Evaluation of the Quality of Signal Progression by Delay Distributions

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The quality of service provided by signalized intersections can be expressed in a number of ways. The volume-to-capacity ratio, the probability of discharge, the load factor, the average delay, the number of stops, the length of queues, or composite measures such as level of service or cyclic flow profiles are frequently used. Among these criteria, the number of stops and the average delay have a special importance for coordinated systems because they are directly perceived by drivers. As a result, they greatly affect public acceptance of the system design. "Delay" is not a simple or exact term. It is defined as the difference between the actual travel time and the unimpeded travel time through a roadway section upstream of (and sometimes including) a signalized intersection. Driver expectations and behavior, speed distributions, and the arbitrary nature of the distance reference are some of the factors influencing the delay. As a result, its measured values are difficult to duplicate. Nevertheless, delay not only remains the most important signal performance criterion but can also be used as an indicator of the quality of signal coordination. The basic idea is simple: when the vehicular progression through a traffic signal is good, most vehicles will encounter no delay. On the other hand, if most platooned vehicles are stopped and delayed, the coordination of signals is suspect. This idea has been employed in a survey system developed at the University of Alberta. Portable field equipment and subsequent computer programs assist in the evaluation of signal coordination by using delays at individual intersections along a coordinated route. The survey method is based on a re-creation of a time-space diagram for a signalized intersection approach lane. The spatial reference extends from an arbitrary point upstream of signal queues to the stopline. The difference between the actual and unimpeded travel times determines individual vehicle delays. Individual vehicle information is summarized in the form of delay distributions and cyclic flow profiles. This paper describes the survey and employs practical examples to illustrate its use.

The quality of signal progression is one of the major determinants of delay magnitude. Naturally, this statement applies only to situations where traffic volumes are below capacity, since oversaturation is characterized by growing queues and, consequently, the stopping of all platoons.

TRB's *Highway Capacity Manual* (*1*) identifies five different arrival types for intersection approaches. They are characterized by flow patterns at the approach (platooning or random) and by their relationship to green or red signal intervals. Because it is difficult to quantify arrival type precisely, the manual recommends the use of an indicator in the form of a platoon ratio:

$$R_p = \frac{PVG}{PTG}$$

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where *PVG* is the percentage of all vehicles arriving during the green interval and *PTG* is the green-to-cycle time ratio expressed as a percentage. Various arrival types can then be identified by their platoon ratios. For example, the most favorable arrival condition—in which most, if not all, vehicles arrive during the green interval—is characterized by a platoon ratio in excess of 1.5. On the other hand, a platoon ratio between 0 and 0.5 is typical of an approach on which most vehicles arrive during the red interval, with 0 indicating that no vehicles arrived during green. Arrival types are then linked to progression adjustment factors, which are used to adjust the value of delay (determined from a formula).

In the *Canadian Capacity Guide for Signalized Intersections* (*2*), only individual intersections are considered; consequently, no adjustments to the delay formula are used. Instead, the guide recommends that the whole route or network operation be examined after a local intersection is designed or analyzed. Such an examination could include cyclic flow profiles (*3*) or other tools to identify arrival and discharge patterns and relationships. For instance, the city of Edmonton evaluates signal control schemes prior to their implementation using a modified version of RCOORD (*4*) for route analysis and TRANSYT (*5*) for networks.

No simple field test exists for the "as-is" coordination of traffic signals. In the past, the evaluation and adjustment of implemented route or network progression schemes have relied on brief observations, floating car surveys, or driver complaints. All of these methods, however, have practical drawbacks. Observations that have not been quantified are unreliable and require review by an experienced engineer to be meaningful. Similarly, although complaints may be valid and may provide the initial impetus for an examination of the quality of coordination, they do not form an adequate basis for engineering analysis. Moreover, since even the best coordination schemes are a result of tradeoffs among conflicting objectives, some complaints can always be expected. Floating car surveys are time consuming, expensive, and previously have had statistically questionable results.

THE DELAY PRINCIPLE

The objective of this research was to develop a practical system for evaluating signal coordination at a series of intersections. It appeared that delay could be employed to achieve this objective.

Individual vehicles arriving during a signal cycle encounter different durations of delay. The three most important factors are the time when they arrive relative to the beginning of the green interval, the rate of their arrival, and the rate of their discharge (see Figure 1).

In the situation illustrated in Figure 1A, which features low arrival rate and high discharge rate (saturation flow), the main factor determining the delay of individual vehicles is the time of arrival. Figure 1B is similar but shows a very low saturation flow, which causes delays to vehicles that could proceed unimpeded in Figure 1A. Figure 1C features a high arrival rate, which also forces delays on vehicles that arrive during the green interval. The latter two cases illustrate the need to supplement platoon ratios with additional information.

A survey system involving the interaction of arrival rate, discharge rate, and signal timing can be employed to determine individual delays. These delays, which depend on the progression of groups of vehicles through a signal cycle, can then be used as indicators of the quality of signal coordination.

In an ideal coordination case, all vehicles would arrive during the green interval and the flow rate of the platoon would not exceed the saturation flow. As a result, no vehicle would encounter a delay (see Figure 2A). The probability distribution of individual delays would be simple, with all vehicles falling into the minimum or zero delay class (see Figure 2B).

If, on the other hand, the arrival pattern remained unchanged but the signal operation were reversed (in other words, the red signal were in operation instead of the green signal), all vehicles would suffer from delays (see Figures 2C and 2D).

The distributions of delay shown in Figure 3 represent more realistic situations. Figure 3A shows what can be expected at signal approaches that provide excellent progression. In this example, most vehicles (the main platoon) pass through without delay. A secondary platoon of "on-turning" vehicles (those that turn into the coordinated route from side streets in a random fashion) experience a range of delay durations, as evidenced by the wide distribution. Figures 3B and 3C show a deterioration of the progression: fewer vehicles experience zero delays and more vehicles encounter increasing delays. Figure 3D represents an intersection approach in which the main platoon is apparently stopped during the red signal and the secondary flow proceeds unimpeded during green.

Since most of the delays in Figure 3 are experienced by vehicles that are stopped, the number of stops was considered to be a major concern.

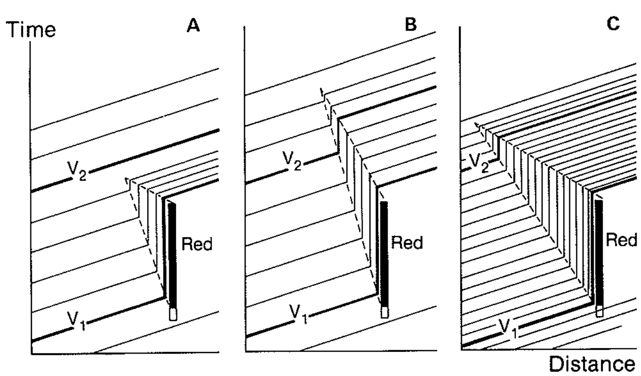
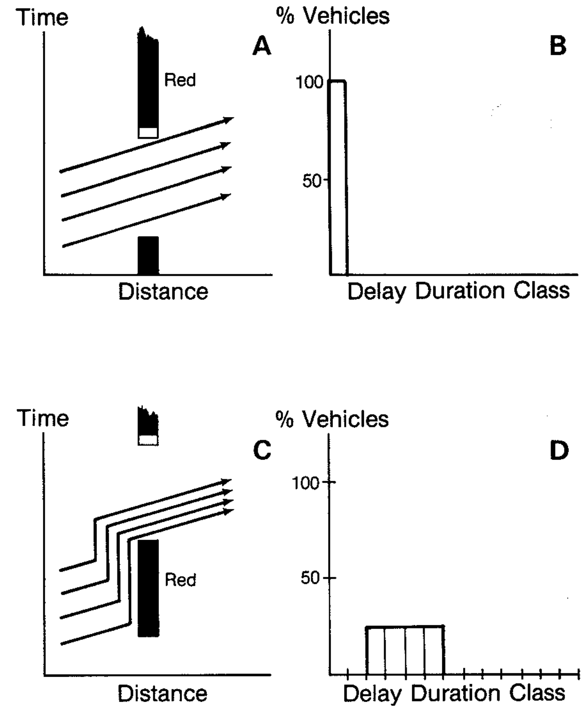


FIGURE 1 Examples of the influence of arrival rate and saturation flow on delay: A, low arrival rate/high saturation flow = short average delay; B, low arrival rate/low saturation flow = long average delay; C, high arrival rate/high saturation flow = long average delay.



NOTE: In Example B, all vehicles fall into the "no-delay" class. Example D has no vehicles in the "no-delay" class since all vehicles suffer some delay.

FIGURE 2 Examples of the influence of arrival pattern on delay: A, arrivals during green interval only; B, the corresponding delay distribution; C, arrivals during red interval; D, corresponding delay distribution.

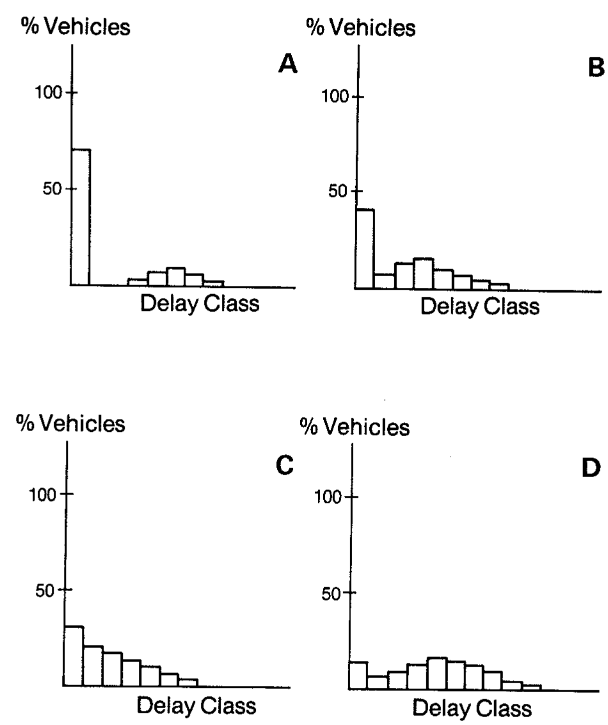


FIGURE 3 Examples of delay probability distributions for four signal progression conditions: A, excellent; B, good; C, fair; D, poor.

As a result of these considerations, delay distributions on individual intersection approaches or approach lanes were the main tool used in this research to assess the quality of signal coordination.

It should be noted that this form of investigation deals with the problem of coordination strictly on an individual intersection basis. As a result, the quality of the whole route or network can be judged only by an examination of all approaches. A single approach with a poor delay distribution may not signify bad design. Good coordination designs frequently sacrifice some approaches to achieve a global benefit of short delays or a minimum number of stops.

SURVEY METHOD

The survey system used in this research is shown in Figure 4. At an intersection approach lane, a reference distance is identified that extends beyond the reach of usual queues. This distance is defined by the stopline (B) and a prominent point upstream (A).

The survey consists of recording the following three time series:

1. The passage of vehicles over point A;
2. The discharge of vehicles across stopline B; and
3. The beginning and end of the green interval.

Information is gathered manually on a classification counter that has been modified with additional keypads. The data is subsequently transferred to a microcomputer. Manual data entry by two surveyors has proven to be a fast and sufficiently accurate mode of operation. All vehicles are entered at the times when they pass the reference points. With the exception of the first and last vehicle in the survey, no matching of arrivals and discharges is required. An occasional miss of green interval entries is not critical, even in the event of traffic-actuated phases, since the data manipulation program can detect these omissions.

The survey consists of a set of individual intersection approaches along a route under investigation. A single "typical" lane (which may be difficult to identify) is generally sufficiently representative of arrival conditions. Since the data collection time required for each approach is relatively short, it is not necessary to survey all approaches in one direction simultaneously. It is usually possible to collect data for two intersection approaches within an hour, provided traffic conditions remain reasonably similar. Naturally, cycle times, green intervals, and offsets in fixed time coordinated systems must not be changed during the survey period. Under these conditions, the surveys along one route can employ the same time of day periods for several days.

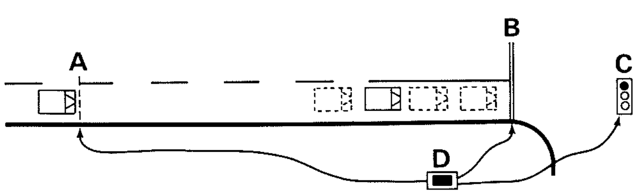


FIGURE 4 A typical layout of the survey system: A, arrival detection point; B, discharge detection point; C, traffic control signal; D, data acquisition device.

SOFTWARE SYSTEM

Data stored on location include a site and survey identification, a vehicle arrival and discharge time series (with a possible classification of vehicles), and a signal interval series. Stored data from all surveys are transferred to a microcomputer. The transfer software provides for both a visual and an automatic inspection on the screen. Illegal data items are stored in a separate file for future reference in the debugging process.

The data are then analyzed on the microcomputer. The main software system performs the following tasks:

- Checking and testing;
- Adjustments to the matching of arrivals and departures;
- Determination of unimpeded travel time;
- Calculation of the delays of individual vehicles;
- Sorting and classification of delays;
- Calculation of aggregate delay statistics, checking, and testing; and
- Sorting and classification of arrivals and departures.

Checking and Testing

The purpose of this software is to match vehicles arriving at the upstream reference point with vehicles discharged at the stopline. Typical errors, such as an arrival/departure imbalance or unusual speed values, are identified and communicated to the user. Negative or extremely high speed values, for example, would indicate a missing vehicle upstream; an unusually low speed may indicate a missing discharge record.

Adjustments to Matching

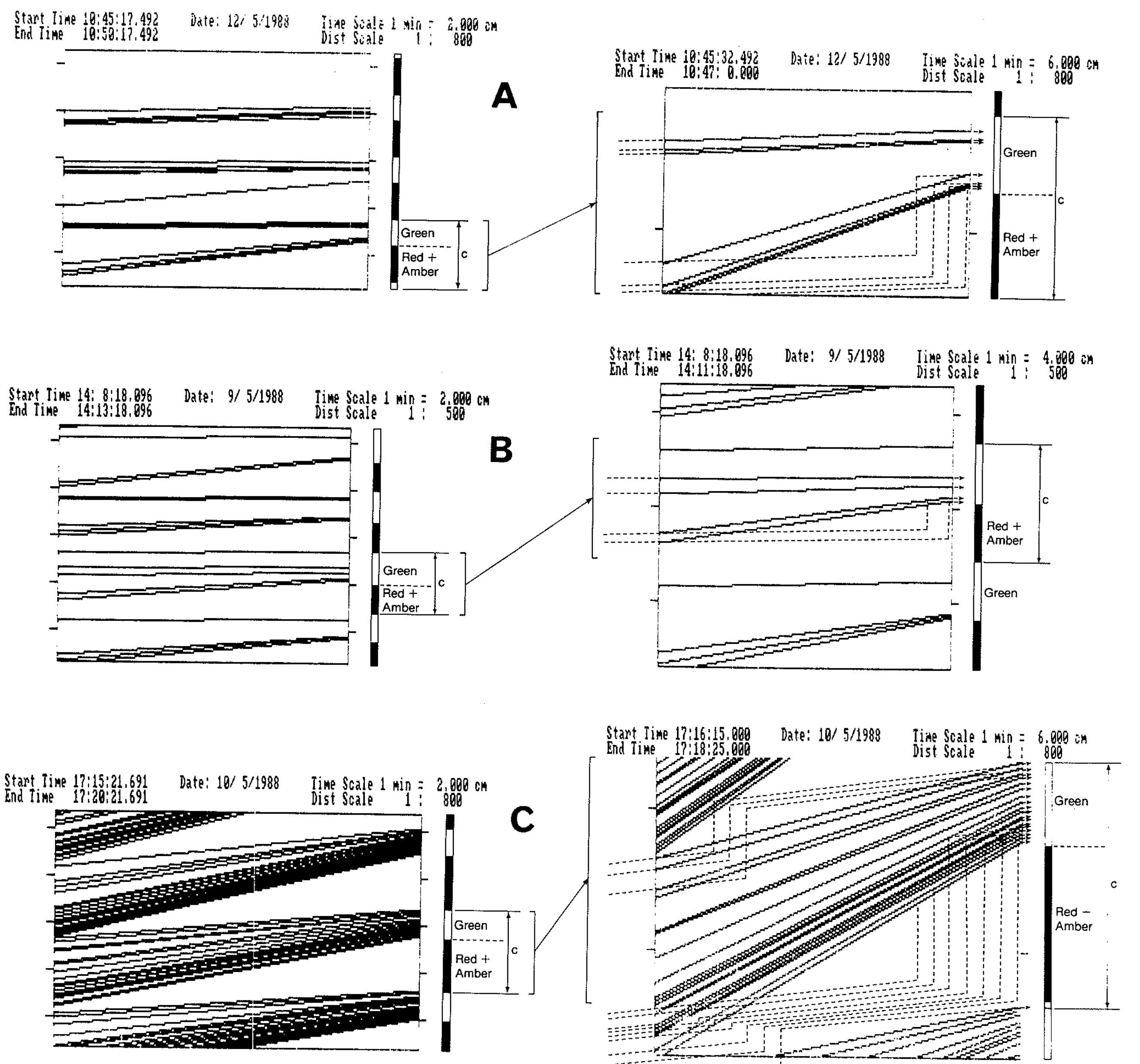
In most cases, some adjustments are necessary to match the arrival/discharge pairs. This task is performed by visually inspecting the simplified time-space diagrams produced by the computer software (see Figure 5). The screen can be scrolled up or down and the scales adjusted to "zoom" on problem areas. Irregularities in the pattern are readily apparent, and erroneous vehicles are deleted. These infrequent corrections do not appear to introduce significant errors to the final delay distribution.

Determination of Unimpeded Travel Time

The time-space display makes it possible to identify those vehicles that proceed through the survey section without delay. The average speed of these vehicles is calculated and can be considered by the user as the unimpeded travel time.

Calculation of Delays

The total travel time of individual vehicles is calculated as the difference between the matched arrival and discharge times. Individual delays are then determined by subtracting the unimpeded travel time from the total travel time. Negative values are possible for vehicles travelling faster than the speed



NOTE: The graphs on the right are "zoom" enlargements of those on the left. They are supplemented by dotted lines showing the usual form of the trajectories.

FIGURE 5 Examples of simplified vehicle trajectories in time-space diagrams: A, low-volume approach; B, medium-volume approach; C, oversaturation.

input by the user. Such vehicles are assumed to have zero delays.

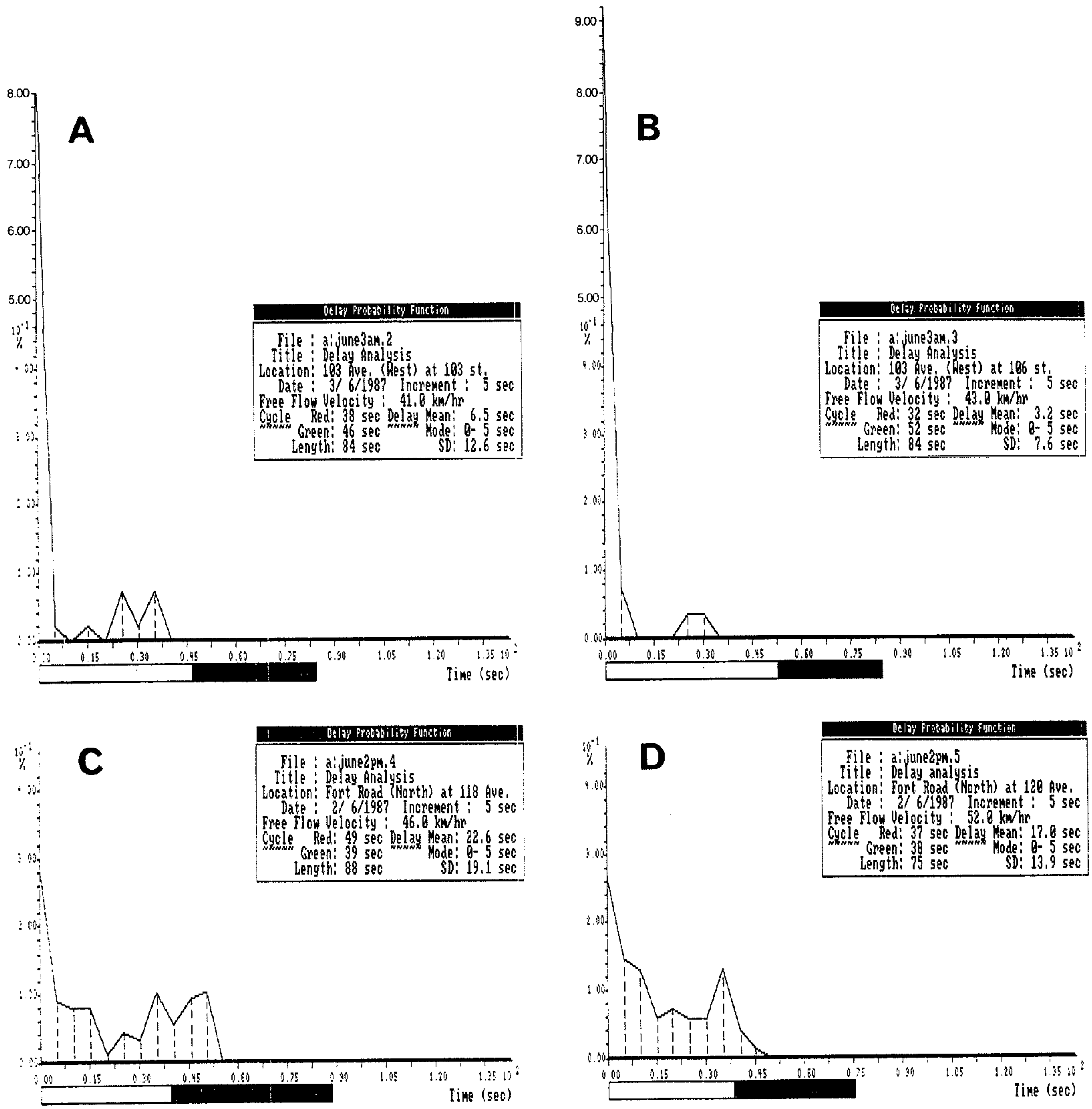
Sorting and Classification of Delays

The user can choose the delay class interval to be used in the determination of delay frequency and delay probability distributions. Intervals of 5 sec are practical in most cases.

Figure 6 shows sample probability distribution diagrams (frequency distribution histograms can also be printed). The first two distribution diagrams illustrate an almost ideal progression at two intersections of a one-way street that has coordinated signals. The second two examples illustrate a very poor signal progression at two consecutive intersections of a major arterial roadway. Only about one-fourth of the vehicles are free-flowing; most experience delays, some of which are considerable. The duration of both major intervals (green and red plus amber) is printed for information, although it is not related to the distribution. The intersections used in these examples operate below capacity since only a few delays exceed the duration of the red interval.

Calculation of Aggregate Delay Statistics

Block inserts in the probability distribution diagrams allow the user to label the survey (by day, location, file/approach,



NOTE: The white and black bars under the diagrams show the length of the green and red intervals as a delay magnitude reference but have no direct relevance to the graphs.

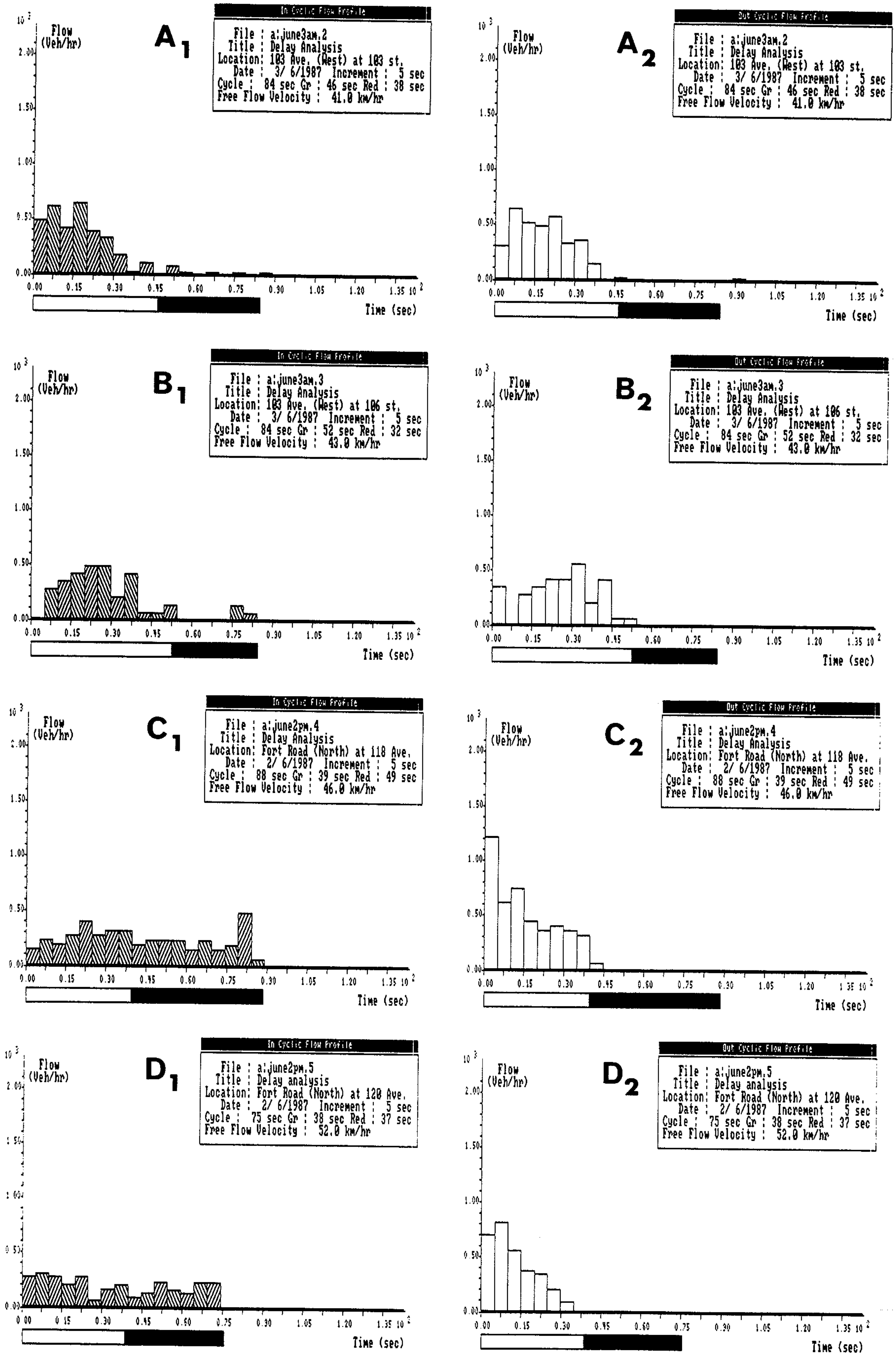
FIGURE 6 Examples of typical delay distributions. A and B—excellent signal coordination; C and D—poor signal progression.

signal timing, and average free flow speed). In addition, the average delay, mode, and standard deviation of the distribution are identified.

The distributions provide a good, relatively condensed illustration of the events in the surveyed lane. Attempts to condense the information further using a combination of average delay, standard deviation, and mode were not successful. Because most of these distributions are bimodal, simple statistical parameters cannot describe them adequately.

Sorting and Classification of Arrivals and Departures

For a detailed analysis, the user can employ a special software routine that organizes the arrivals and departures of individual vehicles into class intervals relative to the beginning of the green interval. Time "slices" of 5 sec are adequate in most cases, although 2-sec slices have been found to be useful for high volume situations.



NOTE: White and black bars below the diagrams relate the arrival or discharge times to the signal cycle.

FIGURE 7 Arrival and discharge cyclic flow diagrams for situations shown in Figure 6: A_1, B_1, C_1, and D_1—arrival patterns; A_2, B_2, C_2, and D_2—discharge patterns.

The arrival and departure information is organized into cyclic flow profiles (*3*), which are familiar from widely used programs such as TRANSYT (*5*). For the delay survey system, cyclic flow profiles for arrivals and departures can be printed either separately or together. These profiles are similar to those used in TRANSYT; however, the delay surveys use a base distance, while most TRANSYT versions queue vehicles directly on the stopline.

Figure 7 shows examples of cyclic flow profiles corresponding to the delay distributions in Figure 6. An examination of the patterns in Figures 7A and 7B illustrates why the progressions in Figures 6A and 6B are so good: virtually all vehicles arrive during the green interval. On the other hand, the arrival pattern along the second route (Figures 6C and 6D) is almost uniform throughout the cycle (Figures 7C and 7D).

The cyclic flow profiles are normalized like the delay probability distributions. The values are given in hourly rates of flow, which eliminate the impact of minor volume fluctuations during different survey periods.

CONCLUSIONS

The system described in this paper provides a practical, effective tool for the evaluation of implemented signal coordination designs. An initial analysis of delay distributions provides a starting point for the assessment. Where more serious problems are detected, cyclic flow profiles can be employed. The surveys are relatively simple and, since the results are presented in a normalized form, comparisons of signal performance at different intersections are easy as long as "typical" lanes can be identified. It is hoped that this system will encourage the use of before-and-after studies for signal coordination. The cities of Edmonton and St. Albert are currently using the system for this purpose.

It appears that a single numerical indicator of the quality of coordinated signal operation—such as the platoon ratio or a mode of the delay distribution—cannot sufficiently describe such a complex issue. Further research is required to supplement the relatively subjective inspection of delay distributions or cyclic flow profiles with more tangible indicators.

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