGNAL evaluates arterial signal timing performance based on travel time, and the travel time is estimated through virtual probe vehicle trajectories generated by the system [45, 46], as shown in Figure 2.6. In other words, SMART-SIGNAL uses controller event data to conduct signal timing performance measurements, but its performance measurement method depends on trajectories.

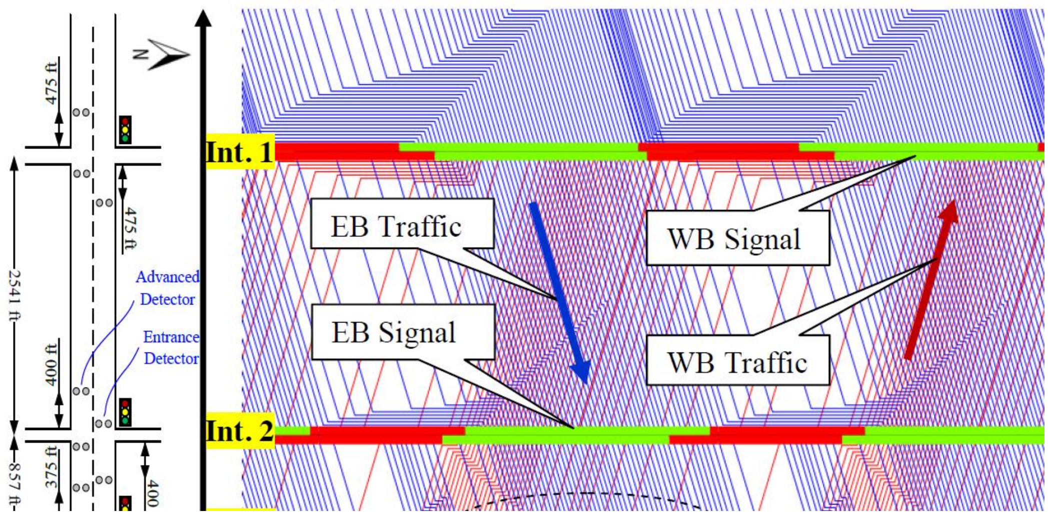



**Figure 2.6: Virtual Trajectories Generated by SMART-SIGNAL [45]**

### 2.2.2 Performance Measurements Based on Travel-run Trajectories

Besides high-resolution controller event data, travel-run data like GPS trajectories are generating more and more interest recently among researchers and engineers regarding their usage in signal timing [47, 48, 49]. High-resolution GPS trajectories can be applied to signal timing performance measurements with great promise thanks to high level of detail of vehicular motions, which indicate where and when the vehicles proceeded or stopped.

Some attempts have been made to develop signal timing performance measures using trajectory data. The Orange County Transportation Authority (OCTA), in collaboration with the California Department of Transportation (Caltrans) and the local agencies within the county, initiated the Signal Master Plan for the countywide synchronization endeavor in 2009. The Signal Master Plan has defined a new parameter to gauge the performance of signalized arterials, which is called the Corridor Synchronization Performance Index (CSPI) [50, 51].

CSPI is a score-based methodology which evaluates the performance of signal timing for arterial operations based on 1) average speed, with the highest possible score of 36; 2) the ratio of the number of encountered green signal indications versus red indications during arterial trips, with the highest possible score of 40; and 3) the average number of stops per mile, with the highest possible score of 33, as exhibited in Figure 2.7. By combining the three scores, the overall CSPI can be computed, ranging from 33 to 109.

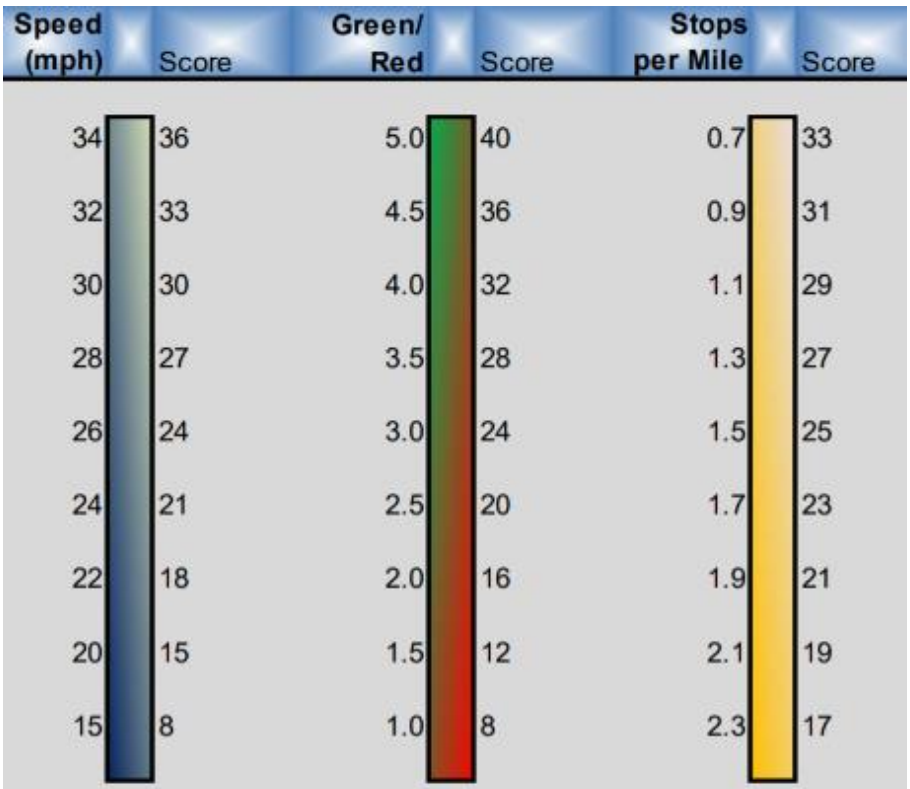



**Figure 2.7: CSPI Scoring Methodology based on Three Measures [51]**

In accordance with the CSPI scores, arterials are categorized into five tiers, as shown in Figure 2.8. Tier 1 refers to very good signal coordination qualities with a CSPI score equal to or greater than 80. Tier 5 corresponds to CSPI scores less than 50, indicating that the corridor would greatly benefit from signal timing improvements and suggest the need for a signal re-timing project.

| CSPI Score | Signal Synchronization Description | Level |
|---|---|---|
| >=80 | Very good progression – traveling through signalized intersections with minimal stops and favorable travel speeds. | Tier 1 |
| 70-80 | Good progression – traveling through signalized intersections with few stops and good travel speeds. | Tier 2 |
| 60-70 | Fair progression – traveling through signalized intersections with moderate stops and fair travel speeds. | Tier 3 |
| 50-60 | Limited progression* – traveling through signalized intersections with moderately high stops and slower travel speeds. | Tier 4 |
| < 50 | Very limited progression* – traveling through signalized intersections with frequent stops and slow travel speeds. | Tier 5 |

**Figure 2.8: CSPI Corridor Synchronization Performance Criteria [51]**

The development of CSPI was initiated by expert practitioners who have a good understanding of the needs of local communities. The methodology of CSPI is concise and clear; not only can be easily adopted by signal timing practitioners, but it can also help those who have limited traffic engineering knowledge understand the quality of signal operations in an intuitive manner. In addition, CSPI does not require additional investments apart from the GPS devices and the resources for conducting probe vehicle investigations.

It should be noted that there are some limitations to the CSPI-based approach when compared with other trajectory-based performance measures [23, 49]. The prescribed parameters may affect the accuracy of performance measurements. For instance, the highest Speed Score of CSPI is attained when the average speed is greater than 34 mph because most arterials in Orange County have speed limits of 40 mph. As a result, CSPI may yield inaccurate results when evaluating signal timing performances when the speed limit is under 40 mph. Practitioners should beware of using CSPI under certain circumstances. The scores of Green per Red are sensitive to the number of evaluated signals. When only few signals are assessed, just one stop may dramatically change the result. In addition, the quality of signal timing may not be fairly reflected by the score of Stops per Miles if the signals are spaced closely.

Other limitations of CSPI include the lack of consideration of arterial congestion level and travelers' perceived quality of signal timing. Accordingly, the methodology cannot adequately assess signal timing quality if a poor performance is primarily due to oversaturated traffic demands, but not the timing design itself. CSPI could not capture a full spectrum of travelers' perceived quality of signal timing, such as the duration and location of stops. For example, making consecutive stops usually would create a worse driving experience, even though the number of stops are the same.

Trajectory-based evaluations can be performed using some software tools [52, 53]. Based on instantaneous speed data pulled from GPS points, these software tools not only can calculate typical metrics values, such as average speed, number of stops, and stop times, but also can estimate fuel consumption and emissions (e.g., CO, NOx, HC, and Co2) [54].

## 2.3 Chapter Summary

This chapter provided a comprehensive review of the state of research and practice related to signal timing performance measurements. Most existing performance measurement systems and methodologies are primarily link based, which may not fully align with the current practice where trajectory-based evaluation still plays a major role. A study is thus needed to develop a performance measurement methodology based on arterial-level metrics using travel-run trajectory data. In addition, the emerging signal performance measurement techniques were reviewed, including ATSPMs which are based on high-resolution controller event data and CSPI that is based on GPS trajectory data.

According to the review findings, the proposed performance measurement in this report seeks to address the following aspects:

1) A performance evaluation framework that is in an HCM-like format, which categories the quality of signal timing into five levels, namely A, B, C, D, and F. This can help practitioners to capture the quality of signal timing immediately and intuitively;

2) Define quality of signal timing based on arterial-level metrics extracted from vehicle trajectory data. The trajectory data can be obtained through a few accessible data sources such as probe vehicle investigations, federal or third-party databases, and connected-vehicle applications. Hence, the proposed performance measurement methodology is applicable regardless of signal control mode, detection configuration, and controller types.

3) Compared to CSPI adopted in Orange County, CA, the proposed methodology adopts a similar framework but possesses two significant refinements. The non-signal-timing factors (e.g., arterial congestion level) are considered so that the performance measurement results can accurately reflect the quality of signal timing under various scenarios like unsaturated or congested traffic operations. Travelers' perceptions of traffic signal timing quality are also considered in the evaluation methodology.

# 3. METHODLOGY DEVELOPMENT

This chapter presents the details of the proposed performance measurement methodology. Two performance metrics are firstly defined, which can effectively scale the quality of signal timing as well as the level of users' satisfaction. The calculations of the two metrics are based on vehicle speed and stop information extracted from travel-run GPS trajectories. The two metrics have respective emphases: the speed characteristics mainly show the effectiveness of platoon progression; and the stop characteristics imply users' perceived quality of signal timing. Stop characteristics are also related to fuel consumption and vehicular emissions, which correlate with environmental impacts. The performance measurement methodology is independent of signal control modes or facilities, which means the methodology is applicable under most conditions regardless of different controller and detection facilities among jurisdictions.

## 3.1 Performance Measure Based on Speed Characteristics

Average speed, which refers to the average arterial operating speed or the average travel speed, has been widely used as a performance measure in practice [55]. Average travel speed of through-movement vehicles has been adopted by the latest Highway Capacity Manual [43] to generate automobile Level of Service (LOS) for urban street facilities, which are defined as having two or more segments including signals and roadway links between signals. Average speed conclusively indicates the degree of mobility achieved by arterial operation regarding delay incurred due to signal control and other influential factors.

Average speed correlates with the quality of arterial signal timing as the delay caused by signal operations could be a significant part of the travel time along an arterial. Effective arterial signal timing can significantly reduce vehicle stops at intersections, resulting in reduced travel time.

As mentioned previously, the automobile LOS methodology in the HCM reflects vehicular mobility along an arterial; however, this methodology cannot be directly adopted for signal timing performance measurements because many non-signal timing related factors can affect signal timing performance results. These factors can influence arterial travel speed but are not related to signal timing. The three major non-signal-timing factors are listed below:

### 1) Level of Congestion along Arterials

As the level of congestion increases, vehicles no longer can move at or near the free-flow speed in the optimal-progression context. Longer queues and slower queue dispersion are often observed. The level of arterial congestion is usually gauged by the arterial volume-to-capacity ratio.

### 2) Arrival Flow Profile

Arterial signal timing creates a “window” of green as traffic moves along an arterial. This has beneficial effects when the “window” coincides with the time interval when most vehicles arrive at the intersections. Traffic arrivals consist of vehicles from upstream arterial through movements and vehicles left-turning or right-turning onto the arterial from the upstream cross-streets. Traffic arrivals of arterial-through origins and cross-street origins are distributed at different time intervals within a cycle. Typically, the progressed “window” of green is designed to accommodate the arterial through traffic, which constitutes the bulk of total arrival, but the vehicles turning onto the arterial from the upstream cross streets very likely arrive on red. Therefore, if the traffic from the upstream cross streets accounts for a considerable proportion of the traffic flow, the beneficial effects of coordinating signals will be limited and the average speed will decrease. This factor can be indicated by the proportion of traffic volume of side-street origins to the total traffic volume along the arterial.

### 3) Signal Density

Traffic signals always have some impact on traffic flow even if signals are optimally coordinated. Signal density, defined by the number of signals per mile, is one of the major causes of stops and delays. In general, the higher the signal density, the more impact it will impose on traffic flow.

Investigations were made during this research to characterize the effects of the aforementioned non-signal-timing factors on average speed. A hardware-in-the-loop simulation facility was utilized to generate a set of simulation scenarios. The simulation setup is illustrated in Figure 3.1.

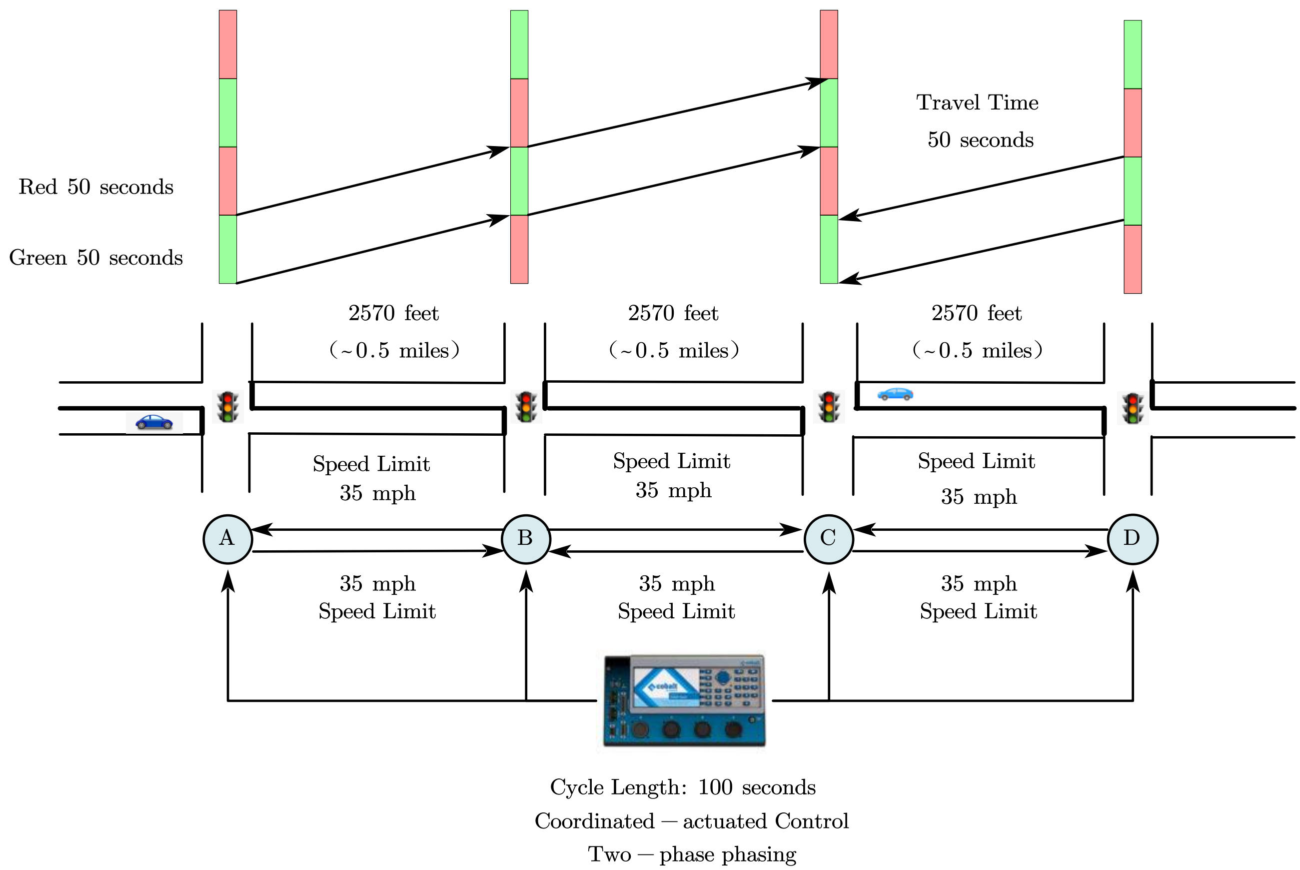



**Figure 3.1: Hardware-in-the-loop Simulation Setup**

A generic arterial network was developed with four equally spaced intersections in the VISSIM microscopic simulation package. The four intersections were controlled by four Econolite Cobalt ATC controllers connected with the VISSIM network. The hardware-in-the-loop system named PASS (exhibited in Figure 3.2) was used in order to authentically test arterial signal timings as it can perform realistic signal actuation and signal coordination functions.

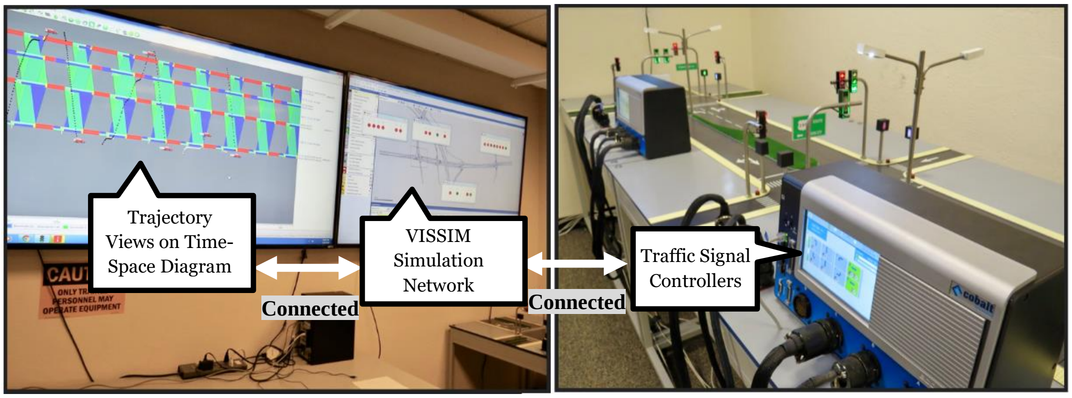



**Figure 3.2: PASS: A Hardware-in-the-loop Simulation System**

The phasing and timing scheme used in the simulation was simplified such that the cycle length of 100 seconds was divided into two phases, an arterial phase of 50 seconds and a side-street phase of 50 seconds. With certain offset values, it is possible to achieve the best two-way progression (e.g., offsets: 50-0-50-0) as displayed in Figure 3.1, or the worst two-way progression (e.g., offsets: 0-0-0-0). Other levels of progression quality can be achieved by using a different set of offsets.

A number of scenarios were analyzed regarding arterial congestion levels, traffic volume of side-street origins, and signal density. Six levels of progression quality were defined according to the six arrival types in the HCM [42], AT-1 to AT-6, with AT-1 being the worst and AT-6 being the best. The ideal arterial operating speed, i.e., the free-flow speed, was set at 40 mph, estimated based on the posted speed limit plus five mph in this research [56]. The following Sections 3.1.1 – 3.1.3 present the details of the simulation study.

### 3.1.1 Effect of Arterial Congestion Level

As noted previously, the level of arterial congestion can be measured by the arterial volume-to-capacity ratio (V/C ratio.) The V/C ratio is typically determined by traffic volume, saturation flow rate, and signal timing. The arterial congestion level becomes more serious as the V/C ratio increases, and vice versa. The computation of the V/C ratio will be further discussed in Section 3.4.

During the simulation study, a total of 16 trials were conducted with various scenarios of traffic congestion levels at four intersections, shown as intersection A, B, C, and D in Figure 3.1. The 16 trials were developed to analyze how traffic congestion would affect traffic speed along an arteria. Traffic volume inputs and signal timing were modified successively at the four intersections in order to simulate different levels of traffic congestion that occur at different intersections. Table 3.1 summarizes the information of the 16 trials.

The investigation began with an ideal operating condition of just the slightest level of arterial congestion occurred equally at all of the four intersections, i.e., the arterial V/C ratio was no greater than 0.3 where free-flow traffic was mostly observed (trial number:1.) Then one intersection was selected, and its level of arterial congestion was changed from the lightest to the heaviest through four increments of arterial V/C ratios. After that, holding the V/C ratios constant at the heaviest level for the intersections where volume inputs or signal timings had been modified, the arterial congestion levels of the remaining three intersections were changed in the same manner one after another until the most serious arterial congestion level had reached at all four of the intersections after the 16th modification (trial number: 16).

It should be noted that it was difficult to use the HCM arrival types as the index of progression quality in this investigation as the arrival types are designated for individual intersections, implying there could be 64 combinations of arrival types. Under certain congestion levels, some of the combinations of ATs were impossible to realize, e.g., AT-6 could almost never happen at four intersections simultaneously if the arterial congestion level was high. Therefore, an alternative index was adopted during this investigation, which was the sum of the three one-way progression bandwidths between every two adjacent signals. Accordingly, six levels of quality of progression were defined as:

Type 1 - the sum of bandwidths < 25 seconds;

Type 2 - 25 seconds < the sum of bandwidths ≤ 50 seconds;

Type 3 - 50 seconds < the sum of bandwidths ≤ 75 seconds;

Type 4 - 75 seconds < the sum of bandwidths ≤ 100 seconds;

Type 5 - 100 seconds < the sum of bandwidths ≤ 125 seconds;

Type 6 - the sum of bandwidths ≥ 125 seconds.

**Table 3.1: Trials to Simulate Various Levels of Arterial Congestion along an Arterial**

| Trial Number \ Arterial V/C Ratio | At Intersection A | At Intersection B | At Intersection C | At Intersection D |
|---|---|---|---|---|
| **Trial 1** | 0.2 | 0.2 | 0.2 | 0.2 |
| **Trial 2** | 0.5 | 0.2 | 0.2 | 0.2 |
| **Trial 3** | 0.65 | 0.2 | 0.2 | 0.2 |
| **Trial 4** | 0.85 | 0.2 | 0.2 | 0.2 |
| **Trial 5** | 0.85 | 0.2 | 0.2 | 0.2 |
| **Trial 6** | 0.85 | 0.5 | 0.2 | 0.2 |
| **Trial 7** | 0.85 | 0.65 | 0.2 | 0.2 |
| **Trial 8** | 0.85 | 0.85 | 0.2 | 0.2 |
| **Trial 9** | 0.85 | 0.85 | 0.2 | 0.2 |
| **Trial 10** | 0.85 | 0.85 | 0.5 | 0.2 |
| **Trial 11** | 0.85 | 0.85 | 0.65 | 0.2 |
| **Trial 12** | 0.85 | 0.85 | 0.85 | 0.2 |
| **Trial 13** | 0.85 | 0.85 | 0.85 | 0.2 |
| **Trial 14** | 0.85 | 0.85 | 0.85 | 0.5 |
| **Trial 15** | 0.85 | 0.85 | 0.85 | 0.65 |
| **Trial 16** | 0.85 | 0.85 | 0.85 | 0.85 |

**Findings:**

As shown in Figure 3.3, the following results were observed:

1) For the six levels of progression quality, when the arterial V/C ratio ranged between 0 and 0.55, increasing arterial V/C ratio only slightly changed average speed, whereas average speed was affected to a notable extent if the arterial V/C ratio was greater than 0.55. The average speed significantly decreased as the arterial V/C ratio increased to 0.85 or greater.

2) The influential effect of arterial congestion receded along with the increase of modification times and eventually converged around 50% of the free-flow speed. The convergence point of "50% of free-flow speed" might account for the

circumstance that the travel time between the neighboring intersections at the free-flow speed was 50 seconds, and the longest stopped time at the intersection was 50 seconds as well. When the intersections along the arterial were congested, most vehicles spent around 50% of the travel time on stops and slowdowns regardless of the quality of signal timing. In practice, the spacing between coordinated signals typically ranges from a quarter-mile to a half-mile (the travel time often varies from 30 seconds to 60 seconds) [57]. And the cycle length generally ranges from 60 seconds to 120 seconds (the longest stop time of arterial through traffic can be regarded as a half time of the cycle, which ranges from 30 seconds to 60 seconds, in accordance with the travel time). Therefore, this "50% of free-flow speed" should be representative of most convergence points observed in reality.

3) The sequential order of the selected intersections did not substantially affect the results, e.g., the resulting differences of average speed were negligible between "modifying the intersection A-B-C-D" and "modifying the intersection D-C-B-A" (the positions of intersection are exhibited in Figure 3.1.)

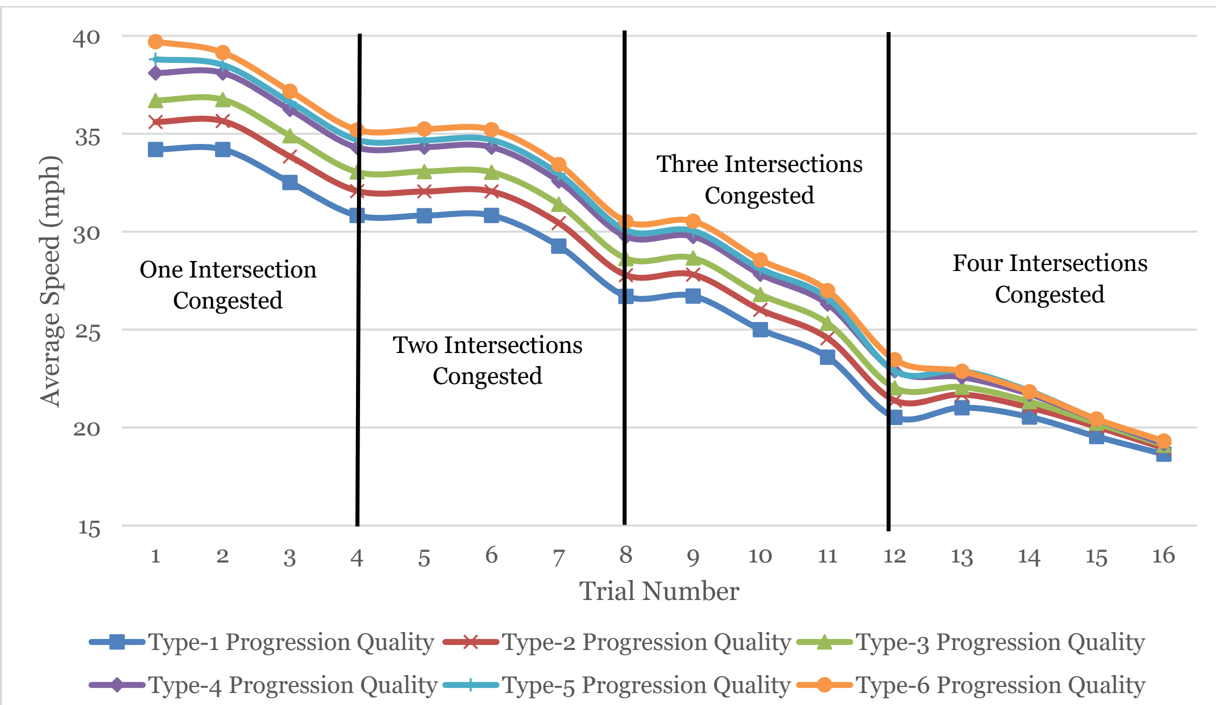



**Figure 3.3: Change of Average Speed under Different Arterial Congestion Scenarios**

This investigation sought to explore the effects of arterial congestion levels in the context of unsaturated operations. Under oversaturation conditions, queue spilling over can happen recurrently during which a measurable decrease of average speed can be observed, e.g., the observed average speed can be slower than 50% of the free-flow speed.

### 3.1.2 Effect of Traffic Volume of Side-street Origins

When timing traffic signals, practitioners need to monitor traffic arrival flow profiles to determine the offset and phase sequence. Arterial through movements are the primary consideration for arterial signal coordination; however, traffic arrivals in other time intervals (e.g., the traffic of upstream side-street origins) may be stopped at the downstream intersection. Therefore, if the proportion of traffic of side-street origins to the overall traffic flow increases, the average speed may be reduced.

Experimental investigations were conducted in this research aiming to reveal the effect of proportion of traffic volume of side-street origins to the overall traffic arrivals. Among the five experiments, the traffic volume of side-street origins made up five different proportions (0%, 12.5%, 25%, 37.5%, and 50%) of the total arrivals at the intersection, while the number of arrivals remained constant (arterial V/C Ratio = 0.4). The offset was adjusted in accordance with each change of the proportion to achieve different qualities of progression, i.e., to achieve Arrival Types 1-6 if possible. The simulation studies only considered the operation in one direction along the arterial and between two adjacent signals.

**Findings:**

As shown in Table 3.2 and Figure 3.4, the major findings can be summarized as follows:

1) The amount of traffic volume of side-street origins is a factor that influences the average speed, and would even cause some certain travel types at an intersection to be unattainable; if the arrival flow profile becomes uniform, some qualities of progression cannot be achieved no matter how well the signal timing could have been developed.

2) The impact of traffic volume of side-street origins on average speed could be related to many factors. If the offset design was inefficient (poor progression, AT-1, 2, or 3), average speed increased as traffic volume of side-street origins increased. On the other hand, if the offset design was favorable (good progression with AT-4, 5 or 6), the average speed decreased as traffic volume of side-street origins increased.

**Table 3.2: Resulting Average Speed under Various Proportions of Traffic Volume of Side-street Origins and Progression Qualities**

| Average Speed (mph) | AT-1 Progression Quality | AT-2 Progression Quality | AT-3 Progression Quality | AT-4 Progression Quality | AT-5 Progression Quality | AT-6 Progression Quality |
|---|---|---|---|---|---|---|
| 0% Volume of Side-street Origins | 21.3 | 23.8 | 27.7 | 31.8 | 33.6 | 37.2 |
| 12.50% Volume of Side-street Origins | 22.8 | 25.1 | 27.5 | 30.6 | 32.1 | 35.0 |
| 25% Volume of Side-street Origins | 25.5 | 26.3 | 27.6 | 29.7 | 31.4 | N/A |
| 37.50% Volume of Side-street Origins | N/A | 27.1 | 27.9 | 28.2 | 29.1 | N/A |
| 50% Volume of Side-street Origins | N/A | N/A | 26.7 | 27.1 | N/A | N/A |

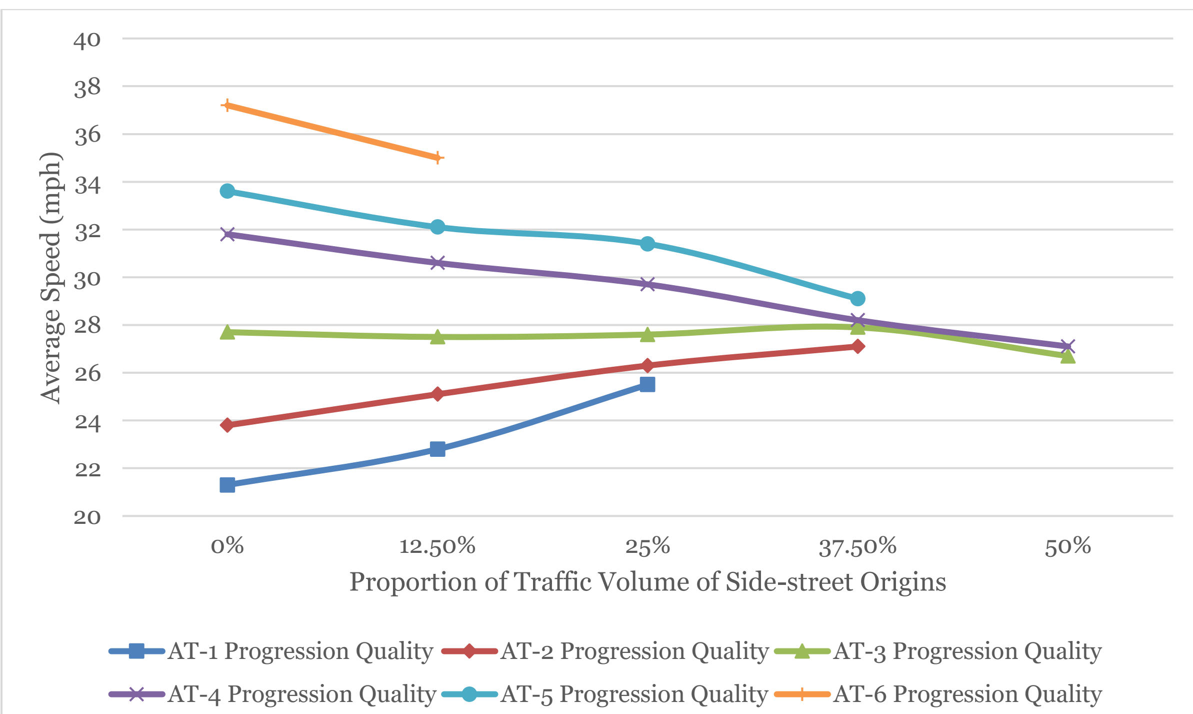



**Figure 3.4: Change of Average Speed under Different Arrival Flow Profiles**

### 3.1.3 Effect of Signal Density

A high density of signals along an arterial can generally lead to reduced average speed because the chance of stopping is directly proportional to signal density. Moreover, if signal density is low, the total time used for vehicles passing through intersection areas would just count for a minor part of the overall travel time, which means that the average speed is mostly determined by mid-block operations rather than the quality of signal timing. Hence, understanding the effect of signal density on average speed is very important.

An investigation was conducted during this research based on four equally spaced intersections as previously shown in Figure 3.1. By adjusting the separation distances, five scenarios with different signal densities were created, holding both the arterial congestion level (i.e., V/C Ratio = 0.4) and the traffic arrival profile (i.e., traffic of the side-street origins accounted for 10% of the total arrivals) constant.  The resulting average speed changes were gauged according to the operations in one direction along the arterial. In Figure 3.5, for example, the legend "AT-1 progression quality" represents that AT-1 was achieved at the three evaluated intersections.

**<u>Findings</u>**

From Figure 3.5, the following major findings were reached:

1) The number of signals per mile could significantly influence average speed if the offset resulted in poor progression, e.g., AT-1, 2, or 3.

2) The number of signals per mile could slightly change average speed if the offset design resulted in good progression, e.g., AT- 4, 5, or 6.

3) The impact of signal timing on average speed became less obvious if signal density was low. The *MUTCD* [58] documents that traffic signals within 0.5 miles (i.e., a signal density of two signals per mile) of one another should be coordinated, but in practice, there was rarely a coordinated signal system with a signal density of less two signals per mile. In this study, the signal density of 1.33 signals per mile was analyzed, and the results showed that the quality of signal timing can still affect average speed even under such a low signal density.

4) The highest signal density tested in this study was four signals per mile, representing the densest cases regarding general urban signalized arterials. Under such a signal density, the quality of signal timing could significantly impact the average speed. In addition, some arterials may have a close signal spacing, e.g., less

than 1,000 feet [57], where the signals are difficult to coordinate, so an adjustment is needed when evaluating the quality of signal timing for arterials with a high signal density.

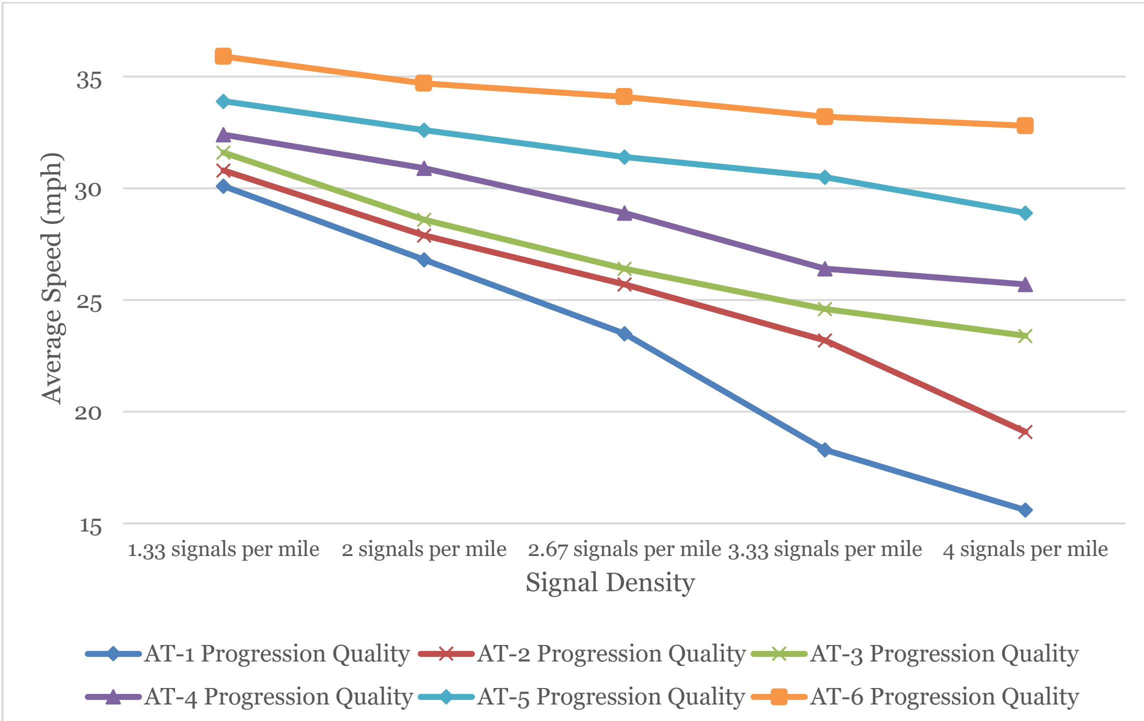



**Figure 3.5: Change of Average Speed under Different Signal Densities**

### 3.1.4 Attainability of Ideal Progression (AIP)

A new performance measure named the attainability of ideal progression (AIP) was defined in this research, and can be denoted by Equation 1:

$$AIP = \frac{Averge\ Speed}{Ideal\ Progressive\ Speed} \times 100\% \qquad (1)$$

where

*AIP* (%) – the attainability of ideal progression;

*Ideal Progressive Speed* (mph) – the speed achieved under ideal progression.

The ideal progressive speed can potentially equal to the free-flow speed if traffic operating conditions are optimal. It is mainly affected by arterial congestion level, cross-street traffic volume, and signal density.

## 3.2 Performance Measure for Stop Characteristics

Empirical evidence has revealed that drivers are more aware of experiencing stops at intersections [59] than of travel time or average speed. Many studies have shown that stops at intersections could be one of the most important contributing factors to driver aggression and frustration, potentially causing red-light running or aggressive driving behavior [60, 61, 62,63]. Stops at intersections can also correlate with environmental impacts such as fuel consumption and emissions [64]. Consequently, stop characteristics are of great importance for the evaluation of arterial signal timing performance because of the comfort, convenience, cost, and safety implications.

### 3.2.1 Effect of Stop Characteristics on Perceived Quality of Signal Timing

Studies have been conducted over the past 20 years, aiming to evaluate the level of service at signalized intersections based on drivers' perceptions [65, 66, 67]. However, research devoted to arterial-level signal timing performance measures has been scarce. In practice, the metric of "number of stops per mile" is empirically used to scale travelers' perceptions of signal operations; however, there are many other characteristics of "stops" which have been neglected. Solely considering the number of stops per mile may result in an incorrect estimate of the perceived quality of arterial signal timing, as many drivers may prefer two short stops of 15 seconds to one long stop of 60 seconds whereas the evaluation based on only the number of stops would indicate the opposite.

In order to further investigate the effect of stop characteristics on the perceived quality of arterial signal timing, questionnaire-based and interview-based traveler surveys were conducted in Reno, Nevada and Las Vegas, Nevada. These surveys were designed to empirically characterize human perceptions of signal operations for engineering research purposes. Most of the survey questions aimed to validate the hypotheses envisioned by expert traffic signal timing professionals. A total of 67 valid responses were obtained. Some socioeconomic attributes of the participants are presented in Table 3.3. The survey questions are presented in the appendix.

**Table 3.3: Participants' Socioeconomic Attributes**

| | | | |
|---|---|---|---|
| **Gender** | Male: 62.7% | Female: 35.8% | Prefer not to say: 1.5% |
| **Age** | Below 25: 12% | Between 25 and 60: 82% | Over 60: 6.0% |
| **Usage of Signalized Arterials** | Frequent: 74.6% | Not frequent: 18% | Unsure: 7.4% |
| **Living Area** | Urban: 62.7% | Suburban:10.6% | Rural:26.7% |

Although the sample size of the survey was limited due to time and budget constraints in this project, some preliminary findings obtained through the survey may still shed light on how to best address the stop characteristics:

1) 94% of the respondents (63 out of 67) agreed that the stop time could affect their impression of the quality of signal timing.
2) 66% of the respondents (44 out of 67) were more aware of the number of intersections that they can traverse without being stopped than the number of stops per mile.
3) The stop time can result in different interpretations of a stop. A sizeable portion of the respondents (27 out of 67) considered stop times less than 10 seconds as minor stops, while stop times more than 20 seconds as full stops. Typically, a 20-second stop was counted as one stop [21].
4) The trade-off between number of stops and stop time might vary at different intersections. A majority of the respondents (58 out of 67) answered that a stop at a major intersection would be more tolerable than at a minor intersection.
5) Over half of the respondents (46 out of 67) would prefer making two stops at different intersections over experiencing a long wait at one intersection, even if the stop times are similar for both scenarios. A similar conclusion was drawn by a previous study [68].
6) 97% of respondents (65 out of 67) agreed that making another stop shortly after a previous one was annoying and dangerous, and about half of the respondents (31

out of 65) agreed that the time interval between two consecutive stops should be at least 20 seconds.

These findings have been incorporated into the development of a grade-based evaluation framework to measure the perceived quality of arterial signal timing, which is presented in Section 3.6. Practitioners and researchers should use care when applying these findings elsewhere. The ratings of the overall perceived quality of signal timing can be measured by the number of stops per intersection, following a form of a logistic function [56].

### 3.2.2 Attainability of User Satisfaction (AUS)

The perceived quality of signal timing correlates directly with the attained user satisfaction, and an explanatory variable is identified. The optimal user satisfaction is specified as "vehicles make no stops at any of the signals involved in the evaluation," and the user satisfaction would diminish as the stop time and the number of stops increase. A performance measure was defined in this study in light of the investigated stop characteristics. The attainability of user satisfaction (AUS) describes the probability that travelers would rate the quality of arterial signal timing as the best, which can be computed using Equation 2:

$$AUS = 1 - P_{not\ satisfied} = 1 - \left(1 + e^{-w \times \frac{Stop\ Equivalency}{Total\ Number\ of\ Signals}}\right)^{-1} \tag{2}$$

where

*AUS* (%) – attainability of user satisfaction;

$P_{not\ satisfied}$ (non-dimensional parameter, $0 \leq P_{not\ satisfied} \leq 1$) – the probability that the travelers would not be satisfied with signal timing; *Stop Equivalency* – the standardized number of stops considering the trade-off between stop time and the number of stops, the dislike of consecutive stops in a short time, and the tolerability variation of stops at different intersections;

$w$ (non-dimensional parameter) – a coefficient which can be determined through user satisfaction surveys. This report provides a recommended value of this coefficient, which will be presented in Section 3.6.

## 3.3 Development of the Performance Measurement Methodology

The proposed performance measurement methodology is presented in this section. The performance measurement results are expressed in different grades, with a hierarchical order that varies from Level F (worst rating), Level D, Level C, Level B, to Level A (best rating). The methodology is comprised of three primary components – the AIP (the attainability of ideal progression) scoring, the AUS (the attainability of user satisfaction) scoring, and the adjustments. A typical procedure is presented in Figure 3.6, which identifies the sequence of calculations needed.

It should be noted that the proposed performance measurements should be applied only to coordinated signals along an arterial. As for mid-block accesses, such as two-way stop-controlled intersections or roundabout where the main-street traffic is not frequently interrupted, they can be considered as general roadway segments. If the arterial traffic is obviously influenced, the evaluation scope should be adjusted accordingly, e.g., the arterial can be partitioned into several segments where the intersections involved are all signalized and coordinated.

The steps included in the proposed performance measurement methodology are summarized below:

**Step 1: Determine Intersection Classifications**

Intersection classification is a new concept that originates from this research. As interpreted previously, many factors (e.g., congestion level along the arterial and the proportion of traffic from side street origins) should be considered when converting average speed and stops to AIP and AUS. Therefore, the conversion process can become too complicated for daily practice due to a large amount of data collection required. Intersection classification was developed as a means of simplifying the process. Intersection classification is determined based on arterial's volume-to-capacity ratio and intersection geometry. Section 3.4 provides more details about intersection classification.

**Step 2: Determine AIP Scores**

The scores of attainability of ideal progression (AIP) are determined in this step. Section 3.5 includes the details.

**Step 3: Determine AUS Scores**

The scores of attainability of user satisfaction (AUS) are determined in this step. The details are stated in Section 3.6.

**Step 4: Determine Scoring Adjustments**

In this step, any necessary scoring adjustments are determined to fine-tune the resulting AIP and AUS scores. Two types of scoring adjustments were applied: 1) cycle length adjustment and 2) intersection spacing adjustment. More details are presented in Section 3.7.

**Step 5: Determine Performance Grades based on Adjusted AIP and AUS scores**

Based on the adjusted AIP and AUS scores, the performance grades are generated for the evaluated travel-run routes.

**Step 6: Determine the Quality of Signal Timing**

After combining the performance grades for various travel-run routes, the quality of signal timing is finally determined.

## 3.4 Determination of Intersection Classification

Intersection Classification (IC) is for the purpose of simplifying the process of counting for non-signal-timing factors such as arterial congestion level and standardizing the number of stops. IC is designated at individual intersections to describe the difficulty level of achieving free-flow-speed arterial operations and optimal user satisfaction. The determination of IC is on the basis of two major considerations: arterial volume to capacity ratio (V/C ratio), and number of lanes on the cross street. Given a signal timing $i$ at intersection $m$, the arterial volume-to-capacity ratio can be computed using Equation 3:

$$Arterial\ V/C\ Ratio_{i,m} = \frac{q_{i,m}}{(n_m \times g_{i,m})} \times \frac{cl_{i,m}}{S} \tag{3}$$

where

$Arterial\ V/C\ ratio_{i,m}$ – arterial volume-to-capacity ratio at intersection $m$ for signal timing $i$;

$q_{i,m}$ (vph) – average hourly traffic counts in each direction along the main street at intersection $m$ during the operating time of signal timing $i$. This data can be obtained from regular traffic volume counts;

$g_{i,m}$ (seconds) – average green time of the arterial phases (through phases and left-turn phases along the main street) in two directions at intersection $m$ during the operating time of signal timing $i$. The value of $g_i$ can be determined based on designed green splits or logged splits history if adaptive signals are used;

$cl_{i,m}$ (seconds) – average cycle time during the operating time of signal timing $i$. The value of $cl_i$ can be determined based on designed cycle length logged cycle time history if adaptive signals are used;

$S$ (vph) – saturation flow rate per lane, typically 1800 vehicles per hour

$n_m$ – number of lanes in each direction along the main street at intersection $m$, including exclusive left-turn or right-turn lanes at the intersection.

It should be noted that the traffic volumes for left-turning and/or right-turning onto the arterial should be considered, which can be reflected by turning movement counts. However, turning movement count data may not be available or up-to-date in practice, and collecting turning movement counts can be costly and labor-intensive. An alternative way is to count the number of lanes on the side street, which roughly represents the side-street traffic demand in lieu of turning movement counts.

Table 3.4 exhibits the five types of IC. Type-I and Type-II ICs indicate that the arterial traffic demand is near saturation, and the side-street traffic demands are also heavy. Therefore, the highest achievable progressive speed along an arterial is generally low, and drivers tend to tolerate longer stop time at Type-I and Type-II IC intersections than at Type-III, Type-IV, or Type-V IC intersections.

**Table 3.4: Determination of Intersection Classifications**

| Arterial / Side Street | 0 < Arterial V/C ≤ 0.3 | 0.3 < Arterial V/C ≤ 0.55 | 0.55 < Arterial V/C ≤ 0.85 | Arterial V/C > 0.85 |
|---|---|---|---|---|
| Number of lanes in two directions ≤ 3 | Type V | Type IV | Type III | Type II |
| 3 <Lanes in two directions ≤ 7 | Type IV | Type III | Type II | Type I |
| Lanes in two directions > 7 | Type II | Type II | Type I | Type I |

Two special cases are highlighted below when determining IC types:

1) A signalized freeway interchange should be regarded as one intersection, even though some interchanges have two physical signals. It is assigned as Type-I if the arterial V/C ratio ≥ 0.55 or Type-II if the arterial V/C ratio < 0.55.

2) If the side street is coordinated at an intersection, which means the change of offset or phasing sequence is restricted to a certain extent, the type number should be decreased by one, e.g., Type-III changes to Type- II if the side street is coordinated already.

In addition, Figure 3.6 indicates the potential ranges of arterial and cross-street AADTs for IC types. Arterial and cross-street AADTs generally increase as IC type changes from Type-V to Type-I. For instance, for Type-V IC intersections, the cross-street AADT is usually lower than 5,000, and the arterial AADT is less than 10,000. In contrast, for Type-IV IC intersections, the arterial and cross-street AADTs are higher than 4,000 and 5,000, respectively (the side street may have higher volume than the arterial movements at some intersections.) However, Type-II and Type-I IC intersections can have an arterial AADT ranging from 10,000 to 50,000 and a cross-street AADT ranging from 5,000 to 45,000. This indicates that some low-volume intersections may be considered as Type-I or Type-II IC intersections; thus, the proposed IC method is different from the conventional classification approaches only using AADT data.

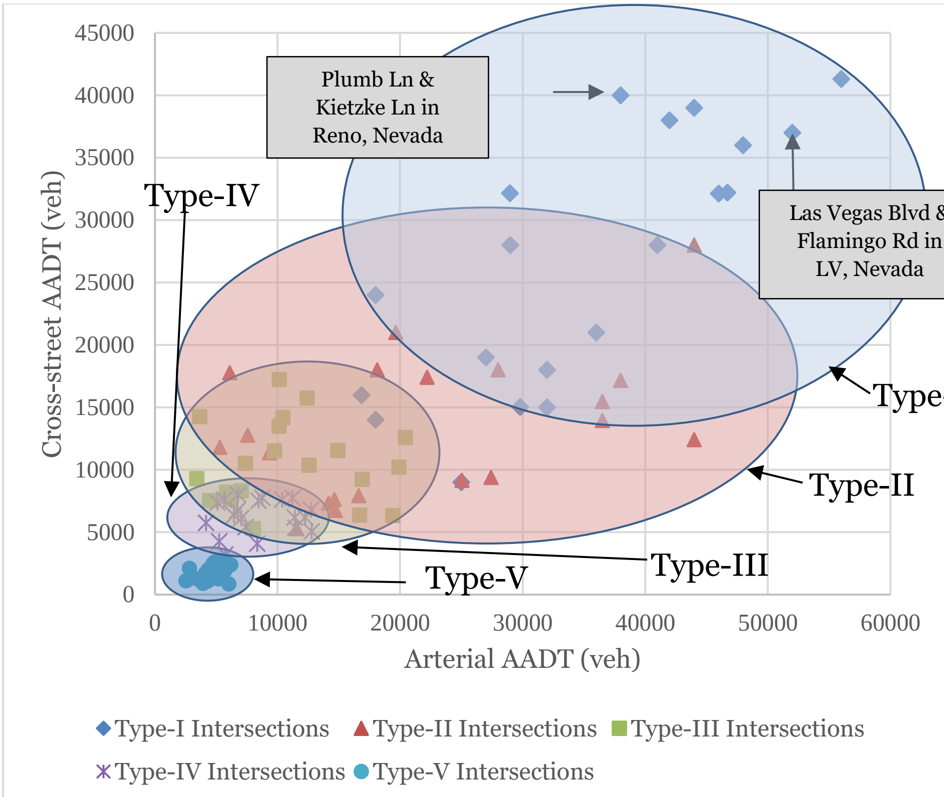



**Figure 3.6: AADT Distributions and Intersection Classification Types**

## 3.5 Determination of AIP Score

Given signal timing *i* for a total of *M* intersections (1, 2, 3, …, *m)* and a total of *N* travel-run samples (1, 2, …, *n*) collected along route *j* (typically route *j* is one of the two through movements in the two directions across the *M* intersections on the arterial), the AIP score can be computed using Equation 4:

$$AIP\ Score_{i,j,n} = \min\left(\frac{Average\ Speed_{i,j,n}}{Ideal\ Progression\ Speed_j} \times 100,\ 100\right) \tag{4}$$

where

$AIP\ Score_{i,j,n}$ ($0 \le AIP\ Score \le 100$) – attainability score of ideal progression for signal timing *i* along route *j* for travel run *n*;

$Average\ Speed_{i,j,n}$ (mph) – the average speed for travel run *n* across a total of *A* intersections along route *j* ($A \le M$) during the running time of signal timing *i*;

*Ideal Progressive Speed$_j$* (mph) – the ideal progressive speed across a total of *A* intersections along route *j* ($A \leq M$).

Ideal progressive speed can be calculated using Equation 5:

$$Ideal\ Progressive\ Speed_j = FFS_j \times \max(\alpha^{N_I} \times \beta^{N_{II}} \times \gamma^{N_{III}} \times \tau^{N_{IV}} \times \upsilon^{N_V}, 0.5) \quad (5)$$

where

*FFS$_j$* (mph) – the free-flow speed across a total of *A* intersections along route *j* ($A \leq M$), which typically equals to the posted speed limit plus five mph;

$N_I$, $N_{II}$, $N_{III}$, $N_{IV}$, and $N_V$ – the number of Type-I, -II, -III, -IV, and -V IC intersections respectively among these *A* intersections;

$\alpha$, $\beta$, $\gamma$, $\upsilon$, and $\tau$ (non-dimensional parameter) – coefficients representing the impacts of intersections with different IC types on the ideal progressive speed. $\alpha$ and $\beta$ are recommended to be 0.9 and 0.95, respectively. This means that the existence of Type-I or Type II intersections can reduce the ideal progressive speed. The greater number of Type-I and Type-II intersections involved in an arterial, the lower ideal progressive speed that can be used in the calculation. $\gamma$, $\upsilon$, and $\tau$ are suggested to be 1, which implies that Type-III, IV, and V IC intersections barely affect the average speed. These coefficients can be determined based on specific travel-run trajectories, which will be further described in the following rationale paragraphs. The recommended values of the coefficients were determined according to the data collected in the Reno/Sparks metropolitan region in Nevada.

**Rationale**

Equation 4 was derived according to AIP as defined in the previous section. The concept of "ideal progressive speed" is to define the highest achievable operating speed by signal timing optimization in the context of various non-signal-timing factors.

The ideal progressive speed can be affected by arterial congestion levels, arrival flow profile, or signal density, as explained in Section 3.1. These factors can be simplified into two explanatory variables – the IC types and the number of intersections of different IC types. The coefficients presented in Equation 5 can be determined through regression analyses using GPS trajectory data. The "ideal progressive speed" can be estimated through some specific trajectories such as the callouts i, ii, and iii illustrated in Figure 3.7. These trajectories indicate the travel runs without being halted by the signals, which represent the ideal operating speed that can be achieved by progression.

Hence, based on the trajectory data, regression studies can be conducted for "ideal progressive speed" and "the numbers of intersections of different IC types". For example, an arterial shown in Figure 3.7 has eight signals, which possesses the number of IC types as "Type-I: 2, Type-II: 0, Type-III: 3, Type-IV: 2, and Type-V: 1". And in this case, the ideal progressive speed can be captured based on trajectories that indicate travel runs across the arterial with no stops, such as trajectories i, ii, and iii exhibited in Figure 3.7. In addition, a trajectory can be divided into several segments, and the segments where the vehicle does not make stops can be used for such a regression study, e.g., the callout iv exhibited in Figure 3.7 represents ideal progressive speed for five signals that have the number of IC types as "Type-I: 2, Type-II: 0, Type-III: 1, Type-IV: 2, and Type-V: 0".

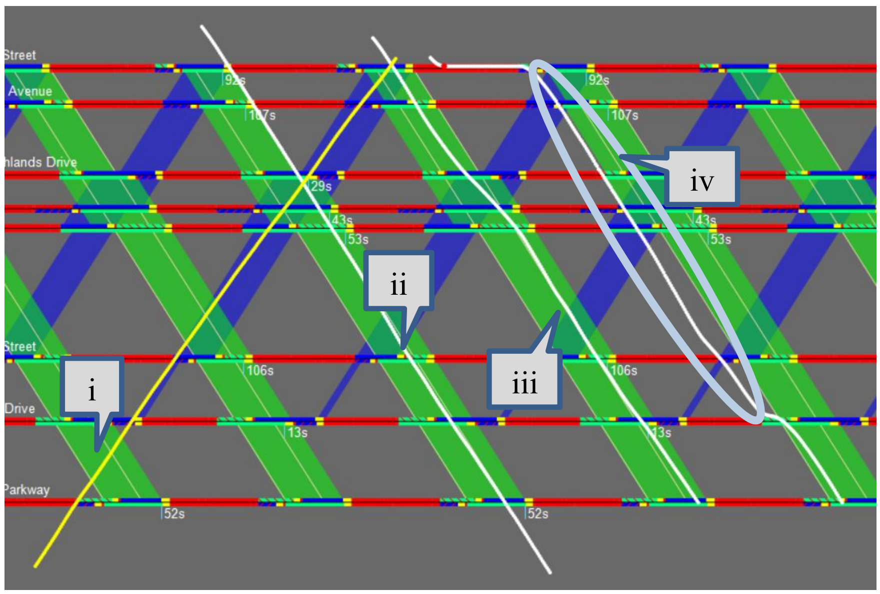



**Figure 3.7: Ideal Progressive Speed Measured by Trajectories**

Based on the cases in Reno, Nevada, a multivariate power function was obtained as Equation 5 in which $\alpha$=0.8862, $\beta$=0.9391, $\gamma$=1.024, $\upsilon$=0.9877, $\tau$=1.0080, and the constant =3.2146 ($R^2$=0.61). Therefore, it is suggested that $\alpha$= 0.9, $\beta$=0.95, $\gamma$=1, $\upsilon$=1, and $\tau$= 1. In addition, because extreme cases (e.g., arterials of more than six Type-I IC intersections) are scarcely found in the real world, the function may not be reliable as the numbers of Type-I or Type-II IC intersections increase. A lower bound, which is "50% of the free-flow speed, has been added to Equation 5 according to the findings presented in Section 3.2.

## 3.6 Determination of AUS Score

Given signal timing $i$ for a total of $M$ intersections (1, 2, 3, ..., $m$) and a total of $N$ travel-run samples (1, 2, ..., $n$) along route $j$, the AUS score can be calculated using Equation 6:

$$AUS\ Score_{i,j,n} = 100 - \left( \frac{50}{1 + \exp\left( - \frac{SPI_{i,j,n} \times 2 - 65}{10} \right)} \right) \tag{6}$$

where

$AUS\ Score_{i,j,n}$ ($50 \leq AUS\ Score \leq 100$) – score of attainability of user satisfaction for signal timing $i$, route $j$, and travel run $n$;

$SPI_{i,j,n}$ (%) – Stop equivalency per intersection for travel-run sample $n$, signal timing $i$, and route $j$

SPI can be computed using Equation 7:

$$SPI_{i,j,n} = \frac{\sum_{a=1}^{A_j} \left( Stop\ Equivalency_{a,n} \times \max\left( \frac{0.1}{Stop\ Distance_{a,a-1,n}}, 1 \right) \right)}{A_j} \times 100\% \tag{7}$$

where

$A_j$ – number of intersections along route $j$ (1, 2, 3, ... $A$, $A \leq m$);

$Stop\ Distance_{a,a-1,n}$ (miles) – the shortest distance between stops at the $a^{th}$ intersection and stops at the $a$-1$^{th}$ intersection of route $j$, measured by travel-run $n$;

$Stop\ Equivalency_{a,n}$ (non-dimensional parameter) – stop equivalency at the $a^{th}$ intersection among $A$ intersections, measured by travel run $n$;

Stop equivalency can be determined using Equation 8:

$$Stop\ Equivalency_{a,n} = \sum_{k=1}^{K} \begin{cases} 0, & Stop\ Time_k < 3s \\ 0.5, & 3s \leqslant Stop\ Time_k < 10s \\ 0.5 + \dfrac{Stop\ Time_k - 10}{\phi_a \times Cycle\ Length_{a,i}}, & Stop\ Time_k \geqslant 10s \end{cases} \tag{8}$$

where

*Stop Time$_k$* (seconds) – the duration time of the $k^{th}$ stop at the $a^{th}$ intersection, assuming there are a total of $K$ stops at the intersection ($K \geq 0$);

*Cycle Length$_a$* (seconds) – the average cycle length of signal timing $i$ at the $a^{th}$ intersection, second. The cycle length is a constant value in most cases. But it could be varying if signal timing $i$ uses adaptive adjustments, and then *Cycle Length$_a$* is determined by the average;

$\Phi_a$ (non-dimensional parameter) – a coefficient related to Intersection Classification (IC) of the $a^{th}$ intersection. $\Phi_a$ is recommended to be 0.5 if the $a^{th}$ intersection is a Type-I IC intersection. $\Phi_a$ is recommended to be 0.25 if the $a^{th}$ intersection is a Type-II or Type-III IC intersection. And $\Phi_a$ is recommended to be 0.15 if the $a^{th}$ intersection is a Type-IV or Type-V IC intersection.

**Rationale**

Equations 6 originates from Equation 2, which is an adjusted logistic function, and the function curve is presented in Figure 3.8. According to Equation 6, AUS scores are computed based on the values of SPI in the ranges I, II, and III shown in Figure 3.8, which have different characteristics. If the values of SPI are distributed within range I, most drivers are not aware of making stops while driving along an arterial, and therefore the AUS scores only slightly change. Drivers may begin to question or complain about the quality of signal timing service as the values of SPI increase; thus, the AUS scores considerably diminish when SPI is in range II. If the values of SPI increase into range III, most drivers' perception of the quality of signal timing will be unsatisfactory, and a AUS score lower than 60 will result, which implies that the perceived quality of arterial signal timing is unacceptable.

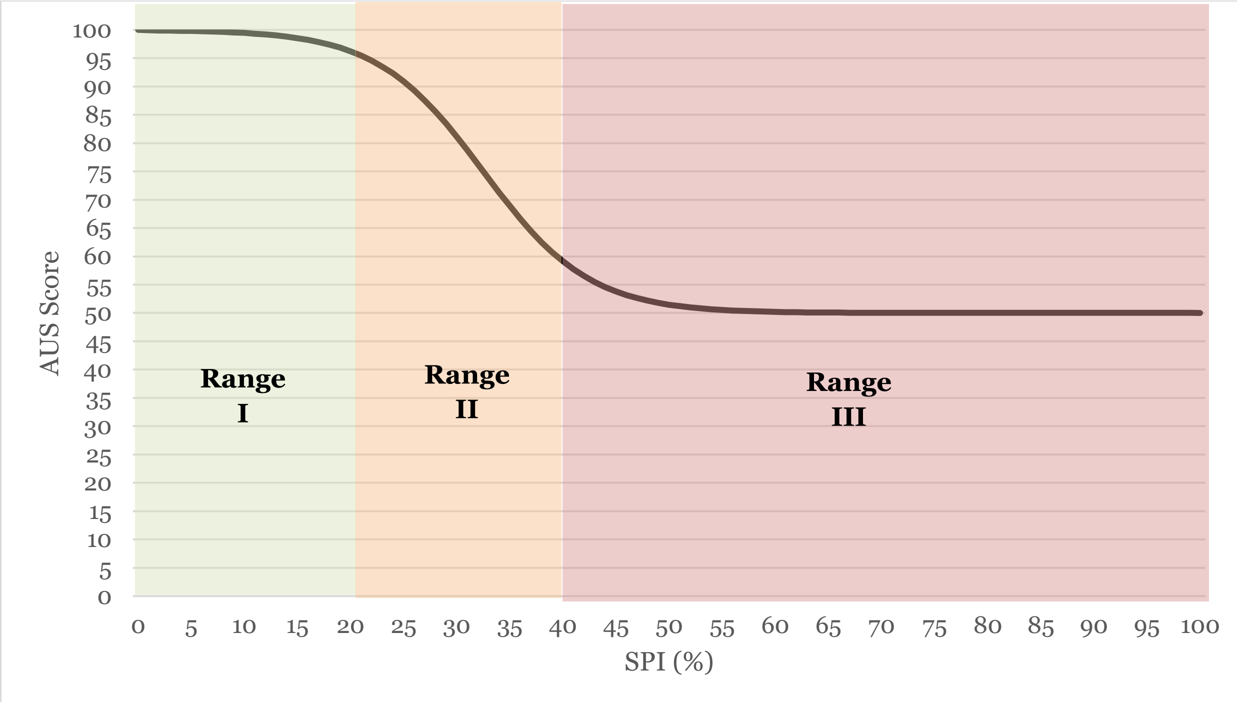



**Figure 3.8: AUS Scoring Curve**

Equation 6 was designed to converge at an AUS score of 50. This aims to prevent the AUS score from being affected by rare samples. Unlike the AIP score, the AUS score can measurably change due to incidental interferences, e.g., vehicles can be stopped because the preceding vehicles are inattentive. Such stops do not occur frequently; however, the AUS score may be significantly influenced if it gets to zero. For example, if nine travel-run samples show AUS scores of 90, but one sample has an AUC score of 20, the average AUS score would be only 83, which is not convincing to most signal timing practitioners. In addition, the change of AUS score can be more sensitive when the number of evaluated signals is small. For example, when there are only three intersections involved in the performance measurement, a trip with a stop equivalency of 1.5 may result in an AUS score below 30 whereas a travel run with the stop equivalency of 1 can result in an AUS score of 75 if a typical logistic function is adopted.

In Equation 7, a penalty is added according to the survey findings – "making two consecutive stops within a short distance or over a short time interval is annoying and dangerous." The distance of 0.1 miles (528 feet) is selected as the threshold to differentiate regular stops and short-distance stops. Most vehicles in the United States can achieve an acceleration performance of 0-60 mph within 8 seconds [69]. The distance required for a vehicle to accelerate from 0 mph to 40 mph (40 mph here is considered a typical operating speed along urban arterials) is around 400 feet, which suggests that a vehicle most likely has just finished accelerating and then is forced to stop if the two stops are less than 0.1 miles apart. This is also considered as "two stops taken in a short time" as the acceleration plus the reaction time within 0.1 miles are typically less than 20 seconds, which may make most drivers feel unsafe and annoyed.

In Equation 8, a stop equivalency is calculated instead of merely counting the number of stops. Stop equivalency accounts for the fact that the longer drivers wait at an intersection, the worse perception they may have about signal timing. Also, based on the findings presented in Section 3.2, the stop equivalency calculation considers two variables – cycle length and Intersection Classification (IC). Figure 3.9 illustrates how the stop equivalency increases along with the increasing stop time regarding "Type-I IC," "Type-II or -III IC," and "Type-IV or -V IC," respectively, under a 90-second cycle length. In general, stop time correlates with cycle length. If a cycle length is 90 seconds, the green time allocated to the arterial through phases is typically about 50% of the cycle length, i.e., 45 seconds in this case. Therefore, the longest wait drivers may experience at an intersection is 45 seconds, which is why cycle length should be considered in the calculation of stop equivalency. In addition, as shown in Figure 3.10, the three traces have different slopes, which represent Type I IC, Type II and III IC, and Type VI and V IC, respectively. For Type-I IC intersections, stop time is more tolerable, which is reflected by a flatter slope than the other two traces.

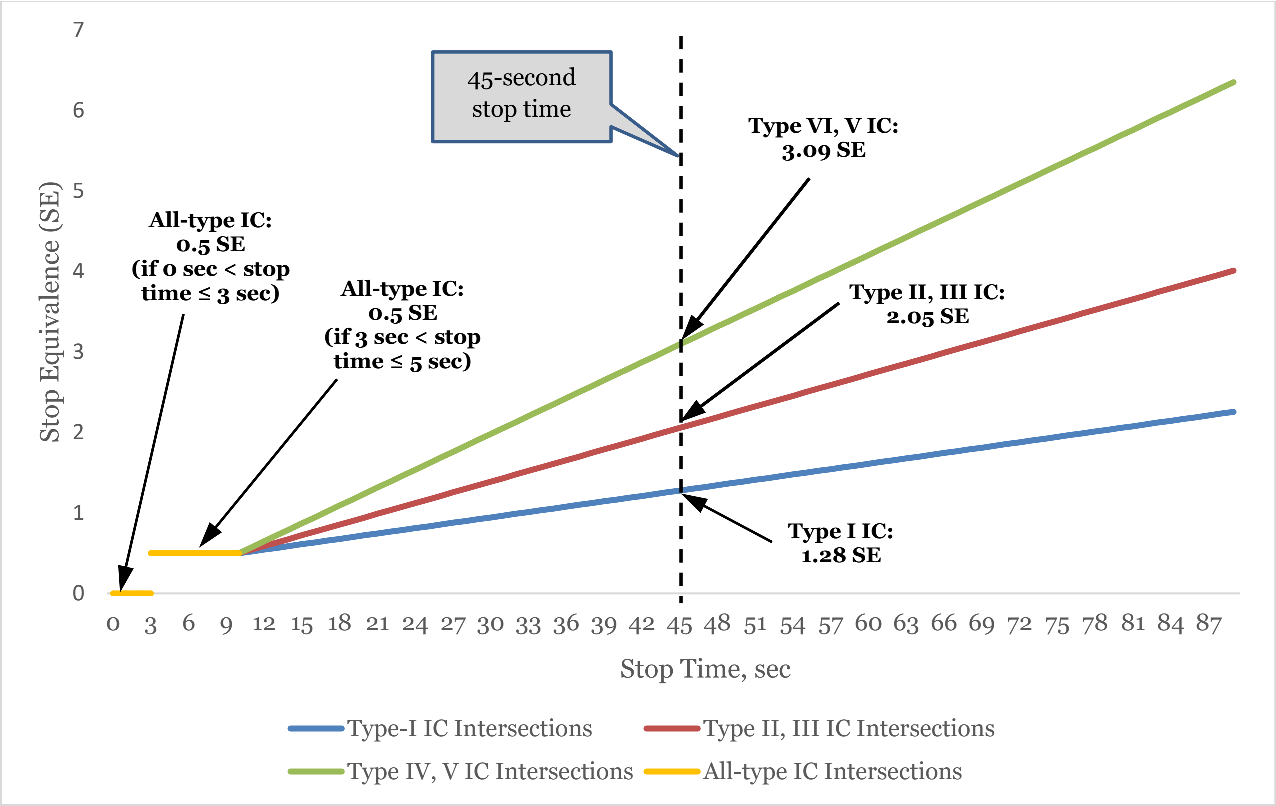



**Figure 3.9: Stop Equivalency for Different IC Types under a 90-second Cycle Length**

## 3.7 Determination of Scoring Adjustments

There are two scoring adjustments used in the proposed methodology – cycle length adjustment and intersection spacing adjustment.

### 3.7.1 Cycle Length Adjustment

The cycle length adjustment is to reward the quality of signal timing achieved by shorter cycle lengths and to penalize the inefficiency of redundantly longer cycle lengths. The justification is that a short cycle length often leads to reduced delay times for side-street traffic and pedestrians.

Given signal timing $i$ for a total of $M$ intersections (1,2,3, …, $m$), cycle length adjustments are mainly determined by the average cycle length (SACL), which can be calculated using Equation 9:

$$SACL_{i,j} = \frac{\sum_{a=1}^{A_j} Cycle\ Length_{a,i,j}}{A_j} \tag{9}$$

where

$SACL_{i,j}$ (seconds) – system average cycle length for signal timing $i$ and route $j$. Typically, route $j$ is one of the two through movements in two directions across $M$ intersections along an arterial;

$A_j$ – number of intersections along route $j$ (1, 2, 3 ..., $A$; $A \leq m$);

$Cycle\ Length_{a,i,j}$ (seconds) – cycle length of signal timing $i$ at the $a^{th}$ intersection along route $j$.

Signals in coordination are usually timed with only one common cycle length; however, if there are intersections where using a common cycle length is infeasible or inappropriate, alternative cycle lengths, such as one-half or two-times of the common cycle length, can be adopted so that the opportunity for a cyclic progression remains. For adaptive signals, $Cycle\ Length_{a,i,j}$ can be determined by averaging the historical cycle times recorded during the operating time period of signal timing $i$ because the cycle length of an adaptive signal system is usually not constant.

Table 3.5 shows the cycle length adjustment values. As seen below, the AIP and AUS scores will be reduced if the system average cycle length is deemed too long, e.g., longer than 140 seconds. A practitioner may be able to decrease the value of SACL by using other cycle alternatives in order to avoid a score reduction. The values listed in Table 3.5 are derived empirically, which are mainly based on judgments of local expert engineers regarding the general cases they have encountered in practice. Additionally, two exemptions for cycle length adjustment are listed as follows:

1) If a cycle length longer than 140 seconds is used due to capacity issues, e.g., any other cycle lengths shorter than 140 seconds would not provide an adequate capacity, negative adjustments should not be applied to the case; and

2) If a cycle length longer than 140 seconds is used due to geometric constraints, e.g., any other cycle lengths shorter than 140 seconds would not accommodate the requirements of pedestrian timing, negative adjustments should not be applied to the case.

**Table 3.5: Cycle Length Adjustments**

| SACL | The Value of Adjustment |
|---|---|
| SACL > 160s | -5 |
| 140s < SACL ≤ 160s | -2 |
| 90s < SACL ≤ 140s | 0 |
| 70s < SACL ≤ 90s | +2 |
| SACL ≤ 70s | +5 |

### 3.7.2 Intersection Spacing Adjustment

Intersection spacing is a factor that should be considered for signal timing performance evaluation because intersection spacing affects the level of difficulty of performing bi-directional signal coordination along arterials [70]. Even if two-way progression can be achieved under various intersection spacings by adjusting cycle length, offsets, and phase sequences [71, 72], it would be challenging to provide high-quality two-way progression if intersections are spaced closely together.

Typically, short intersection spacings exist in central business districts (CBD), where queue management is also crucial for arterial operations. Queuing control may be achieved at the expense of arterial progression. As a result, the scores should not be negatively impacted due to queue management objectives.

For determining the intersection spacing adjustment, an index was developed based on the proportion of number of close-spacing intersections to the total number of evaluated intersections, which is computed using Equation 10:

$$PCSI_j = \frac{n_{spacing \leq 1,000\ feet,\ j}}{A_j} \tag{10}$$

where

$PCSI_j$ (non-dimensional parameter) – proportion of closely spaced intersections to all involved intersections along route *j*, and route *j* is typically one of the two through movements in the two directions across *M* intersections along an arterial;

$A_j$ – number of intersections along route *j* (1, 2, 3 …, *A*; $A \leq m$).

$n_{spacing \leq 1{,}000\ feet,\ j}$ – number of intersections where the distance between either of the two neighboring intersections is less than 1,000 feet. One thousand feet is selected as the threshold because the *Signalized Intersections Informational Guide* by FHWA [57] documented that "arterial signals spaced less than 1,000 feet apart would be difficult to coordinate."

Table 3.6 shows the spacing adjustment values, which is an incentive adjustment, as all adjustment values are non-negative. The values provided in Table 3.6 are empirically determined, which are mainly based on judgments of local expert engineers.

**Table 3.6: Intersection Spacing Adjustments**

| *PCSI* | Value of Adjustment |
|---|---|
| **0.75 < PCSI ≤ 1** | 4 |
| **0.5 < PCSI ≤ 0.75** | 2 |
| **0.25 < PCSI ≤ 0.5** | 1 |
| **0 < PCSI ≤ 0.25** | 0 |

## 3.8 Determination of Performance Grades

Based on AIP and AUS scores, performance grades can be determined. The AIP and AUS scores obtained from individual trajectory samples need to be aggregated into general scores.

Given signal timing *i* for a total of *M* intersections (1, 2, 3, …, *m*) and a total of *N* travel-run samples (1, 2, …, *n*) collected along route *j*, the aggregate AIP and AUS scores can be obtained using Equations 11 and 12:

$$Aggregate\ AIP\ Score_{i,j} = \frac{\sum_{n=1}^{N}(AIP\ Score_{i,j,n} + CLA_{i,j} + ISA_{j})}{N_{i,j}} \quad (11)$$

$$Aggregate\ AUS\ Score_{i,j} = \frac{\sum_{n=1}^{N}(AUS\ Score_{i,j,n} + CLA_{i,j} + ISA_{j})}{Number\ of\ Samples_{i,j},\ N} \quad (12)$$

where

*Aggregate AIP/AUS Score*$_{i,j}$ – the aggregate scores of AIP and AUS for signal timing *i* along route *j*;

$CLA_{i,j}$ – cycle length adjustment for signal timing *i* along route *j*;

$ISA_j$ – intersection spacing adjustment along route *j*. Intersection spacing adjustment does not correlate to specific signal timings;

$N_{i,j}$ – total number of travel-run samples collected for signal timing *i* along route *j*;

Table 3.7 shows the performance grades based on the aggregated AIP and AUS scores.

**Table 3.7: Determination of Performance Grades**

| Aggregate AIP Score / Aggregate AUS Score | AIP ≥ 90 | 80 < AIP ≤ 90 | 70 < AIP ≤ 80 | 60 < AIP ≤ 70 | AIP < 60 |
|---|---|---|---|---|---|
| **AUS ≥ 90** | A | A | B | C | N/A |
| **80 < AUS ≤ 90** | A | B | B | C | N/A |
| **70 < AUS ≤ 80** | B | B | C | D | N/A |
| **60 < AUS ≤ 70** | C | C | D | D | F |
| **AUS < 60** | F | F | F | F | F |

## 3.9 Determination of Quality of Signal Timing

The performance grade is a route-based notion, but the quality of signal timing should reflect the performance of a signal timing plan by combining the performance grades of the routes of interest. The performance grade of routes should not be aggregated by simply taking the average because the importance of each route may not be the same. Different weights may be placed on the routes according to engineering judgments, e.g., if a route is along a transit path and the travel-run trajectories are collected by transit buses, the resulting performance grade should be emphasized when transit signal priority is one of the signal timing operational objectives.

An index named Route Priority Factor (RPF) is proposed for evaluating the quality of signal timing based on multiple performance grades.

Given a total of $J$ routes (1, 2, 3 ..., $j$) considered in determining the quality of signal timing $i$, the PRF of route $j$ can be calculated using Equation 13:

$$RPF_j = \frac{W_j Q_{i,j}}{\sum Q_{i,(1,2,3 \ldots J)}} \tag{13}$$

where

$RPF_j$ (non-dimensional parameter) – priority factor of route $j$;

$Q_{i,j}$ (vph) – traffic volume counts along route $j$ during the operating time of signal timing $i$;

$W_j$ (non-dimensional parameter) – weight for route $j$ which can be determined based on the characteristics of route $j$ such as traffic modes involved (e.g., bicycle traffic or transit traffic), whether route $j$ is a part of major commuting paths, whether route $j$ is a part of ingress/egress paths for special events;

$Q_{i,(1,2,3 \ldots, j)}$ (vph) – traffic volume counts of each route (1, 2, 3, ..., $j$) among the $J$ routes during the operating time of signal timing $i$.

The weights should be carefully determined due to potential equity issues. It is common to see in practice that traffic demands of the two directions along an arterial are distinctly uneven; however, it is not appropriate to disregard the direction with lighter traffic demand. In order to avoid the equity issues, Tables 3.8, 3.9, and 3.10 exhibit an example for determining the quality of arterial signal timing, assuming there are two routes involved.

**Table 3.8: Determination of the Quality of Signal Timing (if 0.5 ≤ the Greater RPF between Two RPFs <0.7)**

| Minor Direction \ Major Direction | A | B | C | D | F |
|---|---|---|---|---|---|
| A | A | A | C | C | F |
| B | A | B | C | C | F |
| C | B | C | C | D | F |
| D | C | C | D | D | F |
| F | F | F | F | F | F |

**Table 3.9: Determination of the Quality of Signal Timing (if 0.7 ≤ the Greater RPF between Two RPFs <0.9)**

| Minor Direction \ Major Direction | A | B | C | D | F |
|---|---|---|---|---|---|
| A | A | B | B | C | F |
| B | A | B | C | D | F |
| C | B | B | C | D | F |
| D | C | C | D | D | F |
| F | F | F | F | F | F |

**Table 3.10: Determination of the Quality of Signal Timing (if 0.9 ≤ the Greater RPF between Two RPFs < 0.1)**

| Minor Direction \ Major Direction | A | B | C | D | F |
|---|---|---|---|---|---|
| A | A | B | C | D | F |
| B | A | B | C | D | F |
| C | A | B | C | D | F |
| D | B | C | C | D | F |
| F | C | D | F | F | F |

Ultimately, the quality of arterial signal timing can be reached. Table 3.11 presents the descriptions of the quality of arterial signal timing grades, and Figure 3.10 summarizes the calculation procedure of the proposed methodology.

**Table 3.11: Description of the Quality of Arterial Signal Timing Grades**

| Quality of signal timing | Description |
|---|---|
| **A** | Excellent performance, no need for re-timing |
| **B** | Good performance, minor adjustments could be made |
| **C** | Average performance, re-timing could significantly improve the operations |
| **D** | Below-average performance, re-timing is strongly recommended |
| **F** | Poor performance, re-timing is urgently needed |

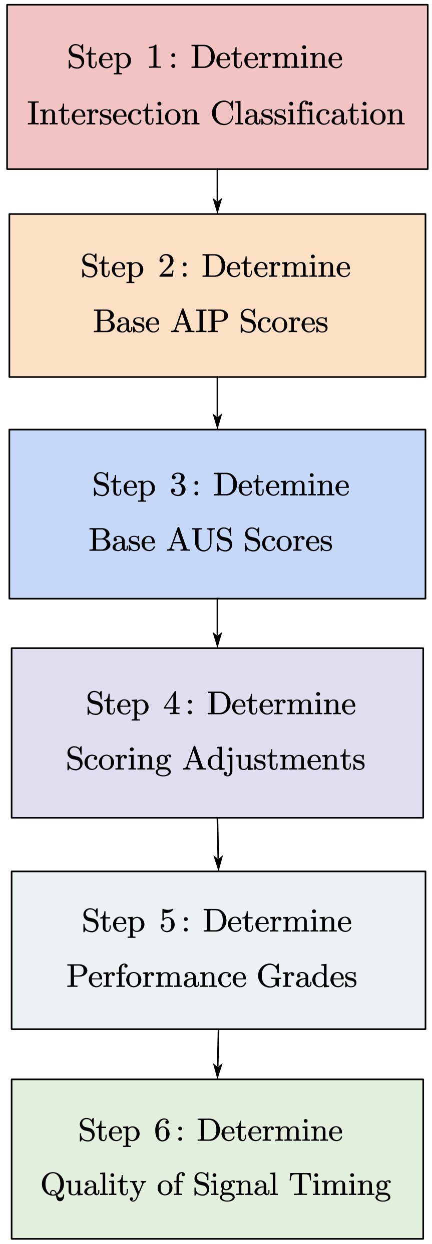



**Figure 3.10: Calculation Procedure of Proposed Methodology**

## 3.10 Chapter Summary

This chapter mainly described the performance measurement methodology proposed in this research for evaluating the quality of arterial signal timing.

The two performance measures attainability of ideal progression (AIP) and attainability of user satisfaction (AUS) were defined based on speed and stop characteristics, which can be extracted from travel-run trajectories. Non-signal-timing factors such as arterial congestion level and arrival flow profile were explored to determine their impacts on arterial travel speed. In addition, driver surveys were conducted to reveal driver perceived quality of arterial signal timing, and some preliminary findings were presented.

Next, a signal timing performance measurement framework was presented. The framework included AIP scoring, AUS scoring, and scoring adjustments based on the system average cycle length (SACL) and the proportion of closely spaced intersections (PCSI).

A new parameter, Intersection Classification (IC) was introduced to simplify the calculations of AIP and AUS. Intersection Classification focused on intersection features related to signal timing, which is different from conventional intersection classifications based on AADT data.

The determinations of AIP and AUS scores, as well as cycle length and intersection spacing adjustments, were also presented. Finally, the determination of performance grades based on the adjusted AIP and AUS scores, as well as the determination of quality of arterial signal timing were presented.

# 4 METHODOLOGY IMPLEMENTATION

This chapter outlines the implementation of the proposed signal timing performance measurement methodology, including data gathering, data processing, and a pre-implementation examination process.

## 4.1 Data Gathering

GPS trajectories recorded during travel runs are an ideal data source for the proposed methodology. Figure 4.1 shows a snippet of a travel-run trajectory recorded by a smartphone application called TranSync-M [73]. Signal timing practitioners can quickly get started with the TranSync-M application and conveniently use it while driving along an arterial. The gathered GPS data will be saved online, which facilitates data management and exchange during signal timing projects.

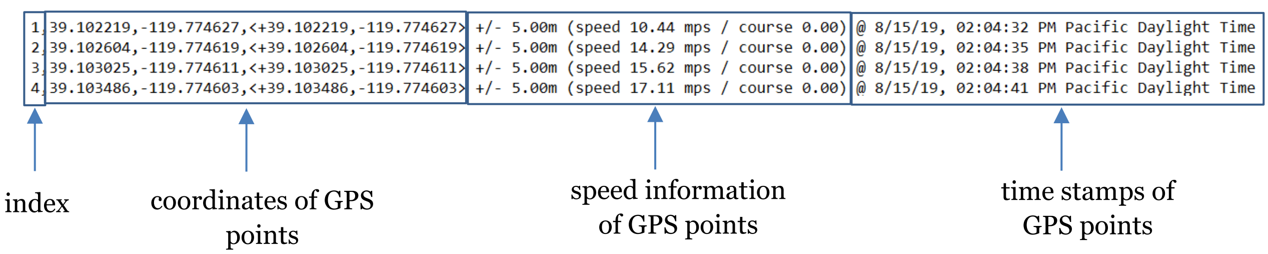



**Figure 4.1: Information Included in GPS Trajectories**

Implementing the proposed performance measurement methodology relies on high-resolution GPS trajectories that can provide information such as average speed, number of stops, duration of stops, and stop locations. Any format of GPS trajectories can be used as long as such information is included. Segmented probe vehicle data (PVD) with time-stamped average segment speed is one example. Such data can also be obtained from some nationally accessible databases (e.g., the National Performance Measure Research Data Set (NPMRDS)) or third-party data vendors (e.g., INRIX,) according to certain spatial and temporal focuses.

### 4.1.1 Collecting Trajectories through Arterial Travel Runs

With GPS receivers or the TranSync-M APP, trajectory data can be easily collected by conducting arterial travel runs. Arterial travel runs represent vehicle trips along an arterial that traverse multiple signals. Figure 4.2 exhibits an arterial segment of four signals along with two vehicle trajectories and the time-space diagram. For evaluating signal timings for the two through movements of an arterial, e.g., NB and SB, travel runs passing through the entire roadway segment need to be conducted. Two valid trajectories shown in Figure 4.2 started at different parts of the green interval, and various trajectories can be collected according to such cyclic moments. A sufficient number of trajectories are needed in order to comprehensively assess the quality of signal timing. To gain trajectories at different cyclic moments, one can adjust the cyclically entering moments by changing the position of making U-turns when doing travel runs, e.g., using U-turn points 1, 2, 3, and 4 illustrated in Figure 4.2 in a staggered way.

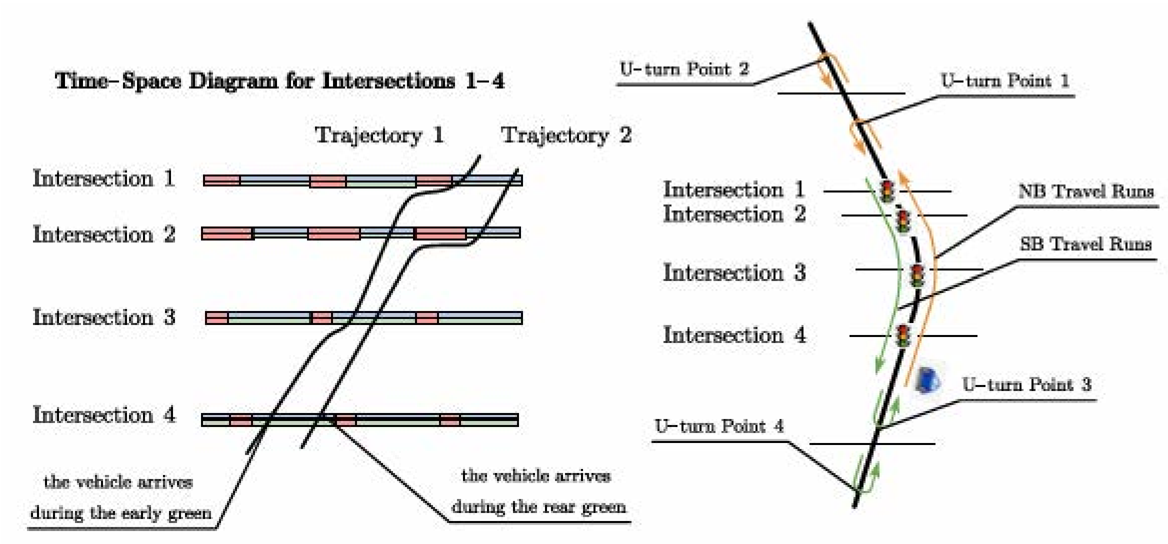



**Figure 4.2: Conducting Travel Runs along an Arterial**

Practitioners should beware that GPS trajectories need to be collected corresponding to the operating time periods of the signal timing plans. It is also recommended that the probe vehicle moves along with platoons in order to obtain representative trajectories.

### 4.1.2 Sampling Requirements

1) **Data Resolution**

The trajectory data may have varying ping frequencies. Time resolution indicates how detailed travel-run trajectories are. Trajectories collected through field probe vehicles using GPS devices or GPS-based mobile Apps can achieve time resolution at one-per-second. For other sourced trajectory data, at least one GPS point must be recorded every three seconds. This minimal resolution requirement aims to recognize the smallest stop equivalency. As presented in Equation 8, a stop equivalency can only capture stops of 3 seconds or higher. Therefore, if the ping frequency of the trajectory data does not satisfy this requirement, i.e., once per three seconds, some stops may be neglected.

In addition, the speed and location information included in the trajectory data should possess the proper resolution. The decimal degrees of latitude and longitude geographic coordinates should have a precision of at least six decimal places, in which feet-level motions can be unambiguously recognized. The precision of speed information usually depends on the resolution of coordinates and timestamps. It requires the speed variation in a scale of miles per hour (mph) to be recognized because a stop is identified according to the decrease of speed. In this study, a stop is recognized when the speed drops below 5 mph [49].

2) **Sampling Size**

Sampling size is a major factor that can influence performance measurement accuracy. Better performance evaluation results usually require a larger scale of data collection; however, project costs would increase accordingly. Hence, it is necessary to establish a minimal sampling requirement to guide data collection processes when agencies' resources are limited. For the proposed performance measurement methodology, the minimal requirement for sampling size is categorized into two types – 1) ad-hoc performance measure studies and 2) daily performance monitoring.

For ad-hoc performance measure studies, this research suggests that at least four trajectories per hour per route need to be collected during the operating time of a signal timing plan. The data collection should be conducted within the same time-of-day periods but can be over different days. A conclusion drawn by one study [49] indicated that a trajectory penetration rates of 0.04% could be used to assess signal timing performance. Given one of the highest urban arterial AADTs in Nevada – 101,000 vehicles observed on Tropicana Avenue in Las Vegas, if the signal coordination plans cover 12 hours a day (e.g., from 6 AM to 6 PM) and the arterial signal timing performance measurements focus on at least the two through arterial movements, 96 trajectory samples will be gathered according to the minimal sampling requirement (12 hours × 2 directions × 4 trajectories per hour per route = 96 trajectories,) which is larger than the 0.04% penetration rate (0.04% × 101,000 AADT=41 trajectories.) Therefore, the minimal sampling requirement for ad-hoc studies should be applicable in Nevada and most jurisdictions across the nation, in order to gather sufficient samples.

For daily performance monitoring, this research suggests that at least five trajectories per route need to be collected every three months. Unlike the data collection for ad-hoc performance studies that needs to be completed within days, performance monitoring lasts for a long term, typically a three-year re-timing cycle. As one study [74] suggested that a trajectory penetration rate of 0.1% may be able to provide insights into the cyclic traffic variance and changing trends in traffic flow as the trajectory data can be stacked over multiple days and months. If performance monitoring is conducted for an arterial with AADT of 101,000, 120 trajectories will be gathered according to the minimal sampling requirement (5 trajectories per route per three-month period × 2 directions × 12 three-month periods during three years=120 trajectories), which exceeds the trajectories penetration rate of 0.1% (0.1% × 101,000=101 trajectories). Such trajectories accumulated in multiple years can help practitioners to identify how signal timing performance varies and determine signal re-timing needs.

## 4.2 Data Processing

Trajectories during timing plan switching periods should be excluded because most signals are forced into transition during these time periods. In addition, caution should be exercised when applying the methodology for oversaturated conditions. Once oversaturation is observed at an intersection, the intersection can become a bottleneck leading to queue overflow. In this regard, signal timing performance evaluation is meaningless for the upstream segment. However, the methodology can still be applied to the segment after the bottleneck. Oversaturation can be detected by GPS trajectories as it occurs whenever at least two trajectory samples collected within 30 minutes have two or more stops on the same intersection approach. Figure 4.3 exhibits two trajectories that were recorded during a time period when oversaturation occurred. The two trajectories were collected 17 minutes apart, and both travel runs had more than two stops at the same intersection, indicating an oversaturated situation.

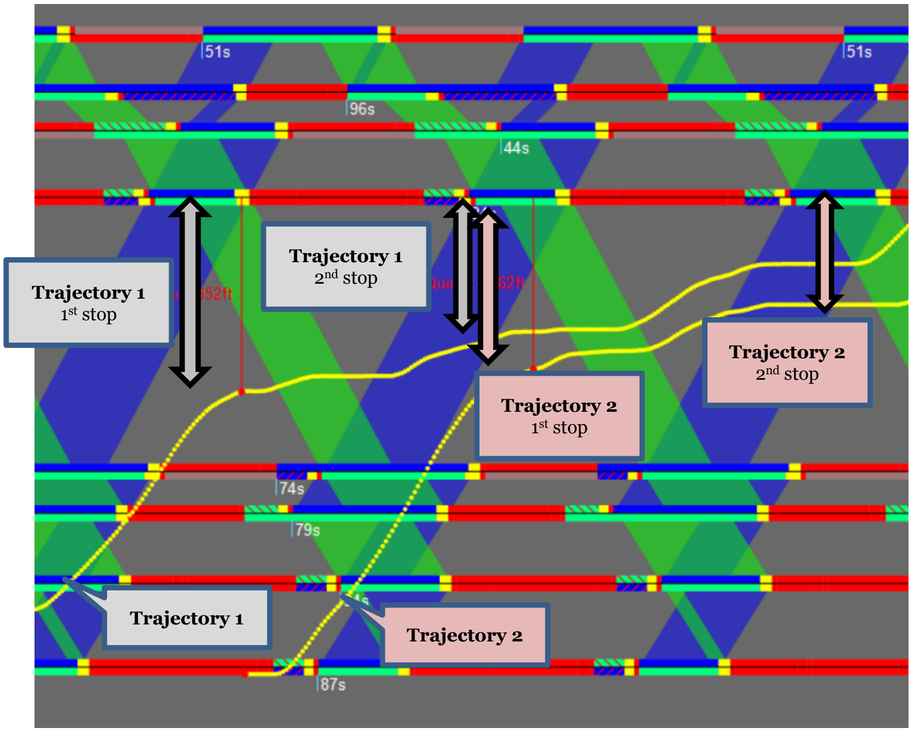



**Figure 4.3: Oversaturation Identified through Trajectories**

## 4.3 Examination Prior to Implementation

The proposed performance measurement methodology should be implemented under appliable conditions. As such, an examination regarding the background conditions is needed prior to implementation, which are described as follows:

1) Detection – the detectors should function well at the evaluated intersections, which can be verified through field observations or through signal management software's detection diagnosis report.
2) Communication – traffic signal coordination requires coordinated signals to be interconnected. If communication with field signals is lost, traffic progression may be influenced and the results become invalid.
3) Controller operations – the signal controllers should function well at the evaluated intersections, which need to run the coordination plans or be capable of adaption. If malfunctions, such as frequent timing drift, are detected, performance measurements should cease until the malfunctions are fixed.
4) Cycle length design – the cycle length should be adequately designed to prevent oversaturation or cycle failures if possible, unless a maximum feasible cycle length

still cannot serve the traffic demand. It should be noted that cycle failures may sometimes occur due to traffic flow fluctuation, which is acceptable.

5) Phase splits design – the phase splits should be adequately designed to serve the traffic demands at the evaluated intersections. This can be verified through phase failures, a condition when a queue cannot be cleared by the end of the phase. Occasional phase failures may also occur due to traffic flow fluctuations, but should not occur frequently.
6) Signal transition – data collection should not be performed during signal transition periods. However, cases where some signals are forced into transition due to preemption calls or pedestrian crossing requests should not be excluded.
7) Traffic incidents – data collection should not be conducted when traffic incidents are observed and arterial traffic operations are clearly affected by events such as crashes and lane closures.

Figure 4.4 presents the workflow for performing the examination, including all of the critical elements and procedural steps.

## 4.4 Chapter Summary

This chapter described the implementation process of the proposed signal timing performance measurement methodology. GPS-based trajectory data was considered as the primary source for the methodology. GPS data could be obtained from probe vehicle investigations or third-party databases; however, the data should fulfill the requirements of the minimal ping frequency, coordinates and speed precision. Discussions were provided regarding sampling size and data validity check. An examination process prior to the implementation was presented, highlighting the key factors and operating conditions necessary to apply the methodology.

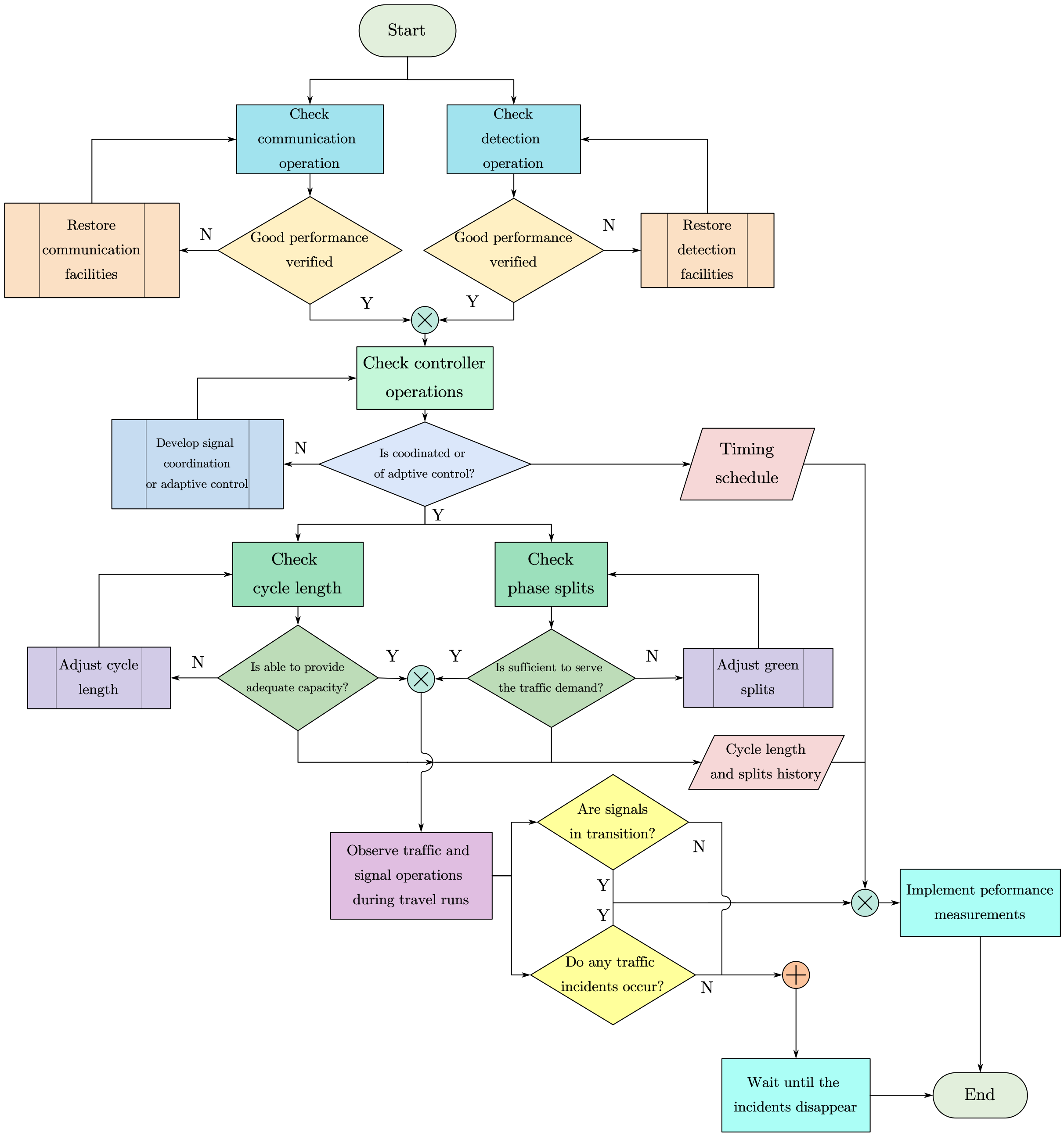



**Figure 4.4: Workflow of Examination Prior to Implementation**

# 5 CASE STUDIES

## 5.1 Case Study 1 – RTC Washoe Signal Timing Phase 5 Project

During the years of 2017-2020, the Regional Transportation Commission of Washoe County (RTC Washoe) sponsored a regional signal re-timing project to re-time 409 traffic signals in the Reno-Sparks metropolitan area. A total of 70 signalized arterials and collectors were re-timed during the project and are shown in Figure 5.1.

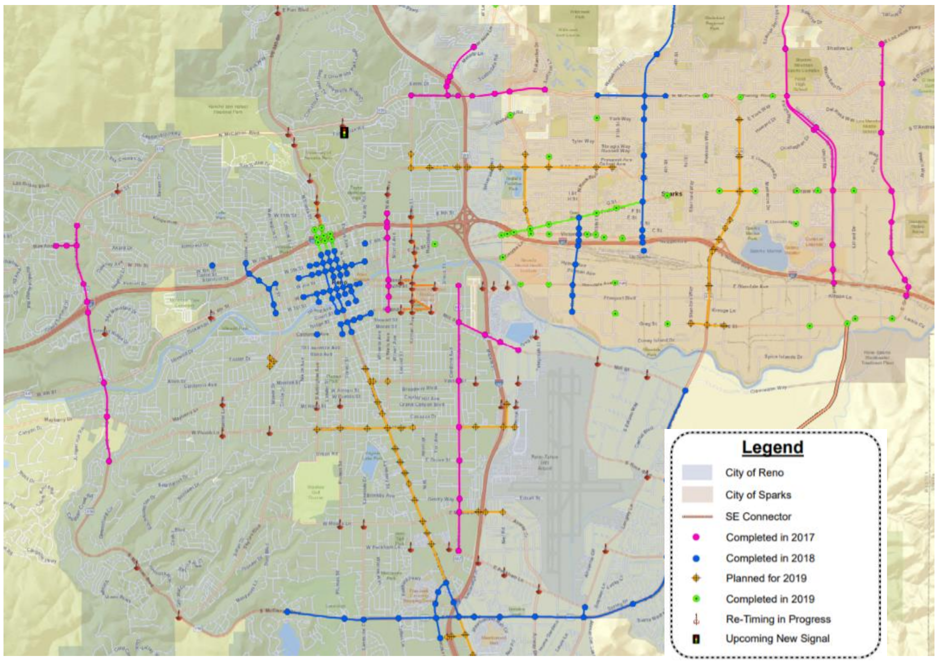



**Figure 5.1: Scope of RTC Washoe Signal Timing 5 [75] (updated as of May 2019)**

GPS trajectories were gathered through probe vehicle investigations along some of the re-timed arterials. Table 5.1 shows a group of GPS trajectories collected for the southbound (SB) and northbound (NB) through movements along Sparks Boulevard for the AM peak signal timing plan.

Based on the gathered GPS trajectory data, the proposed performance measurement methodology was applied to evaluate the quality improvements for five arterials – 1) Sparks Boulevard, 2) Vista Boulevard, 3) Pyramid Highway, 4) North McCarran Boulevard, and 5) West McCarran Boulevard. Table 5.2 presents the performance data, including average speed and numbers of stops, as well as the resulting AIP Scores, AUS Scores, route-based performance grades, and the overall arterial qualities of signal timing using the proposed methodology.

**Table 5.1: GPS Data Collected along Sparks Boulevard for the AM Peak Period**

| Travel-run Trajectories | | | | | |
|---|---|---|---|---|---|
| | Run # | Time @ Trip End | Average Speed | No. Stops | Travel Time(sec) |
| **SB** | 1 | 6:55:15 AM | 30.5 | 2 | 426 |
| | 2 | 7:01:21 AM | 33.8 | 1 | 379 |
| | 3 | 7:15:29 AM | 24.1 | 3 | 537 |
| | 4 | 7:31:23 AM | 22 | 4 | 584 |
| | 5 | 7:46:10 AM | 19.9 | 6 | 626 |
| | 6 | 8:01:35 AM | 27.7 | 2 | 465 |
| | 7 | 8:06:35 AM | 36.2 | 2 | 349 |
| **NB** | 1 | 6:44:21 AM | 29.3 | 4 | 444 |
| | 2 | 6:44:29 AM | 35 | 1 | 371 |
| | 3 | 7:02:59 AM | 35.4 | 1 | 367 |
| | 4 | 7:13:50 AM | 31.5 | 3 | 379 |
| | 5 | 7:48:39 AM | 28.3 | 4 | 457 |
| | 6 | 7:56:20 AM | 25.4 | 4 | 493 |

**Table 5.2: Performance Measurement Results for Five Arterials in Reno and Sparks**

| Arterial | Plan | Route | Before Speed (mph) | After Speed (mph) | Before No. of Stops | After No. of Stops | Before AIP Score | After AIP Score | Before AUS Score | After AUS Score | Before Route Performance Grade | After Route Performance Grade | Before Quality of Arterial Signal Timing | After Quality of Arterial Signal Timing |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Sparks Blvd** | AM-1 | NB | 30.8 | 34 | 3 | 1.7 | 86 | 94 | 62 | 91 | C | A | **D** | **A** |
| | | SB | 27.7 | 33.9 | 2.9 | 1 | 77 | 94 | 65 | 100 | D | A | | |
| | AM-2 | NB | 25.7 | 38.4 | 3 | 0.6 | 71 | 100 | 64 | 100 | D | A | **C** | **A** |
| | | SB | 33.3 | 35.8 | 1.7 | 1 | 93 | 95 | 95 | 100 | A | A | | |
| | MD | NB | 29 | 34.1 | 3 | 1.3 | 81 | 95 | 68 | 97 | C | A | **C** | **A** |
| | | SB | 28.4 | 36.7 | 1.3 | 0.7 | 79 | 100 | 95 | 100 | B | A | | |
| | PM | NB | 25.7 | 31.8 | 3.4 | 1.7 | 71 | 88 | 58 | 92 | F | A | **F** | **B** |
| | | SB | 27.7 | 28.4 | 3.4 | 3.1 | 77 | 79 | 56 | 64 | F | D | | |
| **Vista Blvd** | AM | NB | 28.4 | 32.8 | 2 | 1.25 | 84 | 96 | 89 | 100 | B | A | **C** | **B** |
| | | SB | 24.6 | 24 | 2.75 | 2.69 | 72 | 71 | 68 | 71 | D | C | | |
| | MD | NB | 28.1 | 32.3 | 1.98 | 1.25 | 78 | 89 | 88 | 100 | B | A | **B** | **A** |
| | | SB | 25.4 | 29.3 | 2.25 | 1.38 | 71 | 81 | 86 | 97 | B | A | | |
| | PM | NB | 22.1 | 32.1 | 4 | 1.13 | 65 | 94 | 50 | 100 | F | A | **F** | **A** |
| | | SB | 22.1 | 28.3 | 4.1 | 1.89 | 65 | 83 | 50 | 92 | F | A | | |
| **Pyramid Hwy** | AM | NB | 31.5 | 46.8 | 2 | 0.5 | 66 | 99 | 50 | 98 | F | A | **D** | **A** |
| | | SB | 44.9 | 48.7 | 1 | 0.33 | 82 | 89 | 87 | 100 | B | A | | |
| | MD | NB | 43.2 | 47.1 | 1 | 0.25 | 79 | 86 | 88 | 100 | B | A | **B** | **A** |
| | | SB | 47.6 | 48.1 | 0.6 | 0.25 | 86 | 87 | 95 | 100 | A | A | | |
| | PM | NB | 35 | 43.2 | 1 | 0.33 | 78 | 95 | 86 | 100 | B | A | **C** | **A** |
| | | SB | 31.6 | 38.3 | 2.6 | 1 | 70 | 84 | 50 | 88 | F | B | | |

**Table 5.2: Performance Measurement Results for Five Arterials in Reno and Sparks (continued)**

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **N. McCarran Blvd** | AM | NB | 33.9 | 33.4 | 0 | 0.67 | 89 | 88 | 100 | 100 | A | A | **C** | **A** |
| | | SB | 16.8 | 26.3 | 3 | 1.4 | 58 | 86 | 50 | 87 | F | B | | |
| | MD | NB | 24.7 | 31.3 | 1 | 0.5 | 70 | 89 | 86 | 100 | B | A | **B** | **A** |
| | | SB | 24.8 | 31.2 | 1.5 | 0.83 | 71 | 89 | 90 | 98 | B | A | | |
| | PM | NB | 18.7 | 23.7 | 2 | 1 | 58 | 76 | 78 | 95 | F | B | **C** | **B** |
| | | SB | 23.9 | 24.4 | 1.2 | 1.4 | 77 | 79 | 92 | 88 | B | B | | |
| **W. McCarran Blvd** | AM | NB | 40.4 | 40.8 | 0.7 | 0.3 | 100 | 100 | 91 | 95 | A | A | **A** | **A** |
| | | SB | 37.1 | 40.4 | 1.3 | 0.2 | 93 | 100 | 86 | 97 | A | A | | |
| | PM | NB | 28.8 | 35 | 2.39 | 1.5 | 72 | 88 | 77 | 88 | C | B | **C** | **B** |
| | | SB | 26.9 | 31 | 2.45 | 1.8 | 67 | 80 | 74 | 86 | D | B | | |

****Sparks Blvd*** *– number of signals: 8; arterial segment length: 18,972 feet (3.6 miles); speed limit: 40 mph*

****Vista Blvd*** *– number of signals: 9; arterial segment length: 14,479 feet (2.7 miles); speed limit: 40 mph*

****Pyramid Hwy*** *– number of signals: 4; arterial segment length: 12,278 feet (2.3 miles); speed limit: 55 mph*

****N. McCarran Blvd*** *– number of signals: 7; arterial segment length: 7,484 feet (1.4 miles); speed limit: 55 mph*

****W. McCarran Blvd*** *– number of signals: 8; arterial segment length: 13,298 feet (2.5 miles); speed limit: 50 mph*

As shown in Table 5.2, after the signals were re-timed, the arterial performance measures were significantly improved. Meanwhile, the qualities of arterial signal timing were rated at level A or level B, which demonstrated the effectiveness of the proposed performance measurement methodology gauging the project effort and performance improvement.

In addition, some agencies adopted the HCM LOS methodology to evaluate signal timing performance, which is exhibited in Table 5.3.

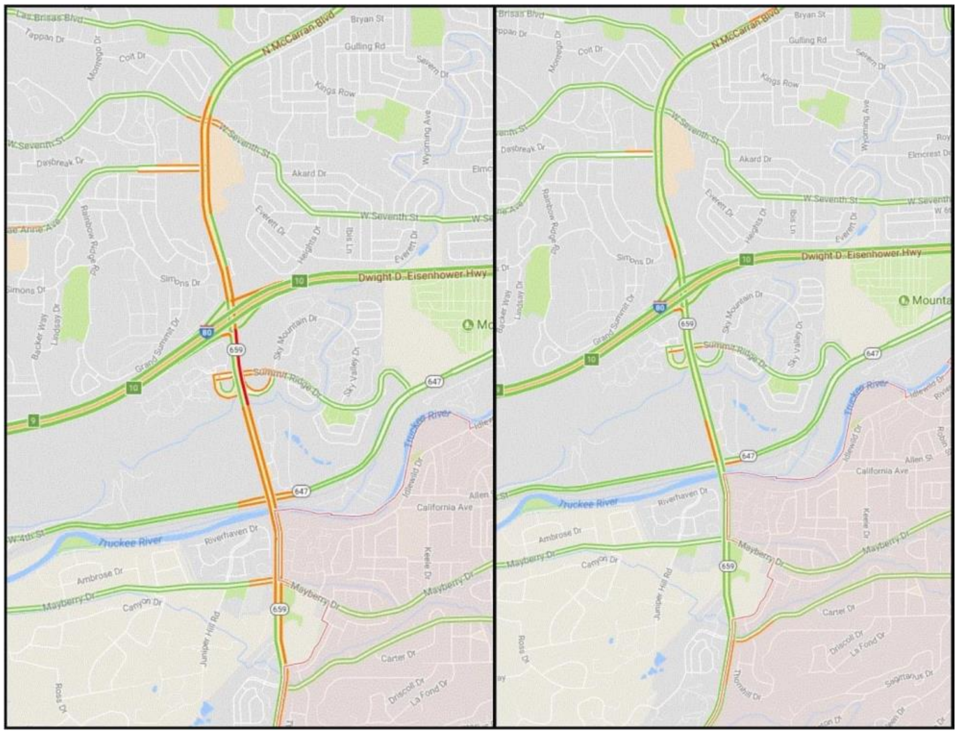
**Table 5.3: LOS Criteria Established for the Automobile Mode on Urban Streets [43]**

| **Travel Speed as a Percentage of Base Free-Flow Speed (%)** | **LOS by Critical Volume-to-capacity Ratio*** | |
|---|---|---|
| | <1.0 | >1.0 |
| **> 85** | A | F |
| **> 64-85** | B | F |
| **> 50-67** | C | F |
| **>40-50** | D | F |
| **>30-40** | E | F |
| **<30** | F | F |

** The critical volume-to-capacity (V/C) ratio is based on consideration of the through movement volume-to-capacity (V/C) ratio at each boundary intersection in the subject direction of travel. The critical volume-to-capacity (V/C) ratio is the largest ratio of those considered.*

The proposed performance measurement methodology is more suitable than the HCM LOS methodology for the purpose of evaluating signal timing quality. Using the PM peak plan of W. McCarran Blvd as an example, the southbound direction was near-saturated. According to the HCM arterial LOS methodology, the level of service along this route was only level D (31 mph = 48% of the free-flow speed, 55 mph) even though the arterial signal timing was significantly improved. Conversely, the quality of arterial signal timing using the proposed methodology achieved a level B according to an AIP score of 80 and an AUS score of 86, which was showing a performance close to level A.

The signal re-timing for W. McCarran Blvd resulted in a measurable delay reduction as indicated in Figure 5.2, which shows a comparison of the travel delays portrayed on the Google map during the same time-of-day period between before and after signal re-timing. Road segments colored in orange or red indicate different levels of congestion.




**Left figure was captured at 5 P.M on Wednesday, April 19, 2017, and Right figure was captured at 5 P.M. on Wednesday, August 23, 2017*

**Figure 5.2: Travel Delay Improvements Shown on Google Map**

## 5.2 Case Study 2 – Carson Street Signal Re-timing Project

Eight signals in Carson City, Nevada along South Carson Street between Koontz Lane and Mica Drive were re-timed in 2019, as exhibited in Figure 5.3. The evaluated arterial segment was 3.1 miles long, and the posted speed limit was 50 mph.

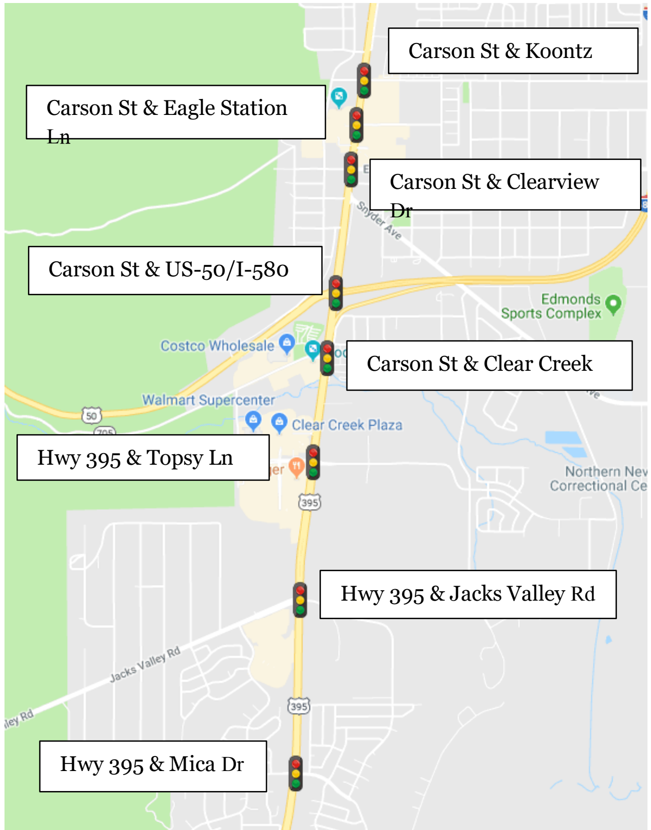



**Figure 5.3: Evaluated Signals along Carson Street in Carson City, Nevada**

For the performance measurement, a total of 64 travel-run trajectories were collected through probe vehicle investigations. The TranSync-M APP [70] was used to record the travel-run trajectories. The trajectory data were gathered in 12 days, including 9 weekdays on Tuesdays, Wednesdays, and Thursdays, as well as 3 weekend days on Saturdays and Sundays. The data were proportionally collected for four different time-of-day periods, as presented in Table 5.4.

**Table 5.4: GPS Data Gathered during Time-of-day Periods**

| Time-of-day Periods | Number of Gathered Trajectories | Time Interval |
|---|---|---|
| **Weekday AM** | 18 | 6:15 AM – 9:00 AM |
| **Weekday MD** | 24 | 9:00 AM – 4:00 PM; 5:45 PM – 8:00 PM |
| **Weekday PM** | 26 | 4:00 PM – 5:45 PM |
| **Weekend Daytime** | 18 | 8:30 PM – 6:30 PM |

Besides the data collected through floating car investigations, third-party probe vehicle data (PVD) were also used. The data were in the format shown in Table 5.5.

**Table 5.5: Third-party Trajectory Data Format (An Example of Trajectory 85207)**

| journeyId | capturedTimestamp | latitude | longitude |
|---|---|---|---|
| **85207** | 2019-08-15T14:20:16.000-0700 | 39.145619 | -119.767691 |
| **85207** | 2019-08-15T14:20:22.000-0700 | 39.144531 | -119.767893 |
| **85207** | 2019-08-15T14:20:25.000-0700 | 39.143993 | -119.768003 |
| **85207** | 2019-08-15T14:20:28.000-0700 | 39.143436 | -119.768106 |
| **85207** | 2019-08-15T14:20:31.000-0700 | 39.142859 | -119.768212 |
| **85207** | 2019-08-15T14:20:34.000-0700 | 39.142285 | -119.768314 |

The acquired third-party data had a ping resolution mostly higher than once per three seconds, and the precision of the coordinates fulfilled the requirement (6 decimal places). Therefore, the data source was qualified to be used for measuring the quality of arterial signal timing. Figures 5.4 and 5.5 show the vehicle speed variance chart and the trajectory views extracted from the third-party probe vehicle data.

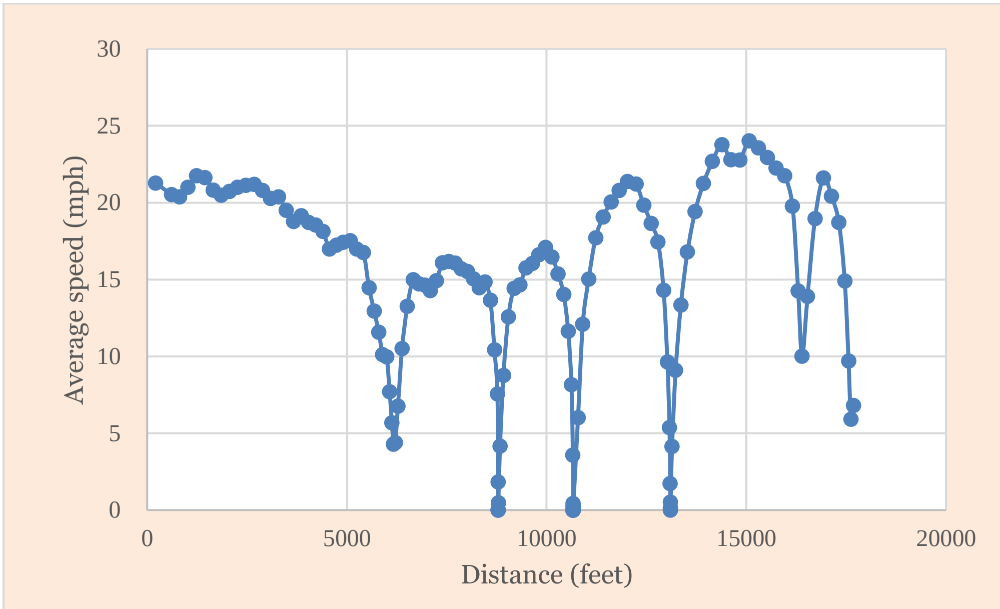



**Figure 5.4: Speed Variance Shown by PVD**

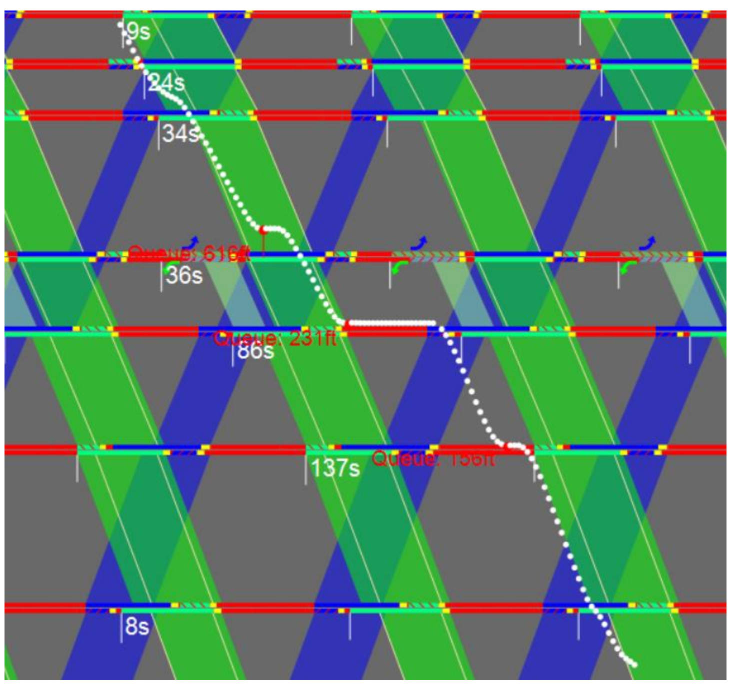



**Figure 5.5: Trajectory View on a Time-Space Diagram Obtained through PVD**

Combining the data gathered from probe vehicle investigations with the data acquired from the third-party, a total of 146 travel-run trajectories were obtained. The travel run covered three major routes of interest: 1) the northbound arterial through movement, 2) the southbound arterial through movement, and 3) the freeway left-turn movement onto Carson Street at the intersection of Carson St. & US-50/I-580 going south, which are illustrated in Figure 5.6.

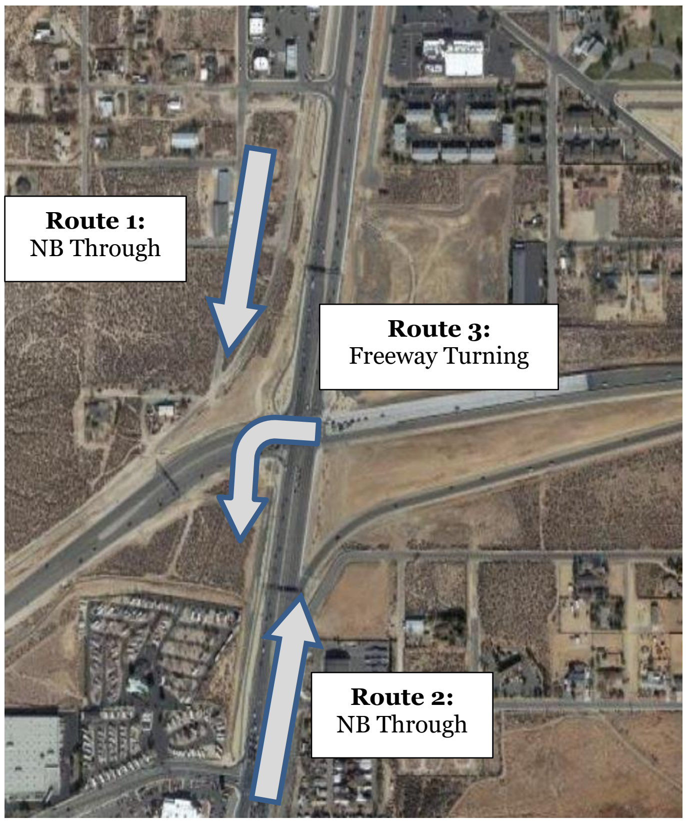



**Figure 5.6: Three Evaluated Routes**

Table 5.6 presents a comparison between the before signal re-timing and the after signal re-timing regarding the resulting travel times and the numbers of stops during the AM, MD, and PM peak periods.

The performance evaluation results indicate that the new timing plans significantly reduced the travel times and the numbers of stops for the NB and SB arterial through routes. However, the performances for the freeway route slightly decreased after the signal re-timing. The reason is that the previous timings were designed in favor of the freeway traffic, but the new timings were mainly to coordinate the arterial through traffic while maintaining some progression opportunities for the freeway traffic. By considering the trajectory data collected along the freeway route, the proposed performance measurement methodology was able to accurately rate the quality of arterial signal timing under this circumstance. Table 5.7 presents a comparison of the resulting levels of signal timing quality with or without considering the freeway route.

**Table 5.6: Performance Data for the Before and After Timing Plans**

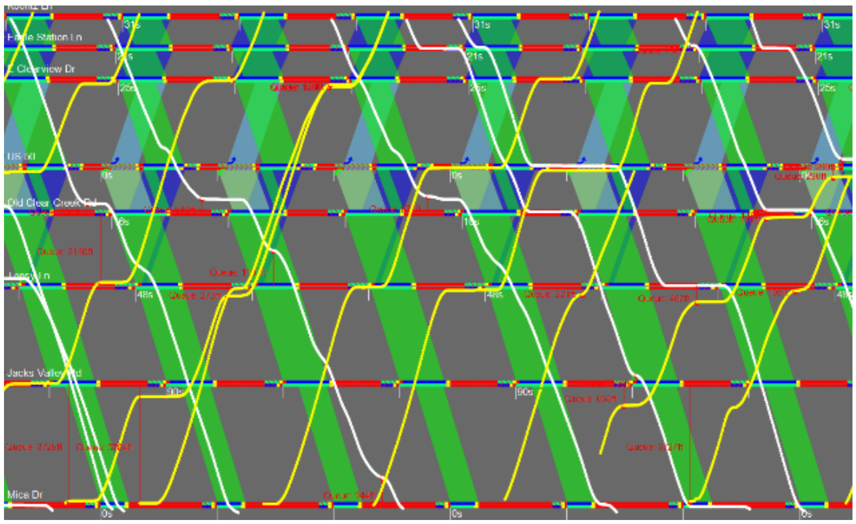
| Plans and Routes \ Performance Measures | | Previous (Before) Timings | | New (After) Timings | | | |
|---|---|---|---|---|---|---|---|
| | | Travel Time (minute) | No. of Stops | Travel Time (minute) | Improved by | No. of Stops | Reduced Stops |
| **AM** | *NB* | 8.61 | 3.7 | 5.02 | 41.7% | 0.8 | 2.9 |
| | *SB* | 6.12 | 2.6 | 4.53 | 26.0% | 0.4 | 2.2 |
| | *Freeway* | 2.72 | 0.3 | 2.88 | -5.9% | 0.5 | -0.2 |
| **MD** | *NB* | 6.27 | 2.8 | 4.89 | 22.0% | 0.3 | 2.5 |
| | *SB* | 6.13 | 2.5 | 4.61 | 24.8% | 0.5 | 2.0 |
| | *Freeway* | 2.61 | 0.1 | 2.96 | -13.4% | 0.15 | -0.1 |
| **PM** | *NB* | 9.67 | 4.2 | 5.58 | 42.3% | 1 | 3.2 |
| | *SB* | 12.85 | 5.6 | 7.51 | 41.6% | 1.6 | 4.0 |
| | *Freeway* | 6.25 | 1.2 | 6.83 | -9.3% | 1.9 | -0.7 |

**Table 5.7: Quality of Signal Timing with/without Considering Freeway Route**

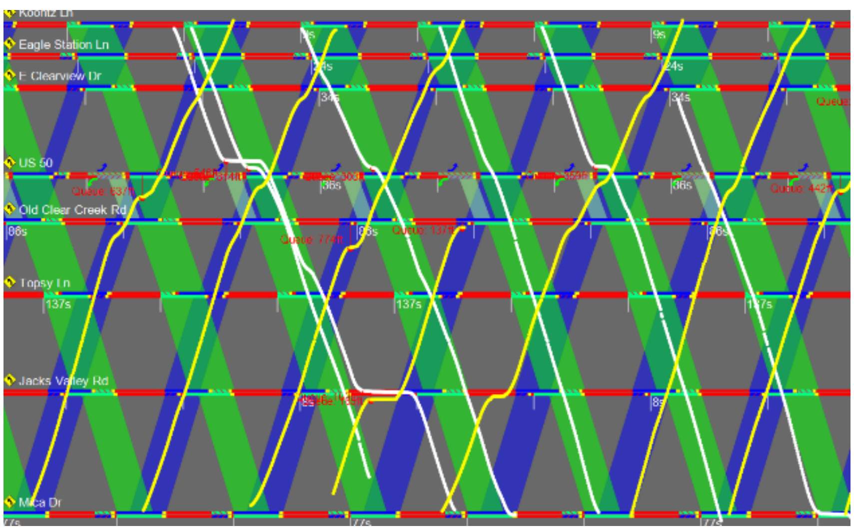
| | Before Timings (Without Considering Freeway Route) | New Timings (Without Considering Freeway Route) | Before Timings (Considering Freeway Route) | New Timings (Considering Freeway Route) |
|---|---|---|---|---|
| **AM** | D | A | C | A |
| **MD** | F | A | D | A |
| **PM** | F | A | C | B |

Figure 5.7 presents the trajectory views on the Time-Space Diagrams for the AM timing. Figure 5.7 (a) is the before timing which was rated at Level C, and Figure 5.7 (b)

is the after timing which was rated at Level A. A visual observation reveals that the trajectories shown in Figure 5.7 (a) were frequently halted at the intersections, whereas the trajectories shown in Figure 5.7 (b) were mostly straight, indicating traffic flows smoothly moving along the arterial. This figure is informative for visualizing signal timing improvements using trajectories.




(a)




(b)

**Figure 5.7: Trajectories Views on Time-Space Diagrams**

**(a: Before Quality of Signal Timing at C; b: After Quality of Signal Timing at A)**

Figure 5.8 displays six trajectories and their associated performance grades, providing a visualization of the relationship between trajectories and quality levels. These trajectories were collected for one signal timing plan along the northbound through route. Even if the travel-run trajectories were collected under the same operational conditions, the resulting quality levels could still be different depending on the time in cycle when a vehicle entered the route. Trajectory 1 represents that a vehicle was moving along the NB arterial through route and traversed the first signal (the bottom signal in Figure 5.8) at the end of the green indication. This travel run only experienced one 15-second stop and was rated at a Level A performance grade. Trajectory 2 was for a vehicle at the start of the green indication, which was rated at a Level C performance grade. The travel run had two stops that are 38 seconds and 31 seconds, respectively. Trajectories 3, 4, 5 were roughly in the middle of the green indication and were all rated at a Level B performance grade. Trajectory 6 was by a side-street vehicle that turned onto the arterial at the first signal. The travel run was stopped three times for 53 seconds, 23 seconds, and 11 seconds, respectively, and rated at a Level D performance grade. Determining the overall performance grade for the northbound arterial through route should comprehensively consider these trajectories, which indicated different levels of travel-run performance.

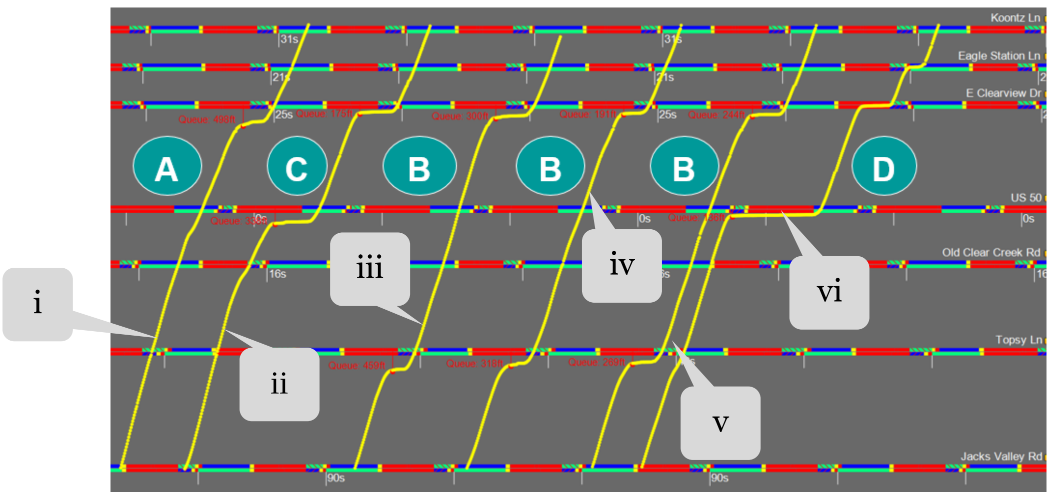



**Figure 5.8: Trajectory Shapes Rated at Various Performance Grades**

## 5.3 Chapter Summary

This chapter documented two signal timing case studies where the proposed performance measurement methodology was implemented. The first case study was based on the RTC Washoe Signal Timing Phase 5 Project. Five signalized arterials were evaluated, and the results demonstrated that the proposed performance measurement methodology could adequately rate the quality of arterial signal timing and reflect the effectiveness of the signal re-timing project. In addition, the difference between the proposed methodology and the HCM arterial LOS methodology was highlighted. It indicated that the proposed methodology was more adequate for signal timing performance measurement purposes.

The second case study was based on the Carson Street Signal Re-timing Project. Besides the trajectory data collected using the mobile devices, third-party probe vehicle data were also analyzed and adopted for the evaluation. The signal re-timing project involved three major routes of interest, including an additional freeway turning movement, which was different from the conventional signal timing practices that mainly focus on arterial through movements. The proposed methodology was applied in two scenarios – 1) considering the freeway turning movement route and 2) without considering the freeway turning movement route. The evaluation results showed that the proposed methodology accurately reflected the quality of arterial signal timing under such conditions. Trajectory views on Time-Space Diagrams and various trajectory shapes were additionally presented where the quality of arterial signal timing could be visually verified.

# 6 CONCLUDING REMARS

## 6.1 Research Summary

This research involved the development and implementation of a methodology for measuring the quality of coordinated arterial signal timing. The methodology relied on vehicle trajectories which can be obtained through conventional probe vehicle travel run studies or through automated data sources. The methodology was considered as the first-of-its-kind in assessing the quality of signal timing on coordinated arterials.

A comprehensive literature review was conducted regarding the state of practice and research. The review identified a need for this research to develop an arterial-level signal timing performance measurement methodology. This research is especially valuable when vehicle trajectories can be broadly collected across a road network through emerging technologies such as connected vehicles. Compared to signal timing performance metrics that were derived from at-intersection detectors, the fundamentals of arterial-level performance metrics were described along with the advantages of using continuous vehicle trajectories.

Based on travel-run speed and stop characteristics, two arterial-level performance metrics were developed: 1) attainability of ideal progression (AIP) and 2) attainability of user satisfaction (AUS). In practice, average travel speed is commonly used to measure arterial signal timing performance; however, this measure alone may not be sufficient as there could be several non-signal-timing factors that can influence average travel speed, e.g., arterial congestion level and arrival flow profile. Investigations were conducted to characterize the effects of these non-signal-timing factors, and the AIP metric was defined based on travel speed but excluded the non-signal-timing factors. The AUS metric was defined to describe the drivers' perceived quality of arterial signal timing, which correlated to the number of stops and stopped time at intersections. Preliminary surveys were conducted to identify the factors related to drivers' satisfaction during arterial travels.

The arterial signal timing performance measurement methodology was derived according to the AIP and AUS metrics, as well as a number of additional parameters. A new parameter, Intersection Classification, was proposed to simplify the calculations by excluding the effects of non-signal-timing factors as well as scaling the change of traveler satisfaction under various circumstances. The performance measurement framework included the AIP scoring, the AUS scoring, and the scoring adjustments. The cycle length adjustment and intersection spacing adjustment were based on considerations of side-street and pedestrian delays as well as arterial geometric conditions. The quality of arterial signal timing can be rated at levels of A, B, C, D, and F. Such letter-based grades are intuitive and can greatly facilitate information exchange, recognizing re-timing needs, and monitoring the quality of regional arterial management programs.

The implementation of the proposed method was outlined, including data collection, data processing, and a pre-implementation examination. The required data resolution and sampling for GPS trajectories were described. GPS trajectory data can be obtained through two approaches: 1) conducting floating-car investigations along arterials using mobile GPS recording devices; and 2) acquiring data from third-party data service companies. Hence, practitioners could select different data sources according to budgetary conditions and purposes, i.e., either ad-hoc performance studies or daily performance monitoring. Travel runs during signal transition or under oversaturated conditions must be carefully examined as including such travel run data could add bias to the performance results. Before conducting performance measurements, several conditions, such as detection and communication issues, inappropriate cycle and split design, timing plan transition, and traffic incidents, should be excluded from the evaluation process.

Two case studies were documented to demonstrate the validity of the proposed performance measurement methodology. The first case study involved re-timing of five arterials as part of the RTC's Regional Signal Re-timing Project – Phase 5. The second case study involved re-timing of 8 signals on Carson Street in Carson City, Nevada. Both case studies demonstrated that the proposed performance measurement could accurately gauge the quality of signal timing in the contexts of various traffic volume conditions and signal timing considerations.

The proposed signal timing performance measurement methodology can improve the current signal timing practice by providing: 1) a scalable performance measurement framework which can be implemented under a wide range of budgetary conditions and for diverse signal timing considerations; 2) accurate performance evaluation results that can demonstrate the effectiveness of the signal re-timing efforts, assist practitioners in identifying signal re-timing needs, and facilitate signal timing improvements, especially when the arterials are congested; 3) an intuitive indicator that can be adopted by decision-makers, practitioners, and the public, which can promote progress reporting, the development of expertise, and public involvement during signal timing projects.

## 6.2 Future Extensions

This research is the first major effort in developing a practical application for quantitatively evaluating the quality of arterial signal timing and coordination. Several enhancements are necessary through future research endeavors:

1) Integrating with Automatic Data Gathering Techniques

At present, GPS trajectories are mostly collected through manual processes; thus, the sample size is limited (penetration rates are usually lower than 1%.) Jointly using the information such as operation event data pulled from field controllers (penetration rate at almost 100%) would significantly supplement the trajectory data sampling. Future research is needed for integrating automatic data collection with the current methodology.

2) Conducting Additional Surveys on Travelers' Perceptions

The preliminary findings documented in this report may be arbitrary and biased for travelers' perceptions as the surveyed samples were informal and very limited. Further investigations that incorporate more formal and broader surveys are deemed necessary.

3) Performing Calibrations Regarding More Cases

The proposed methodology involved many coefficients that need to be calibrated using real-world data. The recommendations given by this research were developed based on the data collected in urban areas in Nevada and limited experts' feedbacks. Additional data collected elsewhere across the nation are desirable to further improve and validate the proposed methodology.

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# APPENDIX: SURVEY QUESTIONS

## Traveler Satisfaction Survey

This is a traveler satisfaction survey on the quality of arterial signal timing. In this survey, you will be asked questions about your attitudes and feelings under different circumstances while driving along an urban arterial. Please fill out the form, and thank you for your time!

Next

### Part I: Basic Information

Gender

- ○ Male
- ○ Female
- ○ Prefer not to say

Age

- ○ < 20
- ○ 20 - 60
- ○ > 60

Living Area

- ○ Urban
- ○ Suburban
- ○ Rural

Usage of Signalized Arterials

- ○ Frequent
- ○ Not Frequent
- ○ I Don't Know

## Part II: Driving Experience

Do you think your experience can be influenced according to how long you are stopped by signals?

- ○ Yes
- ○ No

Which one you are most concerned about while driving along an arterial?

- ○ Number of stops that I have made per mile
- ○ Number of intersections that I have passed without any stops

When do you start to be aware of a stop at the intersection?

- ○ Stopped more 5 seconds
- ○ Stopped more 10 seconds
- ○ Stopped more 15 seconds
- ○ Stopped more 20 seconds

When do you start to feel dissatisfied while being stopped by signals

- ○ Stopped more 15 seconds
- ○ Stopped more 20 seconds
- ○ Stopped more 30seconds
- ○ Stopped more 40 seconds

Do you agree that making two short stops (e.g., two 20-second stops) is better than making one long stop (e.g., one 40-second stop)?

- ○ Yes
- ○ No
- ○ Maybe

Do you agree making two stops in a short distance and a short time interval is dangerous and annoying?

- ○ Yes
- ○ No
- ○ Maybe

Rate your satisfaction degree

When you are stopped more 10 seconds at a big and busy intersection

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| I feel good | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | That is not acceptable |

When you are stopped more 20 seconds at a big and busy intersection

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| I feel good | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | That is not acceptable |

When you are stopped more 40 seconds at a big and busy intersection

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| I feel good | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | That is not acceptable |

When you are stopped more 10 seconds at a small intersection

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| I feel good | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | That is not acceptable |

When you are stopped more 40 seconds at a small intersection

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| I feel good | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | That is not acceptable |

When you are stopped more 20 seconds at a small intersection

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| I feel good | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | That is not acceptable |

Thank you!

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