Paper No. 013286

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Transportation Research Board
80th Annual Meeting
January 7-11, 2001
Washington, D.C.

Paper No. 01-3286

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For Presentation and Publication
80th Annual Meeting
Transportation Research Board
January 2001
Washington, D.C.

November 15, 2000

No WORDS: 3,268
Plus 4 Figures and 1 Table (1250)
TOTAL: 4418

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ABSTRACT

Signal timing optimization of existing systems, signal coordination, and advanced traffic control, all have been proposed as components of ITS measures. However, quoted benefits are based on limited data. This paper presents the findings from the analysis of the impacts of signal control improvements based on a large number of real-world implemented projects. Three major types of signal control improvements were analyzed: optimization of existing signal timing plans, signal coordination, and traffic responsive control. The study quantified both the level of , and the factors affecting the improvements in traffic performance

1. INTRODUCTION

Efficient traffic signal control has been recognized as an important component of the advanced traffic control and information systems (ATMIS) element of Intelligent Transportation Systems (ITS), currently pursued as a way for improving the efficiency of existing transportation facilities. Synchronizing traffic signals along arterials or in a network, and optimizing the signal settings, result in smoother traffic flows, reducing idling and stopping. This, in turn, reduces fuel use, saves motorists travel time, diminishes wear and tear on vehicles, and cuts vehicular emissions.

Continuous traffic growth and difficulties in building new highway facilities through developed areas will mean that existing arterials and networks controlled by traffic signals will have to carry at least a portion of anticipated traffic increases. Transportation management centers (TMCs) incorporating freeway ramp metering and other access restrictions designed to protect mainline freeway capacity will introduce additional traffic on surface streets. New federal, state and regional programs (e.g., transit priority) also may provide an impetus for greater attention to signal systems, particularly along major arterials.

A number of ITS related publications report the benefits of signal control systems in terms of reductions in travel times, delay, number of stops and fuel consumption (*1,2,3*). However, most of the cited benefits are based on limited data, and do not relate to the geometric, traffic and control characteristics of the specific project areas. Furthermore, reporting different measures of benefits from multiple sources could be misleading (e.g., "reduction in travel time of 8 % and increase in travel speed of 14 %").

In this paper, we analyze the impacts of improving signal control based on the results of actual real-world projects undertaken as part of the California's Fuel Efficient Traffic Signal Management (FETSIM) Program (*4*). We also discuss the effectiveness of traffic responsive control based on real-world data from the Los Angeles Advanced Traffic Control and Surveillance System (ATSAC) (*5*). We hope that this ongoing work will contribute to a better understanding of the level of, and the factors affecting the expected benefits from improved signal control systems.

Sections 2 and 3 of the paper briefly describe the FETSIM and Los Angeles ATSAC databases used in the analysis of benefits from signal timing optimization, signal coordination and traffic responsive control. Section 4 presents the findings from the analysis of the results. The last section summarizes the key study findings along with recommendations for future work.

2. THE FETSIM PROGRAM—OVERVIEW AND DATABASE

The California's FETSIM Program provided to local agencies financial assistance, training and technical support to optimize the timing of their signal systems over n eleven year period (1983-1993). The Program's primary objective was to reduce stops, delays and fuel consumption through the implementation of more effective signal timing plans. A second objective of the Program was to enhance the capability of local traffic engineers to continue to manage their traffic signals effectively.

A total of 163 local agencies (154 cities and nine counties) participated in the FETSIM program in 334 projects retiming 12,245 signals at a total cost of $16.1 million, or $1,091 per signal. Most of the participants were located in the urbanized San Francisco Bay Area, Los Angeles, San Diego and Orange counties. Thirty-nine projects (536 signalized intersections) also involved replacement of signal controllers, and installation of time-based coordination units to allow previously uncoordinated signals to function as a coordinated system.

Figure 1 shows the key characteristics of the FETSIM project areas. About 73 percent of the systems retimed were single or crossing arterials with a total of 5,364 (44 percent) traffic signals. The average size of arterial systems retimed was 15 signals, and the average size of grid systems was 51 signals. Signal systems' hardware ranged from electromechanical fixed-time controllers to state-of the art central control systems. Fifty-six percent of all the signals were traffic actuated; on single arterial systems 90 percent of the signals had actuated controllers. Most of the pretimed signals were located in the downtown areas of the larger cities. Coordination was mostly provided through hardwire interconnect, with phone lines used in about 5 percent of the signal systems. A significant proportion of the arterial systems are using on-street masters with time-based coordination units.

Optimal signal timing plans were developed using the TRANSYT-7F computer model (*6,7*). TRANSYT was selected because it is publicly available, capable of handling complicated networks, it has been thoroughly field-tested, and it directly produces estimates of delay, stops, and fuel consumption to determine the savings from signal timing optimization.

TRANSYT includes a macroscopic (platoon-based) deterministic model which simulates existing conditions along signalized arterials or grid systems and estimates degree of saturation, travel time, delay, stops, fuel consumption, queue lengths and other performance measures. Use of TRANSYT requires coding the network into links and nodes, and data on turning movements, saturation flows, speeds, and existing signal settings. The model outputs are compared to observed conditions (normally travel times, delays and queue lengths) and the input data and model parameters are adjusted until the model reasonably represents actual operations. TRANSYT then is used to optimize the timing plans (cycle length, splits and offsets) for each time period (normally am, midday and pm peak periods). The alternative plans are evaluated using the stop, delay, and fuel consumption estimates, and the best ones are implemented in the field. The estimation of benefits is based on the model estimates and "before" and "after" field studies.

Training was provided to the local agencies' staff and their consultants through a series of workshops designed to provide step-by-step guidance through lectures and laboratories in the application of the TRANSYT model. Follow-up technical support and review of interim products was also provided to ensure the successful completion of each project.

3. LOS ANGELES ATSAC CIC CONTROL

A real-time traffic control system can use vehicle detectors to collect cyclic traffic counts, which can be used to determine the best signal timings for each cycle. This allows the green times to never be more than one cycle behind the actual traffic conditions, which seems superior to optimal fixed-time control that is based on average hourly volumes. The Critical Intersection control (CIC) is designed so that at a critical intersection, the green demand for each phase is calculated every cycle, while the cycle length and offsets remain fixed to maintain coordination. The CIC control software implemented in the LADOT ATSAC control system allocates the green times in each cycle to the conflicting movements based on volume and occupancy data from detectors all the conflicting critical approaches.

The effectiveness of the CIC control strategy in improving the operational performance at signalized intersections was evaluated at seven real-life intersections, part of the ATSAC control system. Real time detector data were obtained from the ATSAC *Detector Analysis Report*. The corresponding CIC timing splits was obtained from the ATSAC *Real Time Split Monitor Report*. The existing fixed-time time-of-day signal settings were obtained from the existing timing charts. These timing plans have all been recently optimized, so any benefits obtained from CIC due to obsolete fixed-time timing plans are expected to be minimal.

4. ANALYSIS OF THE PROJECT RESULTS

4.1 Benefits from Signal Timing Optimization

Based on TRANSYT model estimates, signal timing optimization of coordinated signal systems produced an average of 7.7 percent drop in travel time, 13.8 percent reduction in delays, 12.5 percent reduction in stops and 7.8 percent decline in fuel use. The values represent the average percentage changes for an eleven-hour weekday, unless specific volume adjustment factors were available from the individual cities. These average improvements are based on 163 projects (49 percent) of the total 334 projects in the FETSIM program and 6701 signalized intersections (55 percent of the total retimed.)

Because the TRANSYT model often overestimates savings at intersection approaches when oversaturation occurs, such links were eliminated (based on the model outputs when available) in calculating the average improvements for each project. This may result in a slight underestimation of the total benefits.

Field studies were performed "before" and "after" the implementation of the optimized timing plans to measure the improvements in traffic flow using floating cars.. The average measured savings for coordinated systems were 7.4 percent reduction in travel time, 16.5 percent reduction in delay and 17 percent reduction in stops. These measured benefits are generally in agreement with the TRANSYT model estimates. The difference between TRANSYT and field results is due to the selected survey routes, number of test runs and definitional differences. Most of the cities that did field tests selected survey routes that followed the major arterials of their systems (or the through traffic for systems involving a single arterial.) They usually covered less than half of the total number of street segments (but more than half of the total vehicle-miles traveled) and in general undersampled turning movements..

Figure 2 shows the distribution of % savings in delay and stops. The level of improvements in traffic performance varied considerably among the retiming projects. Some agencies found little or no improvement, and other reported gains of over 30 percent in delay and stops, and 20 percent reduction in fuel consumption. The analysis of the results indicates that the following factors account for most of the variability in the estimated savings:

> **Quality of Existing Timing Plans:** Of the agencies that obtained little benefits, the majority reported that the existing timings were quite good, so the lack of substantial improvement appears to represent efficient operations "before" the signal timing optimization. Larger cities (Los Angeles, San Francisco) obtained somewhat lower percent savings in performance than smaller cities, which probably is due to better timings in the "before" case.
>
> **Network Configuration:** Larger savings were realized on arterials than on grid networks (by an average of about 5 percent in stops and delay). Small improvements were obtained on simple systems (e.g., equally spaced arterials, one-way streets) that had been well timed with other methods (e.g., time-space diagrams.) Also, several systems that had to be coordinated with other adjacent systems did not gain significant benefits because the timing optimization, particularly the cycle length, was constrained to maintain compatibility with the other systems.
>
> **Traffic Patterns:** Larger savings were obtained on high volume systems with predominant through movements. The improvements were small on systems with low volumes and no predominant platoons (e.g., networks with minimal activity outside the peak periods). Also, marginal savings were found on systems with several congested intersections that are in need for capacity improvements.
>
> **Signal Equipment:** Higher benefits were obtained on systems with actuated signals and flexibility in choosing control parameters/options. The improvements on those systems

depend on the understanding of the signal operations and implementation of the TRANSYT optimal settings into the actuated controllers. Equipment limitations (e.g., single dial controllers that permit only one cycle length and green times to be implemented) reduced the level of possible improvements in a number of projects. On the average the benefits on arterials and grid networks with actuated signals were higher by 5-7 percent than the improvements on pretimed signal systems

Figure 3 shows the relationship between savings in travel time and savings in fuel consumption based on the TRANSYT model results. The results indicate that the benefits in fuel use are generally linearly related to the travel time improvements. Thus, the travel time savings estimates could be used as a proxy for determining the improvements in fuel use, if direct estimates of fuel consumption savings are not available. It should be noted, however, that fuel savings are generally higher that travel time savings (by 2 to 5 percent on the average) on arterial systems with closely spaced intersections.

4.2 Benefits from Signal Coordination

The benefits from signal coordination were assessed based on field studies "before" and "after" using floating cars. The analysis of the field measurements from 76 projects (that obtained statistically significant results) show that on the average the travel time was reduced by 11.4 percent, delay was cut by 24.9 percent and stops were decreased by 27 percent. Figure 4 shows the cumulative distribution of the percentage improvements in traffic performance. Approximately, 65 percent of the projects had benefits within the 10 to 35 percent range.

Signal coordination produces major benefits for the through traffic for signal spacing up to 0.5 mile and moderate to heavy traffic volumes (volume/capacity > 0.6). The variation in intersection spacing, proportion of turning traffic, and signal phasing are the main factors that influence the expected benefits between sites under the same volumes and average intersection spacing.

Signal coordination generally worsened the traffic performance on the systems' entry links. The increase in delay on those links depends on the difference between the system cycle length and the optimal cycle length for isolated signal operation, the traffic volume on the approach, and the type of control (pretimed or actuated).

The trade-offs between the improvements on the through traffic and the disbenefits on the entry links of a network, should be carefully assessed before assuming that signal coordination is the preferred strategy. The evaluation should consider both the relative percent change and the absolute differences in the delays and stops.

4.3 Benefits from Traffic Responsive --CIC Control

Table 2 shows the impacts of the control strategy in improving the operational performance at seven real-life intersections, part of the ATSAC control system in Los Angeles. The results indicate that CIC control generally improves intersection performance (delay and LOS) over the optimized fixed-time timing plans.

The effectiveness of CIC depends on the intersection geometric, traffic and control characteristics. Significant reductions were obtained on two-phase intersections with exclusive turning lanes, and/or unbalanced critical volumes. The flexibility of adjusting the green splits with CIC becomes limited on multiphase signals (because of the constraints of minimum phase times), and on intersections with more than one critical lane group during the same period of the day (i.e., all conflicting critical lane groups are close to saturation). Under such situations, CIC split adjustments are usually small and any improvements to one-approach results in significant disbenefits to other approaches.

5. DISCUSSION

Signal timing optimization of existing systems, signal coordination, and advanced traffic control, all have been proposed as components of ITS measures. However, quoted benefits are based on limited data. This paper presents the findings from the analysis of the impacts of signal control improvements based on a large number of real-world implemented projects. Three major types of signal control improvements were analyzed: optimization of existing signal timing plans, signal coordination, and traffic responsive control. The study quantified both the level of , and the factors affecting the improvements in traffic performance

Based on results from over 120 implemented projects, signal timing optimization of coordinated signal systems produced an average of 7.7 percent drop in travel time, 13.8 percent reduction in delays, 12.5 percent reduction in stops and 7.8 percent decline in fuel use for a typical weekday.
The major factors affecting the benefits include quality of existing timing plans, network configuration, traffic patterns, and signal equipment (pretimed vs. traffic actuated)

The average improvements from signal coordination include average reductions 11.4 percent in travel time, 24.9 percent in delay, and 27 percent in the number of stops. Signal coordination produces major benefits for the through traffic for signal spacing up to 0.5 mile and moderate to heavy traffic volumes (volume/capacity > 0.6). The variation in intersection spacing, proportion of turning traffic, and signal phasing are the main factors that influence the expected benefits between sites under the same volumes and average intersection spacing. Signal coordination worsens the performance on entry (uncoordinated) movements in the system and the trade-offs should be carefully assessed.

The evaluation of CIC control indicates that traffic responsive control generally improves intersection performance (delay and LOS) over the optimized fixed-time timing plans. The effectiveness of CIC depends on the intersection geometric, traffic and control characteristics. Significant reductions were obtained on two-phase intersections with exclusive turning lanes, and/or unbalanced critical volumes.

The level of percent improvement in performance does not necessarily translate into large amount of gallons of fuel and hours of travel time benefits. For example, modest improvements on heavily traveled systems would generate much larger benefits than high percent reductions in traffic impacts on small systems with light traffic volumes. Overall, however, improved signal control systems are highly cost-effective. The estimated average benefit/cost ratios in the FETSIM project areas is 17:1 using the methodology on benefits and costs recommended by AASHTO (*8)*. Annual fuel savings alone outweigh the total program costs by more than 5:1.

Advanced signal control produced several additional benefits; those include a substantial decrease in air pollutant emissions on project areas. Improvements in traffic safety which result from smoother traffic flow. Bus operators and their riders benefit from better signal timing, since operating costs are reduced and average speeds improve. The value of these benefits depends on the "base case" conditions in each project area. Air pollution reductions, for example, are more important in non-attainment areas than in cities with clean air; bus savings accrue when bus routes are affected. Nevertheless, these additional benefits could be significant at the local level and should be kept in mind in assessing the results from signal control improvements.

There is a need to carefully quantify the benefits of other traffic signal systems and strategies that have been developed to respond to on-line changes in traffic volumes and adjust to current changes in traffic demand. Examples of such systems include SCOOT and SCATS plus recently proposed adaptive systems (RT-TRACS). The estimation of the expected benefits should be based on carefully undertaken field studies and simulation modeling.

ACKNOWLEDGMENTS

The paper was based on the work in support of the FETSIM Program performed by the Institute of Transportation Studies, UC Berkeley under a series of contracts to the California Department of Transportation (Caltrans) and the California Energy Commission (CEC). Richard Macaluso of Caltrans Headquarters provided guidance and support. The collaborative work with the Los Angeles Department of Transportation was sponsored by the California PATH program at UC Berkeley.

The contents of this paper reflect the views of the authors who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views of or policy of the California Department of Transportation. This paper does not constitute a standard, specification or regulation.

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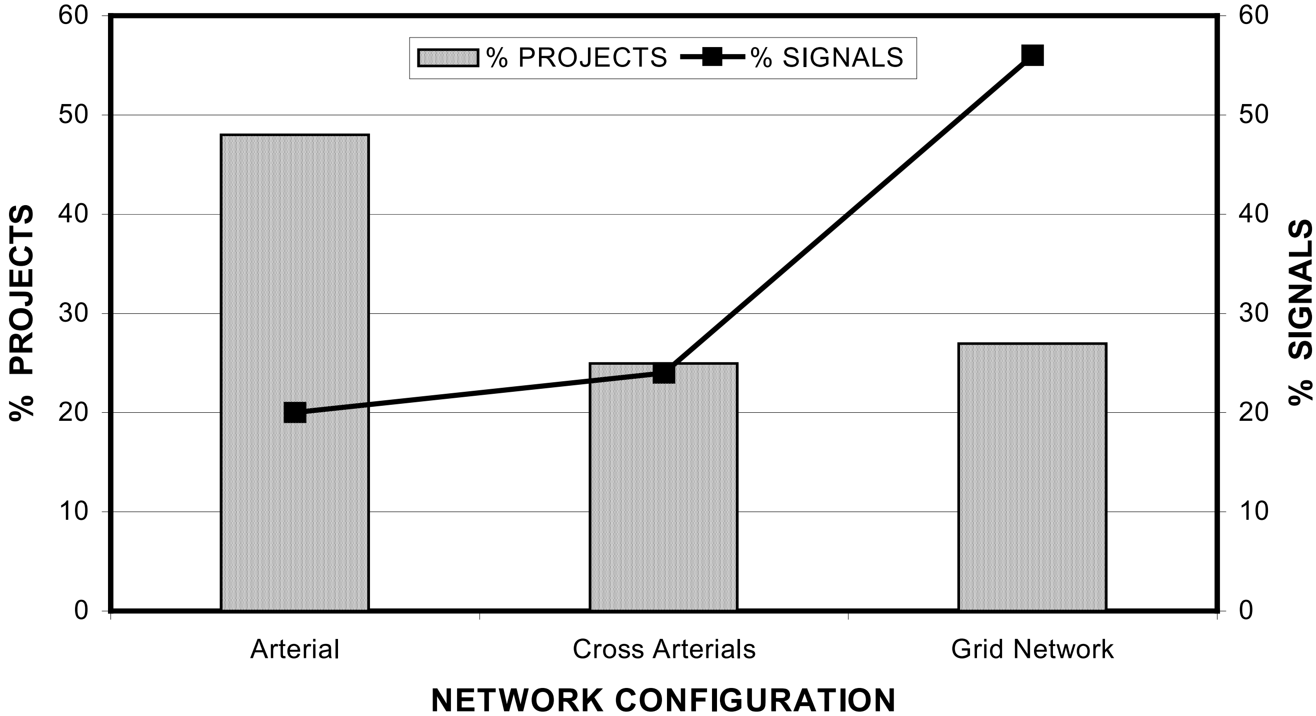
LIST OF FIGURES

FIGURE 1. The FETSIM Database



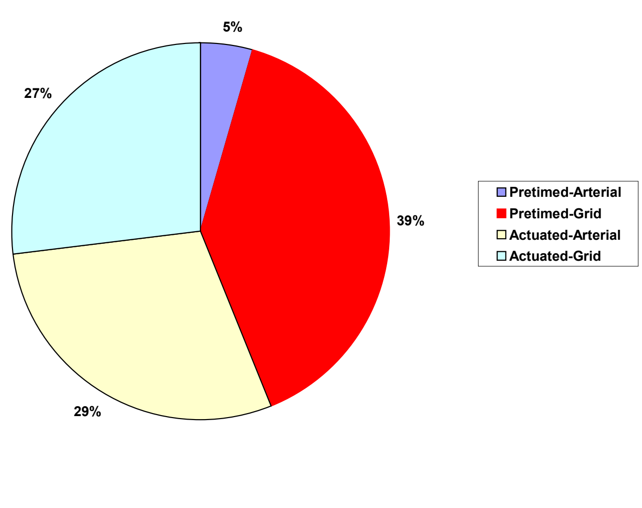


FIGURE 2. Distribution of Benefits—Signal Timing Optimization

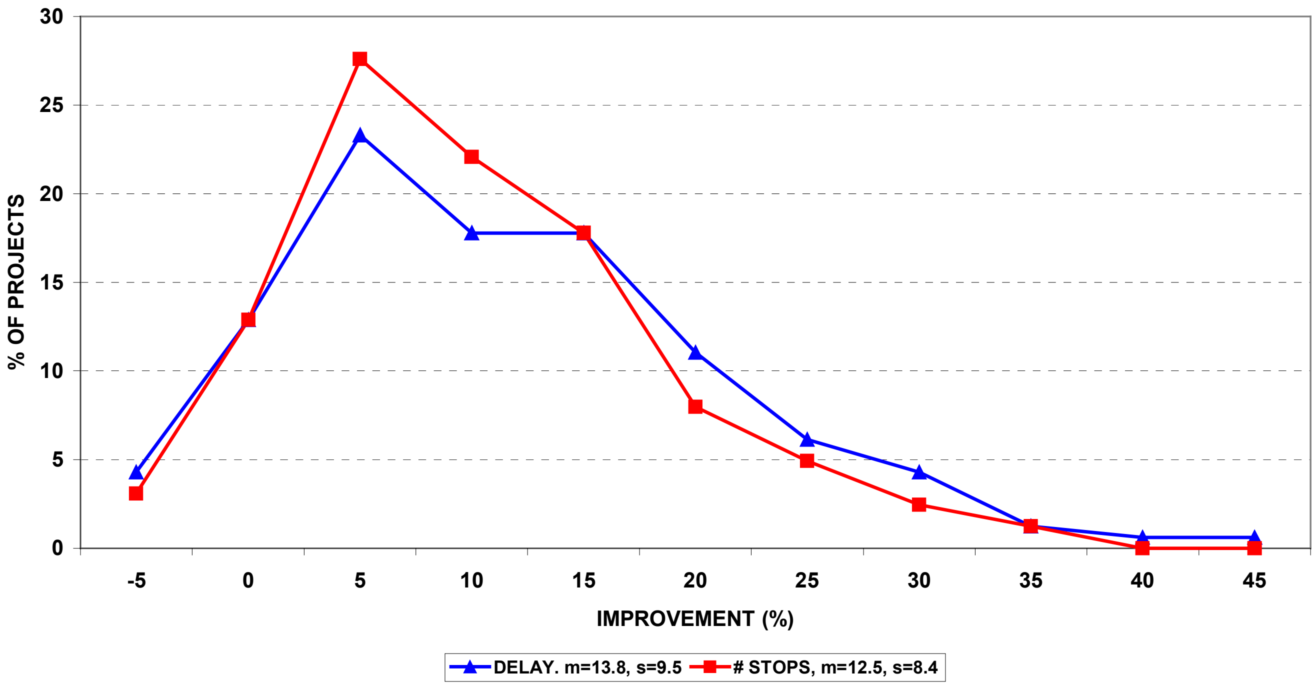


FIGURE 3. Fuel Consumption vs. Travel Time Savings

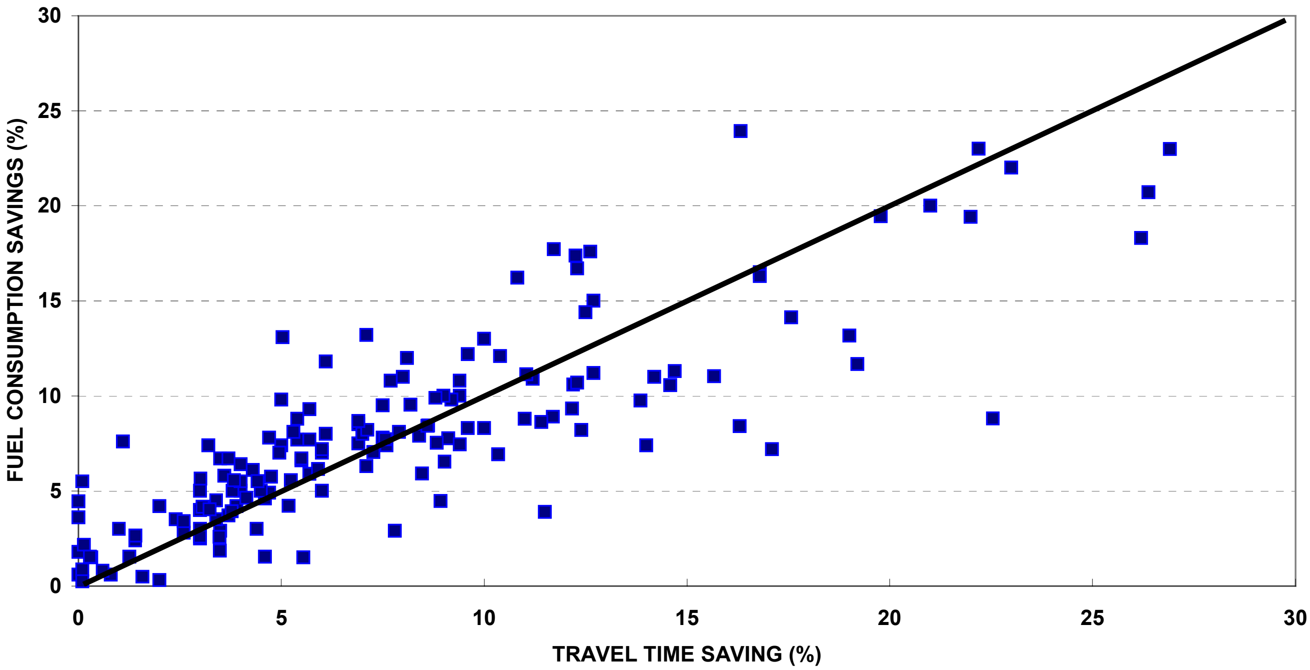


FIGURE 4. Distribution of Benefits—Signal Coordination

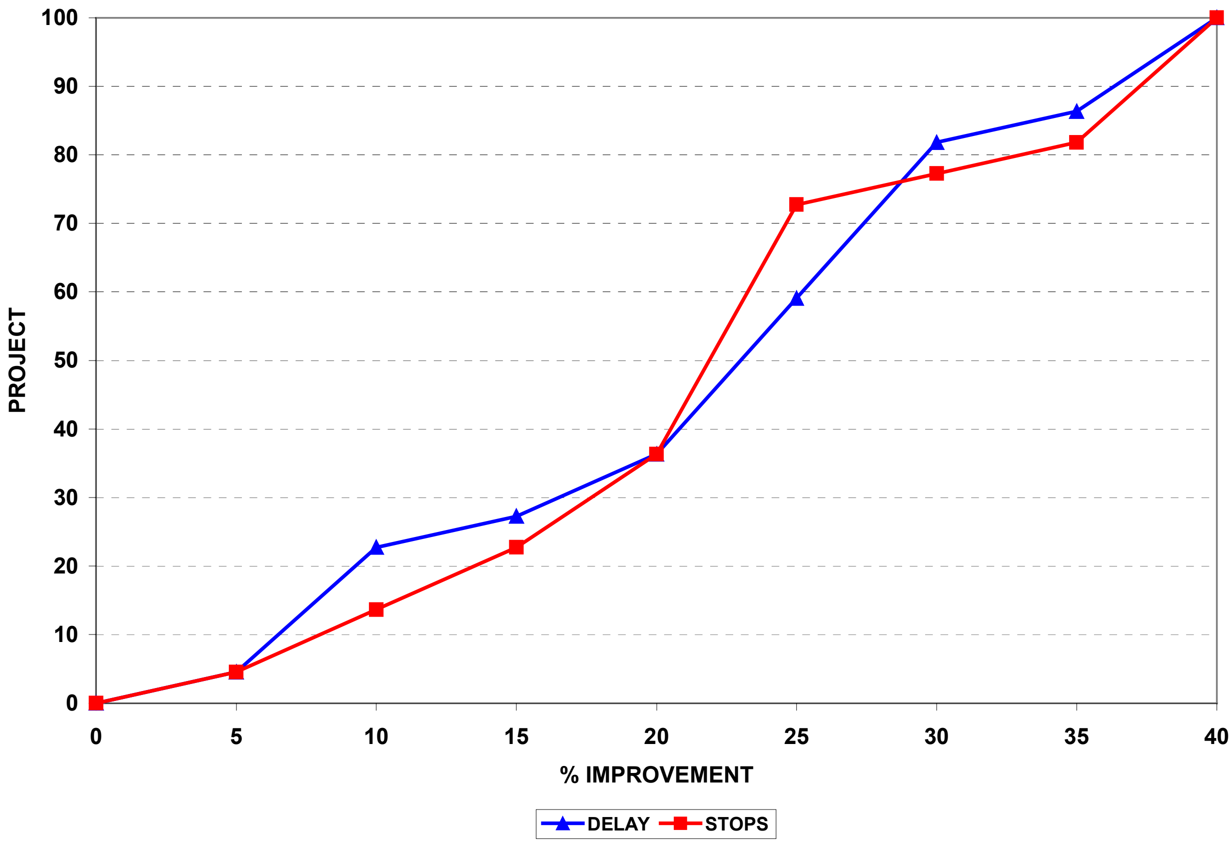


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TABLE 1. Impacts of CIC Control

Intersection	(v/c) Reduction (%)	Delay Reduction (%)	LOS (% of cycles) Improved	Same	Worsened
Melrose/Fairfax	8.3	13.2	41	59	0
Olympic/Sepulveda	1.8	4.0	0	100	0
National/Overland	0.0	3.1	0	100	0
6th Street:**					
-Broadway	14.0	10.8	53	42	5
-Spring	-4.7	4.9	0	100	0
'-Main	13.5	17.7	55	40	5
-Los Angeles	12.5*	16.2*	27	73	0

**Data for 10 cycles were not used-invalid volumes*