

Operation of Closed Loop Signal Systems

Darcy Bullock
Associate Professor
School of Civil Engineering
Purdue University

Quantifying the Impact of Traffic Responsive Signal Systems

Eric Nelson
Research Assistant,
Purdue University
USA

Darcy Bullock
Associate Professor
Purdue University
USA

ABSTRACT

In recent years, there have been two parallel research paths for developing advanced traffic signal systems. Real-time traffic adaptive system research, supported largely by the United States Department of Transportation (USDOT) and smaller scale closed loop systems developed primarily by traffic signal system vendors. Simulation models have been developed for evaluating USDOT supported projects, and those results have been reported in the literature. However, even though there are several hundred traffic responsive systems deployed, most of the vendor developed closed loop signal systems have not undergone such rigorous evaluations. This is an area of significant concern because deployment of efficient closed loop signal systems is one of the most cost effective Intelligent Transportation System (ITS) investment that a small urban area can make. In order to make good deployment decisions, rational quantitative evaluation procedures are required to evaluate feasible options.

This paper reports on an evaluation procedure developed for quantifying the impact of traffic responsive operation in modern closed loop signal systems. The paper reviews the concepts of "hardware-in-the-loop simulation," explains the application of this simulation procedure to evaluate closed loop systems, and reports on the observed results. The same procedure can be applied to systems developed outside the United States such as the SCOOT and SCATS systems.

INTRODUCTION

Over the past several years, there has been extensive public and private sector activity in the development of traffic responsive and traffic adaptive control procedures. Internationally, systems like SCAT and SCOOT have seen broad application. In the United States, traffic signal vendors have implemented many traffic responsive features in their traffic signal systems. The United States Department of Transportation has also sponsored an aggressive program of research and field deployment of new traffic adaptive algorithms and cities throughout the world continue to deploy a variety of traffic responsive and traffic adaptive algorithms.

The common feature of all of these systems is that they use some type of vehicle detection and change the display of signal indications according to some prescribed logic that is designed to optimise certain system Measures of Effectiveness (MOEs). However, virtually all of the signal systems in commercial production implement their control logic on unique computing platforms. Furthermore, the algorithms are usually considered proprietary and are generally not available to the traffic engineering community for conducting a rigorous scientific evaluation.

Computing power has recently reached the point where microscopic network simulations of an entire network are now feasible. Several microscopic simulation packages are available that model vehicle movement and basic coordinated-actuated signal logic. However, because of the proprietary nature of the various traffic responsive and traffic adaptive algorithms, there is no generally available package that can be used for either quantitatively evaluating the performance of alternative algorithms, or to serve as a design tool for "tuning" system parameters prior to deployment.

As a result, the only studies agencies have available to assist in their design and decision-making process are vague "before-after" studies conducted with probe vehicles or system detectors. Many of these studies use the old system with out dated timings as the "before" case so it is unclear if the benefits are simply associated with the new timings, or the new traffic responsive or traffic adaptive system. Furthermore, because of the natural stochastic variation of traffic, and huge costs associated with systematically collecting system performance data, few if any of the studies present rigorous statistical comparisons.

This paper summarises the development of hardware-in-the-loop simulation procedures, discusses procedures for tabulating quantitative data, and concludes by discussing how this type of evaluation equipment can be used to upgrade the traffic engineering profession's design, analysis and operation of modern traffic signal systems.

HARDWARE-IN-THE-LOOP SIMULATION CONCEPT

To address this systematic evaluation problem, there are several efforts in the United States to integrate microscopic simulation programs with traffic signal control hardware to study the performance of vendor specific algorithms [Bullock 98, Bullock 99, Engelbrecht 99, Husch 99, Koonce 99, Nelson 00]. Figure 1 depicts the typical hardware-in-the-loop simulation architecture. There are three basic components:

- A controller interface device (CID). This device provides the interface from the traffic controller to the computer running a microscopic simulation. The interface is typically based upon the discrete voltage levels used to drive the load switches and monitor loop detectors.
- A software interface module to provide the linkage between the CID and a microscopic simulation program. Since the software runs under Windows, this software interface is typically implemented in a dynamic link library (DLL) software module.
- A microscopic simulation engine that is responsible for moving vehicles through a defined network and tabulating MOEs. The simulation engine does not implement any control logic. Instead, external signal state indications (RED, AMBER, and GREEN) are obtained from actual traffic signal control equipment which is connected to the simulation computer. The traffic signal control equipment is "stimulated" by detector calls placed by the simulation program via the CID.

Since all control equipment ultimately controls load switches and monitors detector calls, this discrete signal interface is the lowest common denominator interface that all controllers must have. Consequently, this architecture provides a common evaluation framework that a variety of signal control systems can be connected to for conducting scientifically rigorous and reproducible evaluations. Although not shown in Figure 1, a typical simulation would have each controller connected to either a closed loop master or a central control system which would run an algorithm such as SCOOT, SCATS, UTCS, or other emerging real-time control procedures.

Figure 2 shows a photograph of both control equipment and CID units, which would be used to evaluate a three intersection system. Controllers 1 and 3 are housed in a traditional cabinet, where all their discrete signals are terminated on the cabinet back panel. The corresponding CIDs are then interfaced to these cabinets using a simple alligator clip harness. Controller 2 is interfaced to the CIDs using a direct connect cable. The direct connect procedure has the obvious advantage of using less equipment. However, this direct connect configuration is not as flexible because custom cables must be constructed for each type of controller. Also, when using this environment for educational purposes, students do not gain the experience and insight associated with locating the proper cabinet terminals and connecting the appropriate alligator clip.

Other procedures using a defined communication protocol [Husch 99] can also be used for interfacing control equipment with simulation software. These procedures are typically based upon the NEMA TS 2 Type 1 interface [NEMA 98] and use much smaller and cheaper CIDs. However, such communication based procedures typically restrict the diversity of control equipment that can be included in the simulation. For example, in the United States neither the 170 nor the 2070 currently support the NEMA TS 2 Type 1 interface.

Finally, it is important to point out that this evaluation procedure should not be confused with traditional switch box based testers that allow engineers to verify that desired controller features are operating as expected. Using just switch box based testers, it would be impossible to simulate all the discrete detector actuations associated with a small arterial, much less corridors with more signals or high volumes. Furthermore, without a simulation program tabulating MOEs, it would be impossible to conduct quantitative studies of an algorithm or systems performance.

APPLICATION OF MICROSCOPIC SIMULATION TECHNOLOGY

In order to make the evaluation system, shown schematically in Figure 1, useful for evaluating alternative control algorithms, it is essential that the CIDs be interfaced with a robust microscopic simulation program. The microscopic simulation is responsible for "moving" all vehicles through a user defined network following prescribed vehicle kinematics. This movement is performed by recalculating the position each vehicle at a deterministic frequency, typically between 1 and 10 Hz. During each recalculation, vehicle accelerations in the simulation are updated in response to signal indications obtained from the CID and adjacent vehicles in the network. Also during each simulation interval, appropriate detector states are updated via the CID. In order to ensure the occupancy calculated by the traffic controllers closely models field conditions, the duration of the presence detectors is inversely proportional to the velocity of the vehicle actuating the detector.

Since the microscopic simulation tabulates vehicle positions over the entire simulation period, the resulting data obtained from the microscopic simulation program tends to be extremely detailed. In fact, it is so detailed that some aggregation must be performed in order to understand the impact of alternative control procedures. It is essential that the data analysis (and aggregation) procedure balance overall system performance MOE's with details that help analysts identify troublesome areas and time periods of a network or arterial. In order for this data to be as useful as possible, it is essential to present the analytical data in a graphical format that is easy to understand [Shoup 99].

EXAMPLE DATA FROM ANALYZING TRAFFIC RESPONSIVE OPERATION

To illustrate some of the information that can be obtained from conducting a hardware-in-the-loop simulation, a five intersection arterial (Figure 3) in Indianapolis, IN (USA) was analysed. The analysis was performed with the equipment shown in Figure 2, plus two additional controllers and two additional CIDs not shown in the photograph. The basic phasing for each of the five intersections is shown in Figure 4. Hourly turning movement counts from 6am to 6pm were obtained, and each hourly demand was coded into the network so that a twelve hour period could be accurately simulated. Since microscopic simulation is stochastic in nature, each control scenario analysed was replicated 5 times, for a total simulation time of about 60 hours per control strategy.

Figures 5, 6, and 7 illustrate example data from an analysis conducted using traffic responsive equipment under evaluation for deployment on the five intersection arterial in Indianapolis, IN. Figure 5 depicts a simulation conducted with one set of demand volumes and Figure 6 depicts a simulation conducted with an alternative set of demand volumes. Figure 7 provides insight into the specific location along a Southbound path that is experiencing heavy congestion.

Figures 5 and 6 show more of a "big picture" view comparing plans selected with traditional time-of-day (TOD) schedule vs. plans selected with traffic responsive procedures (TRP). Each bar in the figures depicts the total system delay (veh-min) for a particular one-hour interval. Figure 5 illustrates a case where traffic responsive plan selection performed slightly worse throughout much of the day, but performed much better during the early evening peak hour (2p.m.-4p.m.), because TRP responded to evening peak flows that started earlier than the TOD system was scheduled for. In general, this is the expected performance of a traffic responsive system:

- TRP performance will slightly lag that of a well timed time-of-day system because the traffic responsive system takes additional time to recognise changes in traffic and then transition to appropriate control plans.
- TRP performance will be significantly better than TOD systems if the TRP is properly calibrated to respond to traffic demand that can not be predicted by time-of-day.

The hours 7a.m.-9a.m. illustrate this slight lagging performance. Similarly, the hours 2p.m.-4p.m. illustrate the benefit of TRP recognising that the peak hour has started earlier than expected and then reacting accordingly.

In contrast, Figure 6 illustrates a case where traffic responsive performs significantly worse than the time of day schedule because the traffic responsive algorithm was either too slow or failed altogether to trigger the appropriate timing plans. For example, during the 8a.m.-9a.m. period, the delay with the traffic responsive plan is almost double that selected by the TOD schedule. Similarly, during the 2p.m.-3p.m. period, the delay is about 30% worse with the TRP plan. This degraded TRP performance is an important point to note. Although Figure 5 clearly shows the potential benefits of a well calibrated TRP system, Figure 6 illustrates that if TRP is not well calibrated, the performance of a TRP system can be significantly worse than that of a TOD system.

Although Figures 5 and 6 illustrate the network level performance, they do not provide much insight into where the problems are, so that signal timing improvements can be made. Figure 7 illustrates the average time it takes vehicles to proceed South along the corridor during each of the 12 one hour intervals [Shoup 99]. In general, the cumulative travel times in that direction are on the order of 200 seconds. However, during the morning

peak hour (8am to 9am), the travel time is much larger, on the order of 450 seconds. By inspection, one can see that virtually all the delay is introduced at the first intersection (shown as a square on the X-axis at about 1000ft). An engineer reviewing these plans would then look into causes such as a short main street green or an overflowing left turn as potential causes. In this particular example, the problem was caused by a short left turn phase and the resulting spill back impeded the through movement.

CONCLUSIONS

Although the above example comparisons were very brief, they were intended to illustrate that hardware-in-the-loop evaluation procedures can be used to characterise the operational performance of a signal system during both steady state as well as transition periods. Microscopic simulation programs have been available for many years. However hardware-in-the-loop simulation procedures have only recently become feasible because of a combination of improved computing platforms and the use of a CID to interface traffic signal controllers to the simulation. Using hardware-in-the-loop simulation, scientifically rigorous and reproducible evaluations can now be performed. Such a system has the following application:

1. Using a combination of simulation software and controller interface devices, field equipment can now be evaluated in a shop or laboratory environment under traffic conditions that approximate those that will be experienced in the field. Since the motoring public is not very receptive to online TRP tuning errors (Figure 6), such procedures are particularly important to ensure that a traffic responsive system has no major problems before it is deployed in the street.
2. The quantitative MOEs provided by a Simulation/CID environment provide a mechanism for evaluating alternative control algorithms which can not be simulated. For example, the SCOOT and SCAT algorithms are proprietary and can not be simulated in traditional simulation models. However, the hardware-in-the-loop procedure allows a simulation program to be connected to either system with only a functional description of the algorithms' operation.
3. It is now possible to explore and quantify the impact that the multitude of actuated control, traffic responsive, and traffic adaptive parameters have on system performance without experimenting under live traffic conditions. Many of these features promise to provide significant improvements in operating efficiency. However, without evaluating them in a structured and reproducible environment, it is currently impossible to develop rational design procedures for deploying them.
4. A "Flight Simulator" type experience can be constructed for training personnel new to the profession. Such an environment allows experienced-based learning exercises demonstrating various "what-if" scenarios. This type of system has application to a variety of educational efforts including college engineering curricula, continuing professional engineering education, and training of technicians responsible for daily operation and maintenance of the system.

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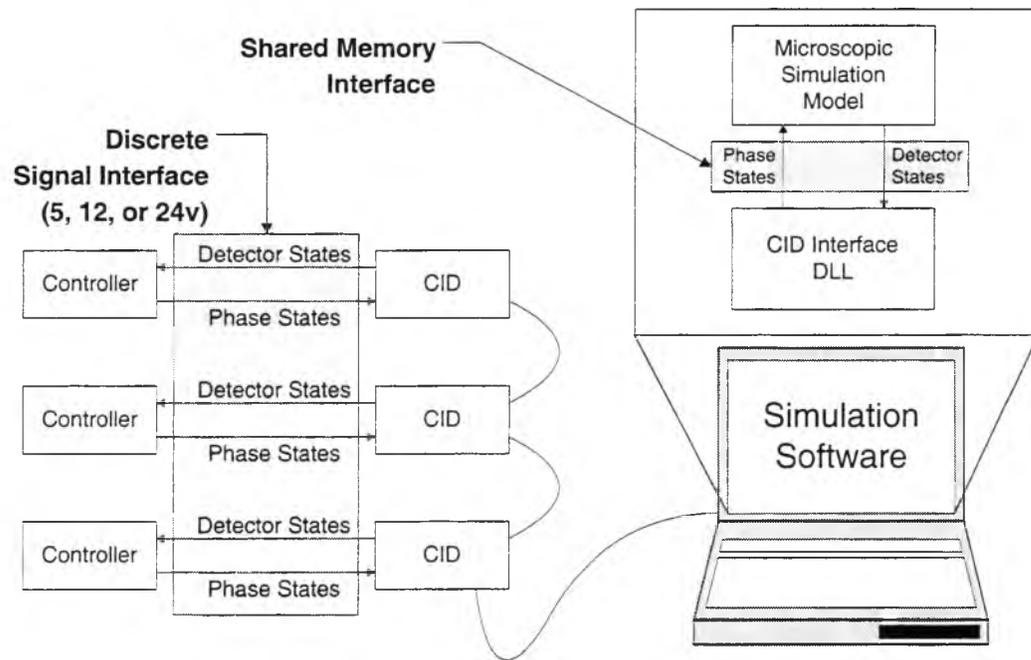


Figure 1: Schematic of Hardware-In-The-Loop Simulation Environment.

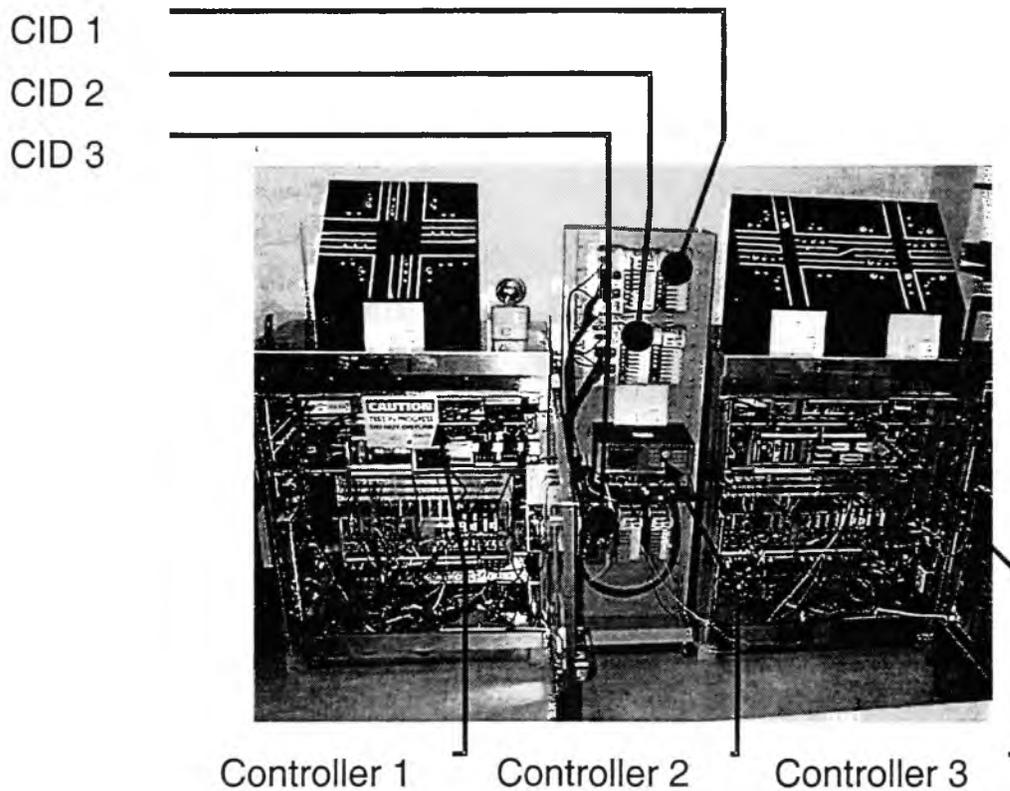
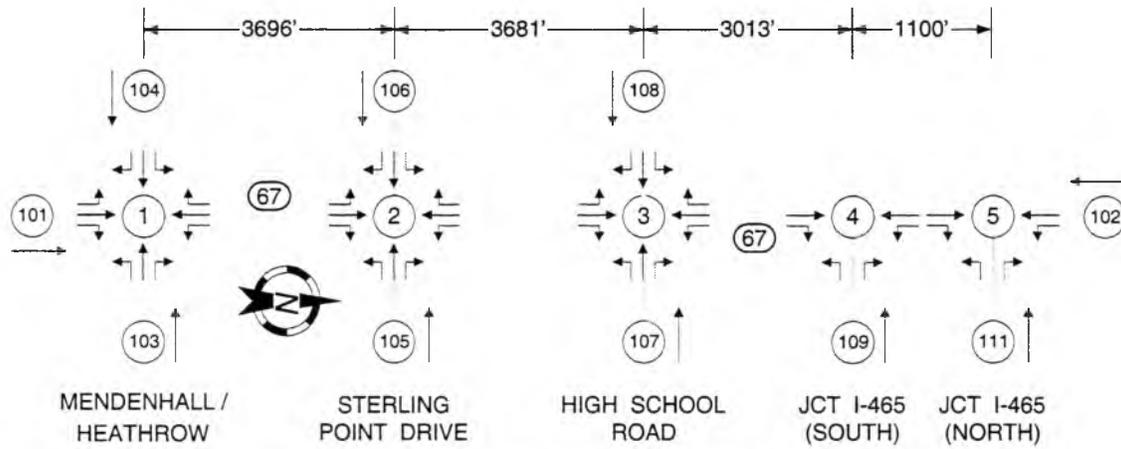


Figure 2: Photograph of Hardware-In-The-Loop Simulation Environment.



SR 67 (KENTUCKY AVE) SYSTEM LAYOUT

Figure 3: Study Network: SR 67 - Mendenhall to JCT I-465 Ramps.

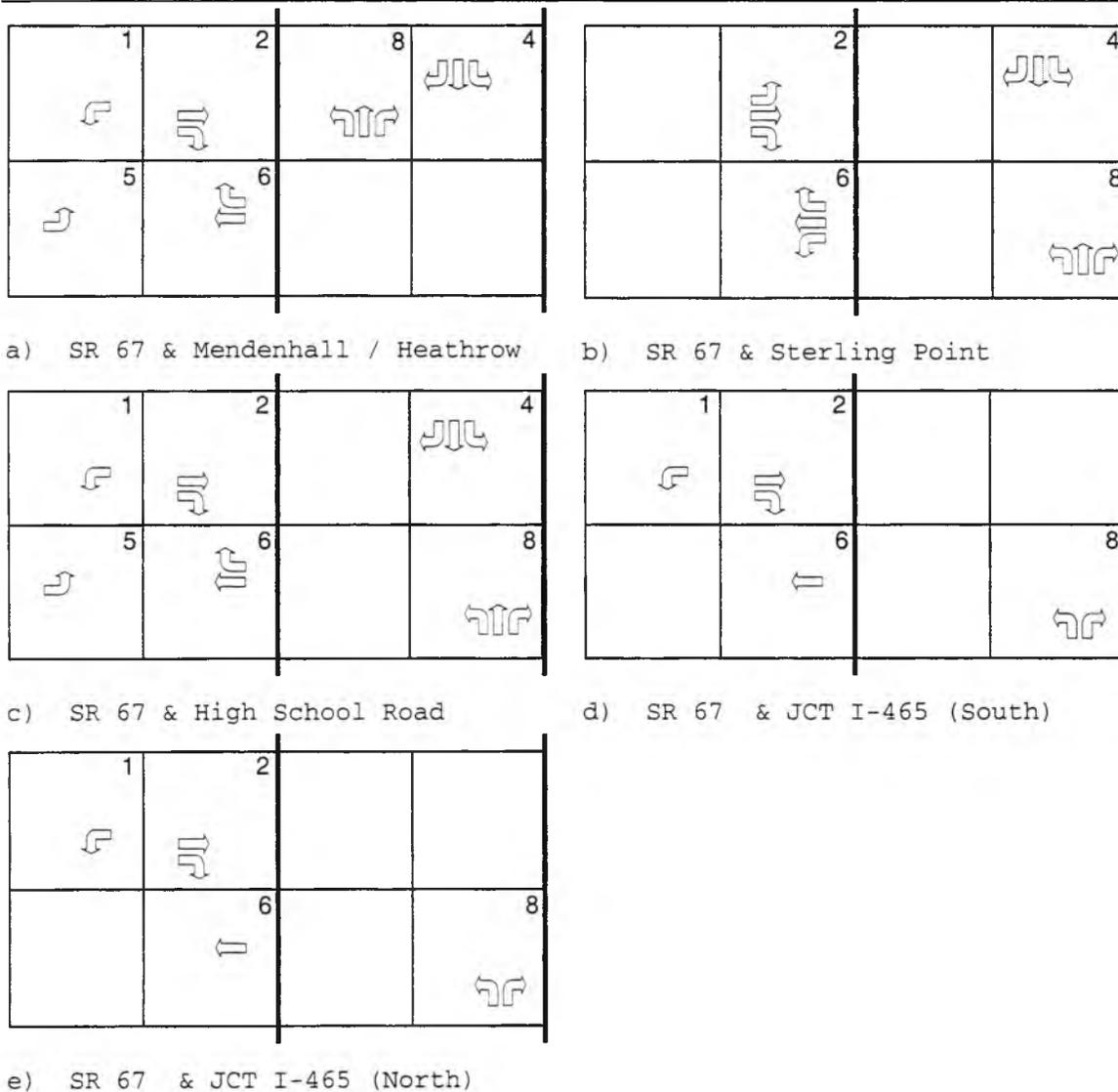


Figure 4: SR 67 (Kentucky) System Ring Structures

TOTAL DELAY TIME (6:00AM TO 6:00PM)

SR 67 - KENTUCKY - (HEATHROW DRIVE TO JCT I-465) - ALL MOVEMENTS

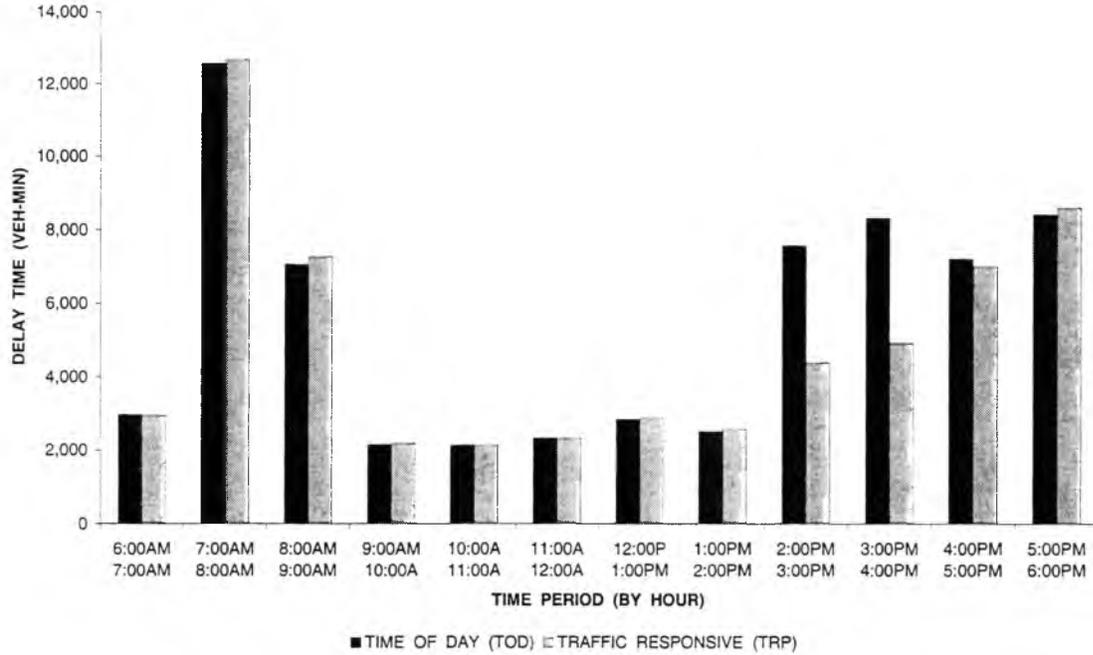


Figure 5: Total Delay Time (Veh-min) - Time of Day Vs Traffic Responsive - Volume Set I

TOTAL DELAY TIME (6:00AM TO 6:00PM)

SR 67 - KENTUCKY - (HEATHROW DRIVE TO JCT I-465) - ALL MOVEMENTS

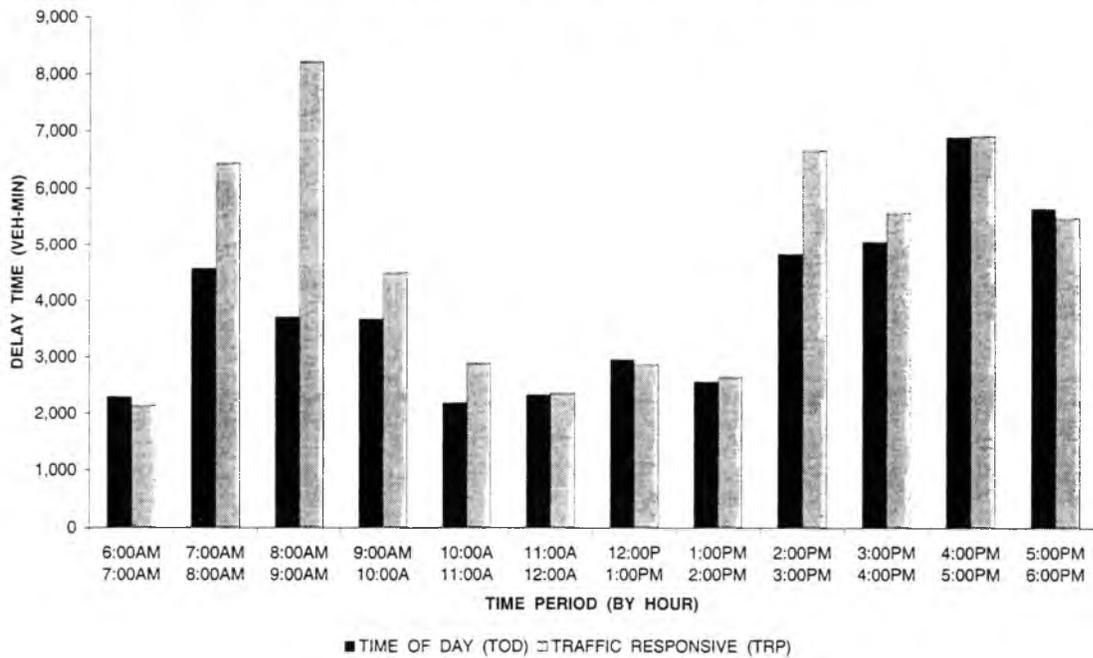


Figure 6: Total Delay Time (Veh-min) - Time of Day (2) Vs Traffic Responsive - Volume Set II

CUMULATIVE TRAVEL TIME (6:00AM TO 6:00PM)

SOUTHBOUND SR 67 - KENTUCKY - (HEATHROW DRIVE TO JCT I-465) - THRU VEHICLES

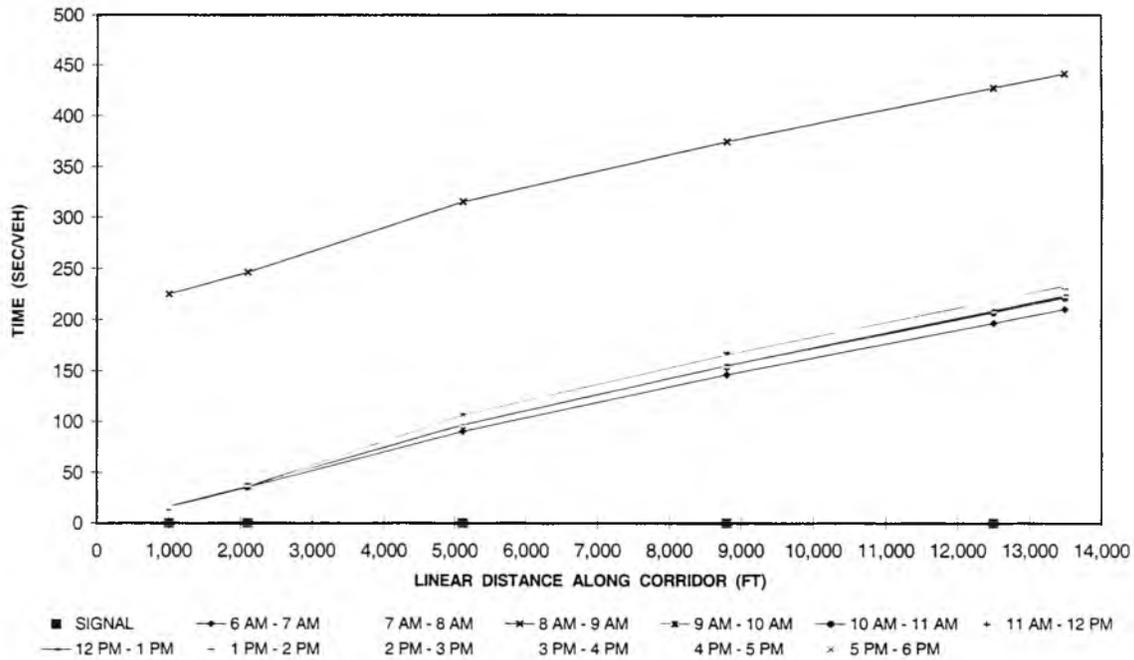


Figure 7: Southbound Travel Time by Time Period using Traffic Responsive - Volume Set II

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