PRETIMED SIGNAL-CONTROL SYSTEM FOR AN UNDERWATER VEHICULAR TUNNEL

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Previous research has indicated that limiting traffic demand in an underwater vehicular tunnel can produce substantial increases in flow rates and speeds. A pretimed control system consisting of a standard traffic signal was used to meter traffic entering the Baltimore Harbor Tunnel. Four different cycle lengths and splits were tested, and the results were compared to those obtained from the uncontrolled situation. The increase in flow rates and speeds of 3 of the control strategies over those in normal operation showed that even a simple control system is capable of significantly benefiting traffic flow through a tunnel. An evaluation methodology was applied to the control alternatives; both quality of flow and flow rates were considered. Primary emphasis was placed on a methodology requiring a minimum of time and effort in data collection. The operation of the tunnel was observed in its 2 basic states—congested and uncongested. The quality of flow in a tunnel is poorest on the downgrade, better on the level section, and best on the upgrade. The results of this research should help to make pretimed, tunnel-bottleneck control a more practical engineering tool.

•BOTTLENECKS on urban streets and freeways greatly affect the flow of traffic. The rate of flow on a highway can be no higher than the flow at its most critical bottleneck. Many bottlenecks, such as those due to construction, are temporary, and the quality of flow can be restored to an acceptable level in a relatively short period of time. Other restrictions, such as underwater tunnels, are permanent fixtures, and operational improvements must improve the level of service.

It is apparent from a review of the literature that many underwater tunnels in urban areas have insufficient capacity, high accident rates, and frequent vehicle stoppages. The research discussed in this paper was performed to show that these undesirable conditions can be greatly improved with a minimal amount of capital investment and technical skill.

It has been found in past research that, because of the geometric configuration of underwater tunnels, a bottleneck frequently exists near the point where the grade changes from level to an upgrade (1). Because vehicles tend to decelerate when they first start to climb the upgrade, the vehicular concentration increases upstream from this point, and further decreases in speed and flow take place. This effect continues upstream until the entire line is moving slowly. This stop-and-go type of movement not only reduces the flow rate through the bottleneck but also increases output of pollutants, fuel consumption, the probability of a collision, and driver frustration. Furthermore, when the concentration has risen to the point where flow deteriorates, it is very difficult to regain a state of efficient flow and lower concentrations as long as the demand remains high.

It was the purpose of this research to determine whether a pretimed signal-control

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system is capable of significantly increasing both the quality of flow and flow rates through a tunnel faced with this type of grade-induced bottleneck. The northbound lanes of the Baltimore Harbor Tunnel were selected as the study site. As will be shown, pretimed signal control, when properly used, can achieve this goal, and a simple and inexpensive tool will be readily available to the traffic engineer. Previous research has shown that the tunnel proper is the critical link in the Baltimore Harbor Tunnel complex (2).

Although no comprehensive summary of research on restricted facilities could be found, Everall (3) has provided an excellent summary of both past research and the state of the art in traffic surveillance and control, particularly for urban freeways.

METHOD OF STUDY

Site Description

The Baltimore Harbor Tunnel, a section of the Harbor Tunnel Thruway, is a major link in the Northeast Corridor that carries not only intercity traffic but also a significant portion of the commuting traffic in the Baltimore area. Like the thruway, it consists of 2 lanes in each direction. The southbound lanes carry the greater proportion of traffic in the morning peak, and the northbound lanes carry the greater proportion in the evening peak. Lane changing is prohibited throughout the tunnel, and trucks are restricted to the right lane. MAINTAIN 45 signs are posted on the approach and within the tunnel.

The plan and profile views of the tunnel are shown in Figure 1. The major northbound problem is the 4 percent grade change at the beginning of the upgrade. Therefore, the tunnel offers an excellent opportunity to study the effect of grades and the effect of grade-induced bottlenecks on traffic flow.

Data Acquisition System

Vehicle Detector System

The Baltimore Harbor Tunnel now is equipped with an extensive data collection system monitoring the northbound lanes. Seven stations in each lane, consisting of 2 photocell detectors slightly over 13.5 ft (4.1 m) apart, are capable of sensing many desired flow characteristics. Use was made of frequency-division multiplexing and frequency-shift keying concepts in the design of the data-transmission system. The location of the stations can be seen on the tunnel profile in Figure 1. More details on this system are available elsewhere (2).

Quality of Flow Data

Because an improvement is likely to gain public approval if the driver notices it, better ride quality must be a main objective in a bottleneck control system. A 1965 Chevrolet equipped with a Greenshields traffic analyzer was driven in the traffic stream to evaluate the effects of traffic control through the eyes of the driver. Runs were made in the early morning hours to obtain a base free-flow condition in average off-peak situations and during peak hours for each alternative to evaluate the relative effects of each control strategy. Smith and Carter (4) describe the operation of the analyzer in greater detail.

Design of Experiment

Data collection using the system of photocell detectors began in February 1973. Included in the first set of data were peak-period flows (3:30 p.m. to 6:30 p.m.) for a Tuesday, Thursday, and Friday. An additional day of Tuesday data was collected in March. This produced 12 hours of traffic characteristics for the uncontrolled situation.

The next phase was the installation of the traffic metering system. One traffic signal with 12-in. (0.3-m) signal lenses was installed in each of the 2 northbound lanes in November 1973. They are located on the downgrade approaching the tunnel, approximately 1,200 ft (366 m) upstream of the entrance. Signs were placed at various locations upstream of the signal to warn the motorist of the possibility of being stopped. The purpose of the signal was to periodically introduce gaps into the traffic system in a manner similar to that used in studies on New York tunnels (5, 6). It was felt that this would disperse some of the long vehicle platoons that commonly form in the peak periods and cause speeds to decay. These gaps were created by programming a short red time into the signal cycle. To observe the effects on traffic of very restrictive and slightly restrictive control strategies, several different cycle lengths and splits were used (Table 1). The results were compared to the no-control data.

The cycle lengths were initially selected by comparing the probable capacity of the bottleneck with the capacity at the signal for various cycle lengths. The capacity for each cycle length was determined by calculating the theoretical maximum number of time headways that can be contained within 1 green indication at the signal. This was expanded to an hourly volume and compared to the expected hourly volume for the foot of the upgrade. The calculation of the alternative cycle lengths was not overly critical, however, because cycles and splits could be changed easily if, after the first day of control, it became obvious that some other control strategy was needed.

Metering generally was begun between 4:00 and 4:30 p.m. The signal was activated only when traffic was congested from the bottleneck to a distance approximately 1,000 to 1,500 ft (305 to 457 m) upstream of the signal. This meant that speeds were approximately 20 mph (32.2 km/h) as vehicles passed the signal and that the potential for rear-end collisions due to the signal was reduced. After the first 5 days of data collection, it was decided that stopping traffic at the signal for 90 sec to allow the tunnel to be cleared of congested traffic would permit each alternative to seek its own traffic state without outside influence. This was then done by a tunnel officer at the beginning of each data collection period.

The vehicle with the traffic analyzer was driven through the tunnel at the same time that the metering was done. The course started approximately 1,000 ft (305 m) upstream of the signal and was completed at the exit portal of the tunnel. Flow parameters, including elapsed time, distance, and change in velocity, were printed every 5 sec. It was felt that this would produce changes in velocity in small enough time increments to accurately calculate the mean velocity gradient, the parameter used to measure quality of flow.

Because the comparison of alternatives was the primary objective, the same driver was used for all runs. This eliminated any difference in driving techniques. Runs were made in both the right and left lanes. It was usually possible to make 6 runs each day during the data collection period. The resultant data from the detectors and analyzer were then processed and analyzed.

EVALUATION METHODOLOGY FOR ALTERNATIVE CONTROL STRATEGIES

Before a tunnel administrator selects pretimed signal-control strategies, he or she must determine which strategy yields the best results for a given traffic condition. The purpose of the methodology developed in this study was to provide the administrator with procedures to use that will result in a good decision.

Figure 1. Detector locations, plan and profile views of the Baltimore Harbor Tunnel.

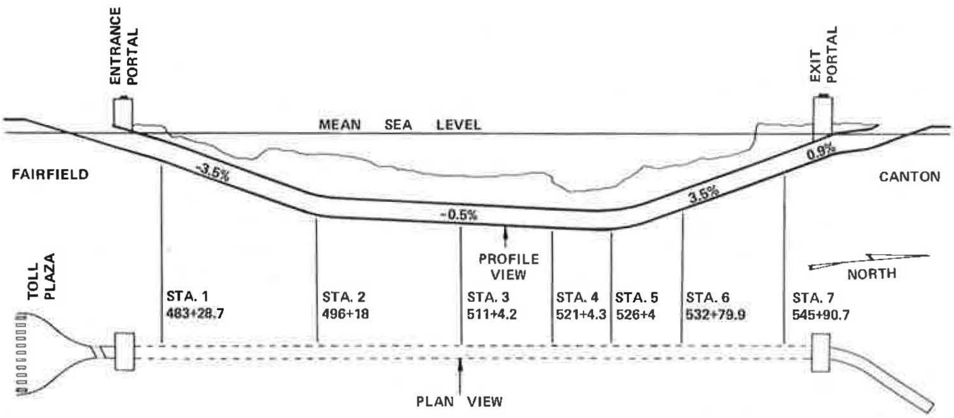
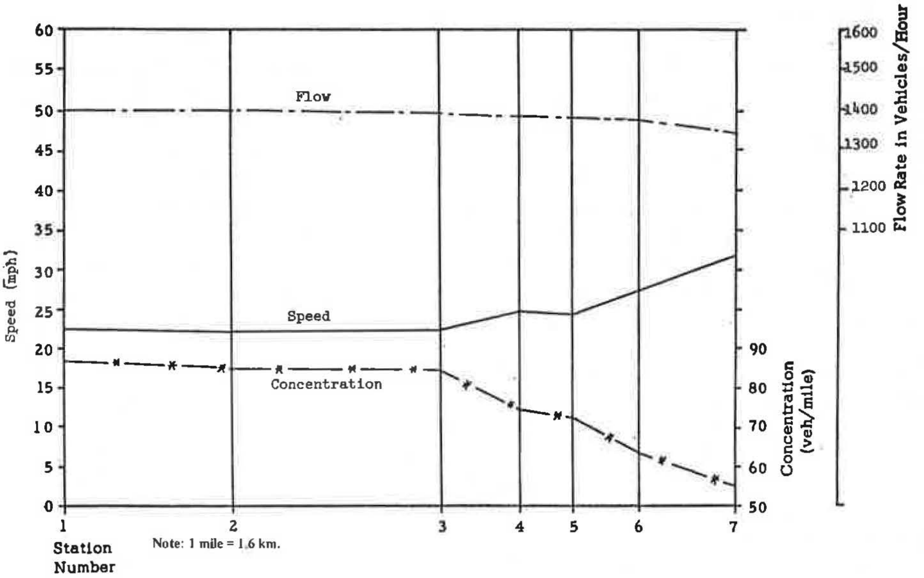


Table 1. Cycle lengths and splits.

Cycle Length (sec)	Green Time (sec)	Red Time (sec)	Amber Time (sec)	Green + Amber Time (percent)
120	109.2	7.2	3.6	94
160	147.2	8.0	4.8	95
180	169.2	7.2	3.6	96
240	225.6	9.6	4.8	96

Figure 2. Traffic-flow profile, Feb. 15, 1973, left lane, uncontrolled.



Note: 1 mile = 1.6 km.

Location of the Bottleneck

This is the first step in the technical phase of implementing and evaluating a tunnel control system. In many situations in which congestion occurs, the bottleneck is readily identified by visual inspection. A queue of vehicles usually indicates the presence of a bottleneck at the front of the queue. For instance, a traffic signal acts as a bottleneck on its red indication.

Previous research showed that the toll plaza acts as a bottleneck when demand is less than about 2,800 vehicles per hour (vph)(2). This can be seen from the short queues and delays that occur during off-peak hours. When demand begins to exceed 2,800 vph, the location of the bottleneck is less obvious. It was a normal occurrence before the early 1974 gasoline shortage for vehicles to back up from the tunnel to the toll plaza during peak hours so that drivers often had to wait in the toll booth even after they had paid their toll, which indicated that the bottleneck was somewhere downstream of the toll plaza.

Observations of flows inside the tunnel indicate that the bottleneck cannot always be located by examining queue lengths alone because vehicles are constantly moving and concentrations are constantly changing. One might be led to believe that the horizontal curve at the tunnel exit could be the bottleneck.

Through a statistical analysis, Palaniswamy (7) showed that speed is a good parameter to use to identify a bottleneck. Any point in a congested system at which speeds are increasing is likely to be downstream from a bottleneck. As can be seen from the speed profile of the tunnel during congested conditions (Fig. 2), the increase in speed more precisely identifies the beginning of the tunnel upgrade as the critical bottleneck. There is a slight increase in speed after station 3, but there is a major increase after station 5, which indicates that the foot of the upgrade is the critical bottleneck. Figure 2 also includes profiles of flow and concentration. When the bottleneck in a congested tunnel cannot be determined by visual inspection, a speed profile should be helpful.

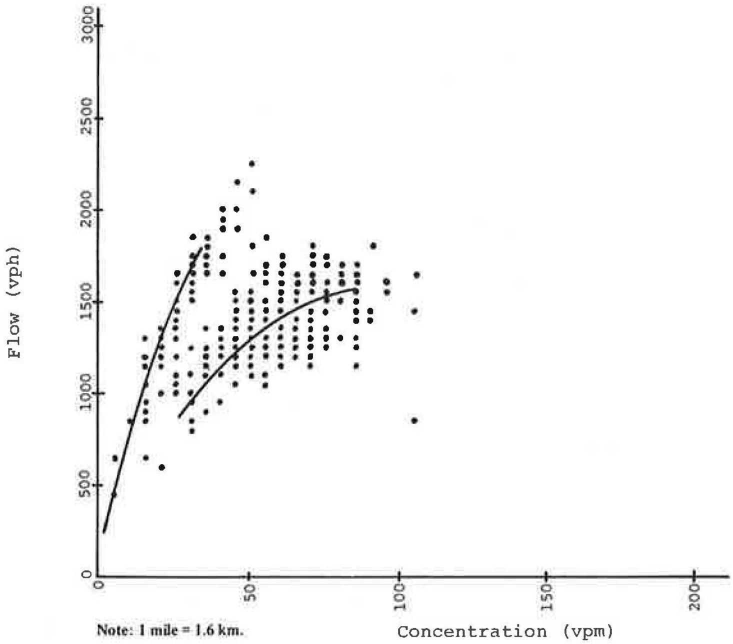
Capacity of the Bottleneck

According to theory, the point of zero slope of the flow-concentration (q-k) curve is the capacity of the roadway. A question arises, however, when there is a discontinuity in the data representing the bottleneck as shown in Figure 3 (4). Although much further analysis must be done to validate this point, it appears from Figure 3 that there may be 2 q-k curves representing traffic flow at the bottleneck. The tendency toward 2 curves is indicated by the 2 lines drawn through the data points. This presents a rather confusing picture when one is trying to determine the capacity of the bottleneck. An average of the data points at the apex of the lower curve would indicate a capacity of approximately 1,500 vph. Some of the data points on the upper curve indicate that higher flow rates are obtainable. To resolve this question a deeper analysis was undertaken.

Because the slope of the chord drawn from the origin to any point on the curve indicates the speed corresponding to the flow rate and concentration for that point, it is evident that speeds on the upper curve are higher than those on the lower curve. A histogram of 30-sec speeds (Fig. 4) suggests that speeds in the middle range [28 to 35 mph (45.1 to 56.4 km/h)] occur much less frequently than do those of either high or low range. This lack of middle-range speeds corresponds to the area between the 2 curves in Figure 3 where few data points exist. It appears, therefore, that traffic in the bottleneck region can take on basically 2 different states, which are described by these 2 speed ranges. When concentrations are not yet at the point where speeds break down, average speeds are normally between 35 and 48 mph (56.4 and 77.2 km/h) (state 1). When concentrations become too high, mean speeds drop abruptly into the 18- to 28-mph (29- to 45-km/h) range (state 2). These states correspond to the upper and lower q-k curves respectively.

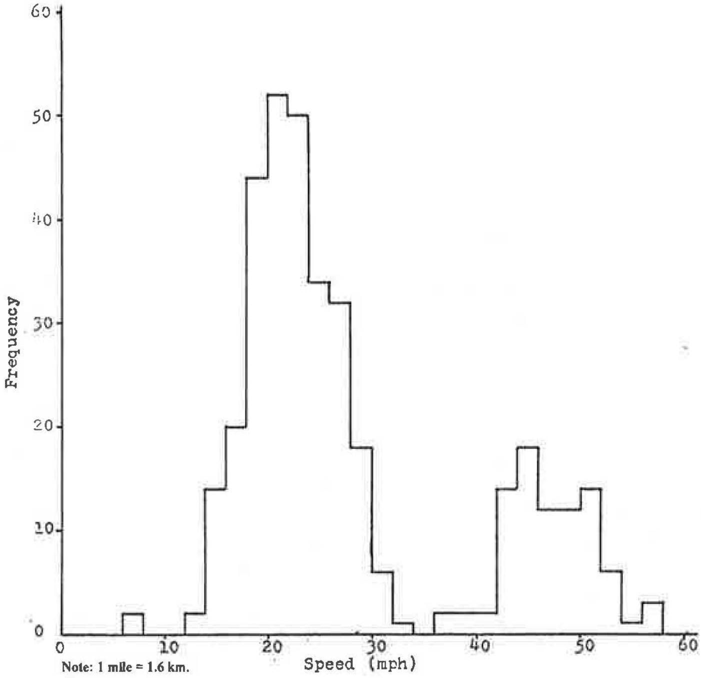
Palmer (8) also suggested the possibility of 2 q-k curves for bottlenecks from a study of a construction bottleneck. As demand increases, the flows may correspond to the

Figure 3. Flow versus concentration, Feb. 13, 1973, station 5.



Note: 1 mile = 1.6 km.

Figure 4. Frequency of 30-sec speeds, Feb. 13, 1973, station 5.



Note: 1 mile = 1.6 km.

high-speed curve (state 1), but, when concentrations reach the critical level, the flow drops into the lower curve described by state 2. Thus it may be possible for flow rates to be at the same level for 3 different combinations of speed and concentration. Because some of the highest flow rates are found in state 1, it would be advisable, for the purpose of tunnel-bottleneck control, to maintain speeds in this range. Maintaining high speeds would yield not only a better quality of flow but also high flow rates that could be maintained longer than they could in state 2.

Palaniswamy (7) has noted that the high kinetic energy of vehicles traversing the upgrade at higher speeds may account for higher flow rates. For instance, a car whose speed has doubled has 4 times the kinetic energy it would have at the lower speed. The additional energy and the motive power of the engine are used to maintain the higher speed throughout the upgrade. Thus the shock waves caused by the deceleration of vehicles may be less severe and occur further downstream. The higher kinetic energy is of special benefit to trucks whose great inertia helps to minimize the loss of speed in climbing. This leads one to believe that flow increases are obtainable in the truck lane as well as in the left lane. The necessity of the driver's being more alert at higher speeds may also contribute to higher flows. Unfortunately, it takes only 1 driver to adversely influence the traffic flowing in a single lane. An abnormal number of these drivers on 1 day may cause flows to be poor even at high speeds. Conversely, flows at low speeds also may be high on some days.

In summary, tunnel-bottleneck flow tends to assume 1 of 2 basic states, which are defined by 2 speed ranges. The flows allowed by the pretimed signal should be set at a level that will cause speeds to remain in state 1. At present, it can be deduced (from experience on the New York and Baltimore tunnels) that for state 1 the capacity of a traffic stream without trucks is about 7 percent higher than the average hourly volume during congestion in a tunnel. A properly operated demand-responsive system should further increase the capacity of the bottleneck. Because a tunnel is unlike an open roadway in geometrics and because of the differing psychological responses of drivers to a tunnel, the Highway Capacity Manual (10) procedure for calculating capacity does not apply to tunnel bottlenecks.

Development of Control Alternatives

When the maximum controlled flow rate of the bottleneck has been determined, control alternatives should be designed. Although the restriction may be at a point other than the foot of the upgrade, previous research in the New York and Baltimore tunnels indicates that the upgrade will be the critical section in most underwater tunnels. If a toll plaza is the problem area, vehicle processing might be improved by the installation of another toll booth. Each tunnel will present its own particular set of problems.

As stated previously, a traffic signal acts as a bottleneck on the red indication. In essence, a traffic signal on an urban street is a controlled bottleneck to alleviate a possibly greater bottleneck and thus increase the capacity of the street system. By introducing a controlled bottleneck into a section of the roadway upstream of the critical bottleneck, flow through that critical bottleneck can be increased. Ideally, the capacity of the control point should be regulated so that it is the same as or just below the capacity of the bottleneck.

Various control methods and strategies have been considered in the past, but, because the traffic signal is a widely accepted control device that is simple and inexpensive to operate, it is highly recommended for tunnel-bottleneck control. Several combinations of cycle lengths and splits should be chosen for initial experimentation. Other strategies may be designed after the first few days of data collection based on observation of traffic flow during the initial strategies.

Analysis of Control Strategies

A major problem with comparing flows achieved by each of the control strategies is that the same drivers do not pass through the tunnel every day, which makes flows dependent on the human factor. Also incidents occur at random, and flow can be interrupted for as little as 2 or 3 min to as long as half an hour. The number and duration of incidents during each alternative testing period may bias the results. The human factor cannot be realistically eliminated, but for evaluation purposes it is assumed not to vary between alternatives. The effect of incidents can be eliminated either by taking data for an extended period of time or by removing all flows affected by incidents. Long data collection periods are not desirable, particularly if several control strategies are to be attempted. Although comparing flow rates by removing incident-related data is slightly more complex, it takes much less data collection time. It also indicates more specifically what the cause of an improvement actually was. If, for instance, daily peak-hour flows, including incidents, are averaged over time, one cannot be sure how much of the improvement is due to control and how much is due to the reduced frequency of incidents. Eliminating data related to incidents would directly yield the effect of control on flow rates. Accidents and vehicle stalls could then be evaluated separately, either by longer periods of record keeping or by drawing correlations between incidents and other parameters such as speed and the mean velocity gradient. Any increase in flow due to fewer stoppages would be more than the increase due to control.

The use of 30-sec flow rates facilitates the extraction of data during incidents and provides a sufficient number of points for the construction of flow relationships. Zero flow rates for a period of at least 2 or 3 min is enough to identify the time at which an incident took place. In this study, 30-sec flow data were printed on computer cards, and the appropriate cards were removed for final analysis. One- or 2-min intervals also would permit removal of data occurring during incidents.

Selection of Appropriate Control Strategy

The decision-maker is nearly always faced with the problem of making trade-offs. Analysis of traffic flow does not alleviate this dilemma. One cannot achieve both smoothest flow and maximum flow rates at the same time. The problem is somewhat easier to solve for tunnels because high rates of flow can be maintained at high speeds. It is not wise to strive for excessive speeds, however. One way to select the control strategies is to develop a speed-volume curve by using average speeds and flows at the bottleneck for each data collection period as data points. This was done for 19 days [4 days with no control and 15 days with 4 control strategies (Fig. 5)]. Because no off-peak flow data were obtained, all of the points are close to the peak of the curve. No regression analysis was performed on this curve. Each control strategy is represented by a different symbol so that a range of operation for each strategy can be identified. If a shorter cycle length had been attempted, more points would be on the high-speed side of the curve. The decision-maker may take a curve such as this and select whatever strategy may be appropriate for a given traffic condition. For instance, on a hot day when stalls are more likely to occur, the decision-maker may wish to minimize their occurrence within the tunnel and set the cycle for a high speed. He or she may do the same for Friday traffic if a high percentage of drivers not familiar with the tunnel is a problem. When the strategies have been selected and implemented, the traffic engineer may then proceed to monitor speeds, flow rates, and incident rates over a longer period of time to measure the full effect of the control system.

EFFECTIVENESS OF PRETIMED SIGNAL CONTROL

From the analysis of data obtained from the Baltimore Harbor Tunnel, we believe that pretimed signal control offers the tunnel administrator an effective and practical tool that can significantly improve the peak-period congestion problem. In addition, use of this inexpensive control system may lead to the use of more complex control measures.

Analysis of Control Alternatives at the Baltimore Harbor Tunnel

From Table 2, it is evident that metering produced marked effects on speeds at the bottleneck. As would be expected, the 120-sec cycle caused speeds to be highest, but the 160- and 180-sec cycles also caused substantial increases. The 240-sec cycle was essentially identical to an uncontrolled alternative.

An examination of the profiles of speed shown in Figures 2 and 6 indicates that a bottleneck does not exist at the foot of the upgrade when speeds are relatively high. Speeds tend to drop slightly as vehicles proceed along the upgrade probably because of the effect of both the 3.5 percent grade and the horizontal curve near the exit of the tunnel. Also speeds increase at the entrance portal of the tunnel; this indicates that a bottleneck exists somewhere upstream of that point. An extension of the profile to the signal would indicate that the control system now acts as the bottleneck because speeds at the signal seldom exceed 25 mph (40.2 km/h). This validates the primary purpose of control, which was that the bottleneck should be shifted to a point of higher capacity.

Flow rates for the control strategies also revealed a significant improvement over the no-control case. Weighted average hourly flows indicate that the 120- and 180-sec cycles were the most desirable. Indeed, other research and literature indicate that a more than 7 percent flow increase is substantial especially considering the simplicity of the system and that the entire increase is due solely to control. To the extent that incidents are reduced because of control, the increase will be even greater. The results of the 85 runs with the traffic analyzer indicate that a significant improvement in the quality of flow (indicative of safety) was realized for all but the 240-sec control alternative (Table 2). It is likely, then, that the number of incidents will be reduced for the controlled situation. It should be mentioned again that this increase is for the left lane only and is not an overall increase although similar increases are very likely possible in the right lane. Because some technical difficulties in right-lane hardware were encountered during data collection, only a limited amount of data was obtained. However, analysis of 1 day's data for each strategy in the right lane indicates that flow increases as high as 10 to 11 percent may be obtainable for both lanes combined.

Theoretically, the 160-sec cycle should have produced results somewhere between the 2- and 3-min cycles in traffic throughput, but this was not the case. This may have occurred because of a gap insufficient to allow the tunnel to be cleared of traffic before data collection was begun. The results of a t-test revealed that with a 95 percent level of confidence both the 2- and 3-min cycles were better than no control.

The speed-volume curve shown in Figure 5 does not decisively indicate the optimum cycle. The 2-min cycle has several advantages; the primary one is improved level of service. Therefore, if pretimed control were to be employed full-time at the Baltimore Harbor Tunnel, the 120-sec cycle should be used. An even shorter cycle for Fridays and the summer months might be considered.

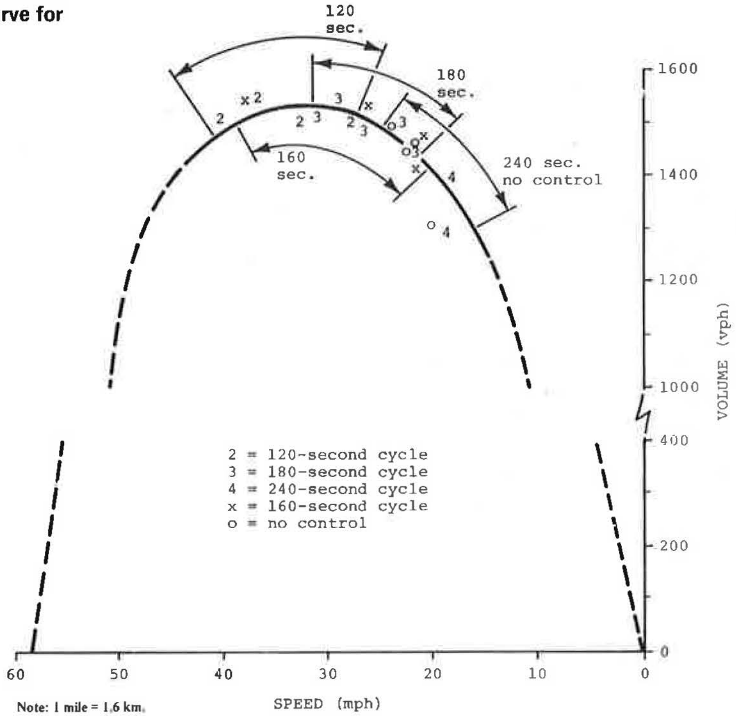
If the capacity of the left lane of the tunnel for pretimed control is the apex of the speed-volume curve (1,530 vph), the control system has the potential to increase the capacity of that lane by 9 to 10 percent above normal operation. If the reduced frequency of incidents is taken into account, the potential increase is even greater, perhaps as high as 15 percent if an average of 1 incident per peak period is eliminated. This level of flow will be difficult to maintain in practice because of the unpredictable nature of driver behavior within the tunnel.

Guidelines for the Use of Control

The following procedures should be applied if the critical bottleneck has been identified as being at the foot of the upgrade:

1. Install speed and volume detectors at the bottleneck;
2. Determine average speeds and flow rates at the bottleneck under congested conditions;
3. Install signals with driver information systems at appropriate locations;

Figure 5. Speed-volume curve for 19 days of data collection.



Note: 1 mile = 1.6 km.

Table 2. Comparison of mean flow rates, mean speeds, and mean velocity gradients.

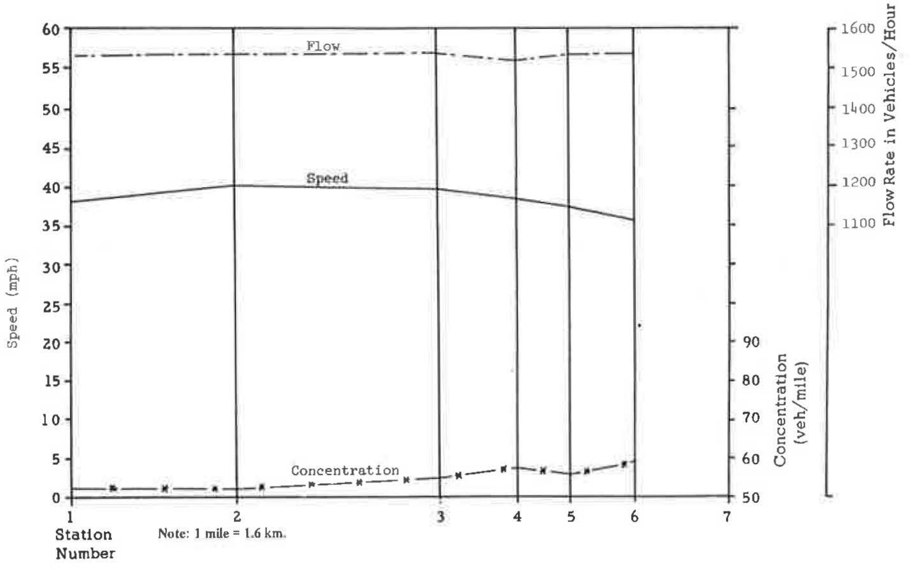
Strategy	Mean Speeds[a] (mph)	Increase Over Normal		Mean Hourly Flows[a] (vph)	Increase Over Normal		Mean Velocity Gradient[b] (sec^{-1})
		Number	Percent		Number	Percent	
No control	21.9	—	—	1,388	—	—	0.0327
120 sec	34.2	12.3	56.2	1,493	105	7.6	0.0218
160 sec	26.6	4.7	21.5	1,469	81	5.8	0.0248
180 sec	26.1	4.2	19.2	1,495	107	7.7	0.0256
240 sec	19.6	-2.3	-10.5	1,366	-22	-1.6	0.0367

Note: 1 mile = 1.6 km.

[a] Measured at bottleneck in left lane.

[b] Measured through entire tunnel in both lanes.

Figure 6. Traffic-flow profiles, Feb. 6, 1973, left lane, 120-sec cycle.



Note: 1 mile = 1.6 km.

4. Determine capacity at the signal for various cycle lengths and splits;
5. Select several cycle lengths; some should have capacities higher than those of the bottleneck and some should have capacities lower than those of the bottleneck;
6. Test each alternative strategy for several days, and make cycle adjustments if necessary;
7. Evaluate the tested strategies and select those that yield the best combination of flow rates and quality of flow; and
8. Implement chosen strategies and continue long-term monitoring of flows and incident rates.

The proposed metering system is rather primitive when it is compared to some of the extensive control systems being developed. But a solution need not be complex to be practical. Pretimed signal control may be the tool that can fit both the needs and capabilities of a staff managing a tunnel facility. Furthermore, if simple control systems can build the confidence of those authorized to spend the money for their use, the path will be cleared for more widespread use of sophisticated control measures. The initial outlay of funds for a pretimed system can be more easily rationalized if there is little to lose and much to gain.

CONCLUSIONS

Experimentation with and evaluation of the pretimed traffic-control system on the Baltimore Harbor Tunnel has yielded a number of conclusions.

A pretimed signal-control system has several advantages.

1. The system can increase flow rates. Left-lane flows in the Harbor Tunnel were increased by about 7 percent at the bottleneck.
2. The system can improve the quality of flow through the entire tunnel. Speeds in the Baltimore Harbor Tunnel for the 120-sec cycle were 56 percent higher than were speeds with no control.
3. Equipment is low in cost and easy to maintain.
4. Cycle lengths and splits may be designed for different traffic situations. The 120-sec cycle provided a good balance of flow rates and flow quality in the Baltimore Harbor Tunnel.
5. Equipment may be gradually added to the basic system to further improve traffic flow.
6. The system can be used to improve flows both for peak hours and for clearing traffic rapidly after incidents.

The disadvantage of the pretimed signal-control system is that it cannot react automatically to traffic conditions within the tunnel unless it is supplemented with computerized detectors.

Speed data at the foot of the upgrade indicated that the Baltimore Harbor Tunnel operates essentially as a 2-state system at either high or low speeds with few speeds in between.

Elimination of data during the occurrence of incidents is a good means to evaluate the effects of control alone. Incidents then can be examined independently.

Pretimed control may be a stepping-stone to the widespread acceptance of more sophisticated control measures.

RECOMMENDATIONS

Data from other tunnels should be collected for the purposes of

1. Determining whether the framework presented here offers a solution to the problems in tunnels other than the one studied here;

2. Supporting the hypothesis of 2-state tunnel operation;
3. Increasing existing knowledge of tunnel traffic flow; and
4. Examining how flows in the right lane are affected by control.

Methods of sensing traffic characteristics within tunnels and methods of recording them more accurately without affecting traffic flow must be determined.

The apparent discontinuity in the q-k curve for bottlenecks should be examined further.

ACKNOWLEDGMENT

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