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Application of Pareto Front to Evaluate Adaptive Traffic Signal Timing for Multiple Objectives

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ABSTRACT

This paper examines the effects of policies on coordinated traffic signal control using a multi-objective framework inspired by the Pareto front concept. The Pareto front describes the set of optimal outcomes in a space defined by multiple objectives. This concept is applied to a nine-intersection signalized corridor in a microsimulation study comparing performance from an array of conventional signal control policies that represent a spectrum of options with performance tradeoffs between locally optimal and system optimal control. This is used to identify a Pareto front using delays for coordinated and non-coordinated movements, which offers a frame of reference for comparing the performance of adaptive control algorithms. Two different real-time adaptive control algorithms, a self-organizing algorithm and a schedule-based algorithm, are examined and their performance compared to the Pareto front of conventional controls. The self-organizing algorithm was found to extend the region of feasible performance beyond the capabilities of the conventional methods in different directions relative to the Pareto front.

Keywords: Traffic signal timing, Adaptive control, Performance Measures

1. INTRODUCTION

Operational objectives are important to the development of a traffic signal control plan. Often, multiple objectives are in tension with one another. An example that often arises in coordinated traffic signals is the tradeoff between locally optimal control at local intersections (e.g., balancing delays among movements) versus system operation that seeks other objectives (e.g., smooth traffic flow) and imposes constraints on the local control. The importance of identifying objectives has been emphasized in recent FHWA guidance on traffic signal timing [*1*].

Recent research has applied the concept of Pareto efficiency to explore such tradeoffs [*2, 3, 4*]. The Pareto front allows the identification of tradeoffs in performance that result from alternative control policies. Figure 1 shows an example Pareto front for two objectives. In this example, each objective represents an undesirable quantity (for example, delay), so minimization is desirable. A "feasible region" of possible performance is located above and to the right of the curve. The Pareto front can be identified from various observations (points A, B, C) optimized with alternative objectives having different degrees of priority. The curve represents a set of solutions where one objective cannot be improved without worsening the other. A change to the control policy may cause movement along the front (e.g. from A to C) or into the front (e.g. to G). Finally, new technology might yield performance that is infeasible for conventional controls (points D, E, F).

The general location of the Pareto front could be found by testing several ideally optimal or near-optimal control options that favor one objective or the other to differing degrees. This study accomplishes this by using common variants of conventional signal control forming a spectrum of options favoring either local or system control. After finding the Pareto front, adaptive signal control methods are compared to determine whether they extend the envelope of performance beyond the conventionally feasible range. This study investigates whether a Pareto front can be readily found by testing a series of conventional control methods in a simulation model of a corridor and compares these against three different adaptive control methods to demonstrate use of the Pareto front as an evaluative tool.

2. METHODOLOGY

1.1 Simulation Model

A nine-intersection network of two intersecting signalized corridors in Ames, Iowa was modeled (Figure 2). Traffic volumes were obtained from the Iowa DOT. A scenario reflecting the PM peak hour volumes was developed. Signal timing plans for the network were obtained using Synchro [*5*]. The network was modeled in VISSIM using the Econolite ASC/3 virtual controller to implement signal control. Phase assignments were made according to the standard eight-phase layout. Further details are provided elsewhere [*6*].

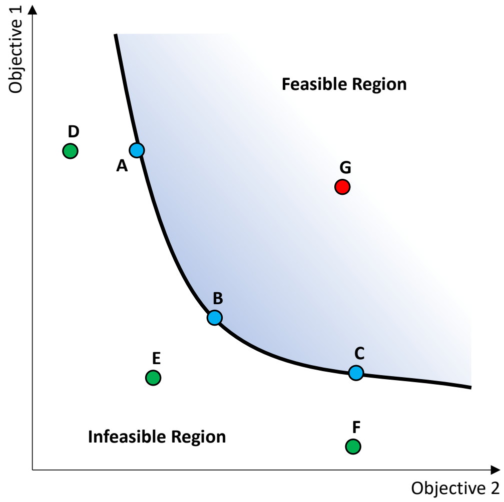

Figure 1. Pareto front diagram

1.2 Traffic Control Methods

Nine conventional signal control methods and three adaptive control methods were implemented in the Lincoln Way network, as explained in Table 1. The conventional control methods span a variety of options emphasizing either system or local control at different priorities. At one end, CFL favors system control by favoring coordinated phases during actuation. At the other end, FA1 has no method to facilitate coordination and each movement is served using actuation rules that terminate green shortly after queues have cleared. Two methods (FA2 and CPT) are known to be suboptimal and are included to verify that such methods reside away from the Pareto front. Two adaptive control methods (one having two variants) are tested to determine whether they extend the Pareto front into the otherwise infeasible region.

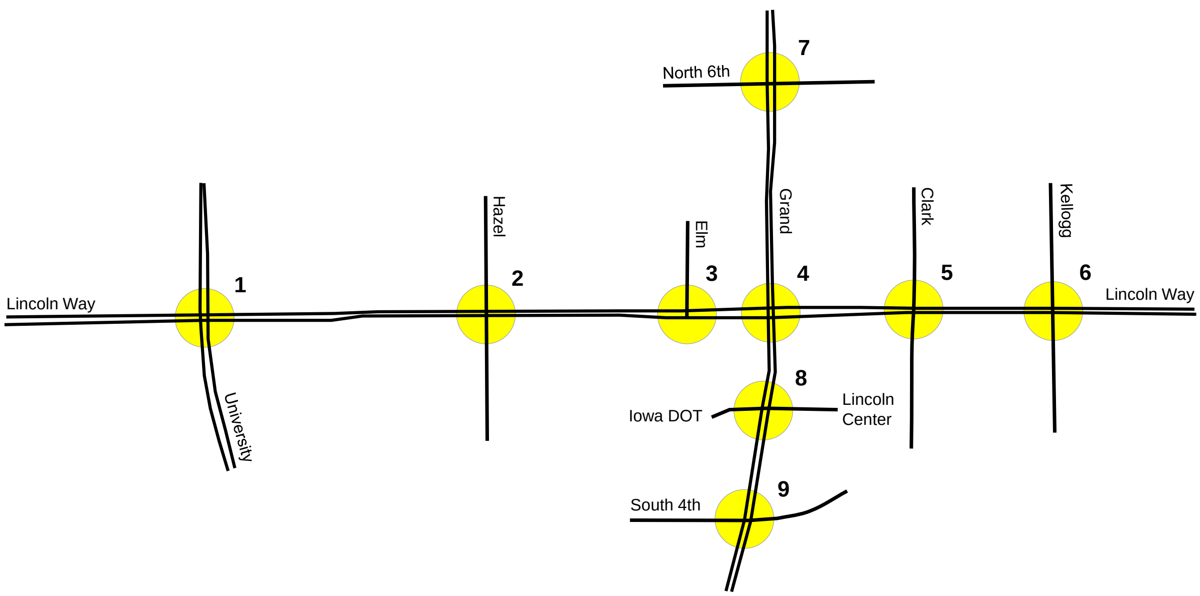

Figure 2. Location of the modelled signal network (Lincoln Way and Grand Ave., Ames, IA)

Table 1. Control methods examined in this study

Abbreviation	Method and Description
FA1	Fully-actuated control without coordination, with short extension times, lane-by-lane detection, and soft recall to the major through movements. Intended to represent locally-optimal fully-actuated control.
FA2	Fully-actuated control; identical to FA1 except that the major through movements are set on max recall and the maximum green times for the through movements are increased to 90 seconds. Intended to represent a poor control strategy that tries to coordinate by making the mainline greens as long as possible but without any real provision for coordination.
CPT	Coordinated pretimed control. All phases at all intersections operate with the same green time in every cycle, without use of any actuation.
CFL	Coordinated-actuated with floating force-off. All green time yielded by actuated phases is inherited by the coordinated phases.
CFX	Coordinated-actuated with fixed force-off. Green time yielded by actuated phases may be used by other actuated phases.

Table 1. Control methods examined in this study

Abbreviation	Method and Description
CY1	Coordinated-actuated with fixed force-off and early yield of 10% of cycle. Identical to CFX, but with a portion of the coordinated phases (equal to 10% of the cycle length) actuated. The coordinated phases may thus end when they have no remaining demand, and that time is accessible by other phases.
CY2	Coordinated-actuated with fixed force-off and early yield of 20% of cycle.
CY3	Coordinated-actuated with fixed force-off and early yield of 30% of cycle.
CY4	Coordinated-actuated with fixed force-off and early yield of 40% of cycle.
PAA	Phase Allocation Algorithm. A schedule-based real-time adaptive control method that uses a table of anticipated vehicle arrivals to determine the optimal phase sequence and duration within a planning horizon. The duration of the planning horizon is set equal to the cycle length used in coordinated methods. Vehicles are detected up to 1000 ft upstream of the intersection.
Self I	Self-Organizing Control, version 1. Identical to FA1, but with the inclusion of a "secondary extension" that will extend a currently green phase if there is a platoon of vehicles approaching it. In this version, secondary extension is available on major street through movements. Vehicles are detected up to 1000 ft of the intersection.
Self II	Self-Organizing Control, version 2. Identical to Self I, but with secondary extension additionally applied to side street through movements.

3. RESULTS

1.3 Character of the Control Methods

To illustrate each control method, Figure 3 presents a series of coordination diagrams [*7*]. These diagrams depict how well the vehicle arrivals (black dots) align with green intervals (shaded green region) on one signal approach. Clusters of dots represent platoons of vehicles. The diagrams show how consistent the patterns are from one cycle to the next and how well aligned arrivals are with green.

- CPT (Figure 3a) is the most rigid form of control, with each cycle having the same durations of red and green. CFL (Figure 3b) and CFX (Figure 3c) both introduce only minor variations in the start of green.
- PAA (Figure 3d) introduces adaptive adjustments of the starts and ends of green which leads to more variation. Interestingly, conventional methods CY1-CY4 (Figure 3e-h) appear to have a similar effect.
- The self-organizing methods (Figure 3i,j) have much more flexibility, which is not surprising as they are based on fully-actuated methods FA1 and FA2 (Figure 3k,l). Self-organizing control introduces some extensions to facilitate coordination in response to detected platoons, and there are more platoons coincident with green than the fully-actuated control methods that lack this mechanism.

Altogether, this collection of methods represents a spectrum of control policies that have different favor coordination or local control to various degrees.

1.4 Pareto Front

Figure 4 shows the performance of each control method using the total delay of the entire system. From this perspective, it is possible to observe that the fully-actuated and pretimed methods have higher delay (with FA2 performing very poorly), the actuated-coordinated methods have lower delay, while one of the adaptive methods (PAA) yields marginally lower delay than these whereas the other (Self I / II) seems to perform about the same as the actuated-coordinated methods. With PAA having 4.5% less total delay than CY4, there appears to be only a small difference between the actuated-coordinated and adaptive methods.

Figure 5 presents the same data, but with the delay broken out between the major movements and the minor movements. When arranged in this way, the position of the actuated-coordinated methods (CFL, CFX, and CY1-4) along with FA1 reveal the likely position of the Pareto front, assuming that their performance is close to optimal, for the given balance between objectives relevant to the control method. The upper end at FA1 represents methods that optimize local control, while at the other end, CFL emphasizes system control. Two methods (CPT and FA2) are contained inside of the feasible region, which shows that they are not optimal, as expected. The adaptive methods seem to be able to reach into the infeasible region. PAA seems very slightly below and to the left of the Pareto front, while the self-organizing methods seem to move to the right.

This arrangement of the data facilitates the inference of characteristics of the different control methods. The most common actuated-coordinated control methods CFL and CFX have similar performance, and strike a certain balance between local and system control. Use of early yield strikes a different balance, with less emphasis on system control (with an increase in major movement delay), balanced by better local control (with a decrease in minor movement delay). The larger the actuated portion of the coordinated phase (i.e., when moving from CY1 to CY4), the greater the effect, however, beyond CY2 there is virtually no additional reduction of minor movement delay, and only an increase in major movement delay. FA1 is positioned almost directly above CY2, CY3, and CY4. Meanwhile, the self-organizing methods have higher major movement delay compared to the conventional coordinated methods, but yield lower minor movement delay. Finally, PAA has similar performance to CY1, with marginally lower major and minor movement delays.

1.5 Applicability of the Method

These results demonstrate an application of the Pareto front concept in evaluating new traffic signal control policies when balancing multiple objectives. Often, new control policies or technologies such as adaptive control are compared against a single mode of operation that represents conventional control (or control that is likely to be quite far from optimal, such as fixed-time control). The results of such comparisons are likely to be misread if the objectives of the two alternatives are different. Rather than comparison against a single representative form of conventional control, using a few different options that bracket different balance points between competing objectives can offer a more comprehensive manner of comparison. This can help isolate the value added by the new method.

The main use case of this strategy would be simulation studies. It is impractical in most cases to operate a real-world traffic network under an array of alternative policies. However, most new methods are initially tested in simulation long before they see real-world use. In a simulation environment, it would be relatively easy to develop a series of perhaps 3-4 different scenarios to identify the range of possible performance with conventional controls. Results from this study show that fully-actuated control and actuated-coordinated control are likely to bracket the two ends of a spectrum of options that tradeoff between local and system control.

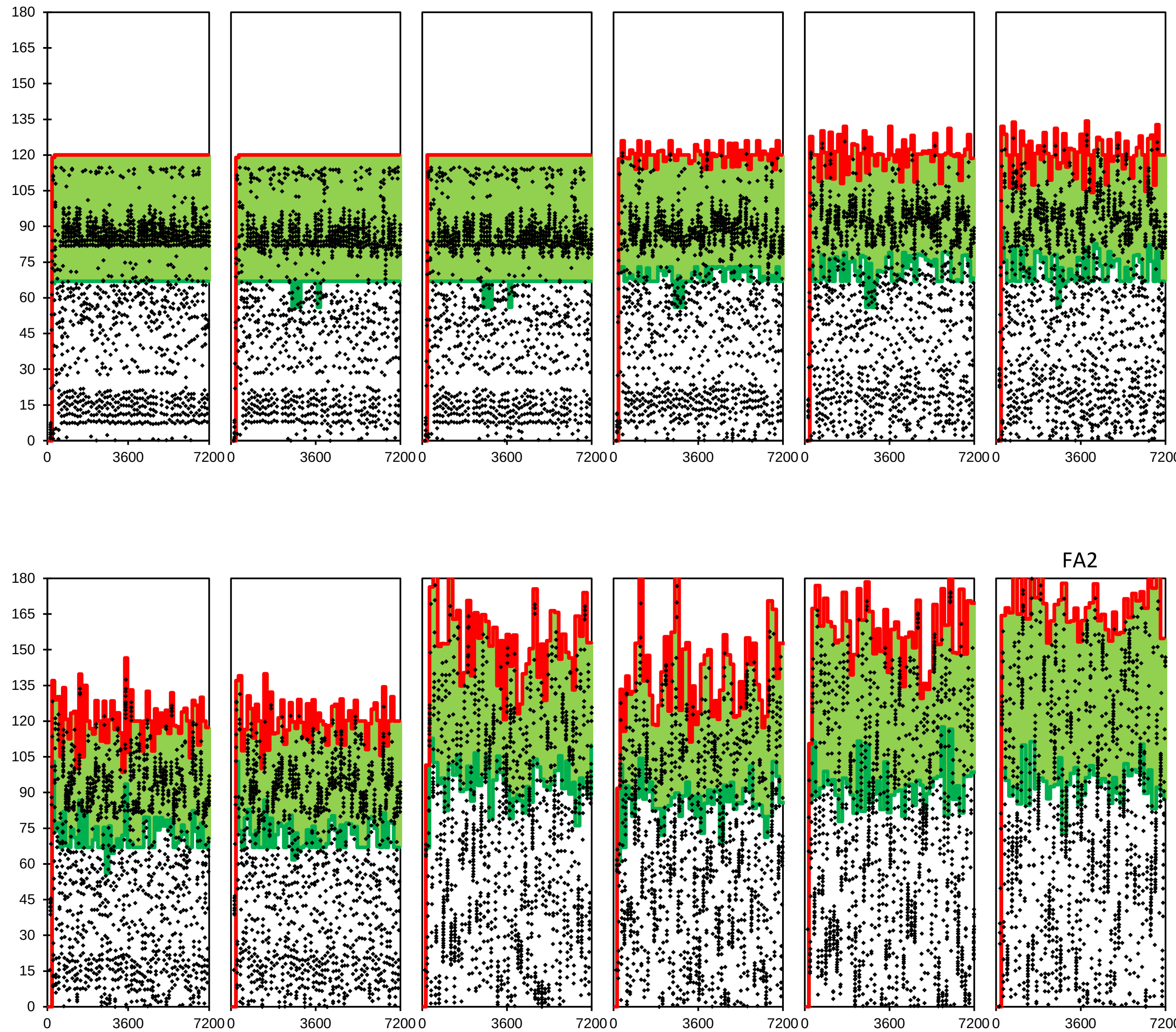

Figure 3. Example coordination diagrams (Westbound movement at Lincoln Way and Grand)

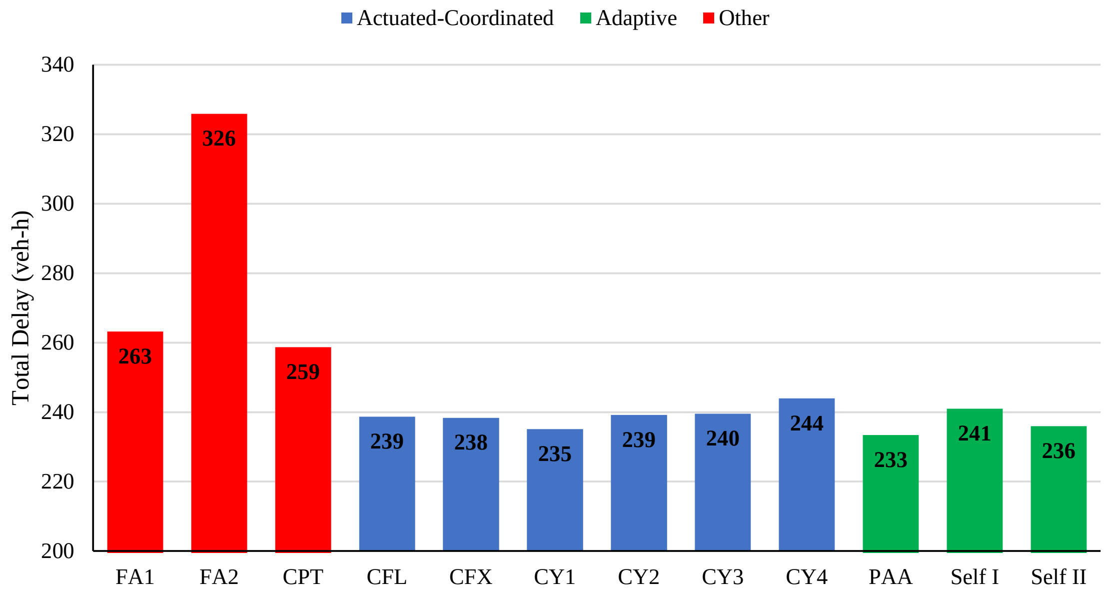

Figure 4. Total delay by control type

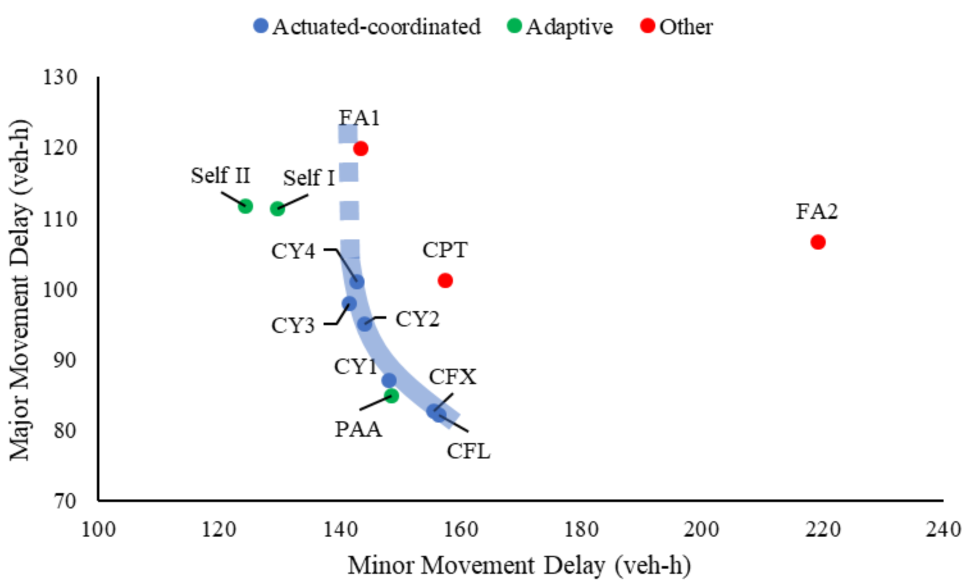

Figure 5. Pareto front found in a chart of major versus minor movement delay

4. CONCLUSION

This paper explored the application of the Pareto Front concept to traffic signal control, with an emphasis on the evaluation of adaptive control methods relative to conventional control methods. The concept was tested in a simulation of a signalized corridor with nine intersections and two crossing streets. An array of control methods was tested, including nine conventional and three adaptive control methods. Most of the conventional methods were selected to identify different potential locations on the Pareto front when considering objectives of minimizing delay for major or minor movements. Two methods were included to demonstrate that sub-optimal options reside within the feasible region. The adaptive control methods exhibited performance that was slightly more optimal than the methods residing on the Pareto front. The results demonstrate that a methodology for locating the Pareto front in a signal control system may provide a beneficial perspective for evaluating new control methods, especially in simulation studies where new methods are usually first tested. Future work would seek to improve this methodology by examining whether it works well for a variety of traffic scenarios and other sets of objectives.

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