Development of An Automatic Traffic Flow Monitor and Control System

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●RISING TRAFFIC DEMANDS and roadway costs are confronting engineers and roadway operators with problems that seem likely to continue and increase. As one factor that might improve the productivity of existing roadways, traffic monitor and control equipment is receiving increasing interest. This paper describes development work on such equipment systems being undertaken by The Port of New York Authority.

The problems of rising traffic demands and roadway costs are especially clear for the Port Authority, which is responsible for building and operating bridges and tunnels connecting New Jersey and New York. The five existing two-lane tubes of the Holland and Lincoln Tunnels total less than seven miles of roadway, but they are among the most expensive roadways in the world. The present cost of constructing such tubes is about $18,000,000 per lane per mile. Including approaches, the addition of two under-river lanes at the Lincoln Tunnel in 1957 required an investment of nearly $95,000,000.

These costs highlight the importance of assuring the best possible operation of tunnel roadways. Today, tunnel traffic operation is basically the same as it was more than 30 years ago when the Holland Tunnel was first opened to traffic. But great strides have been made, particularly in recent years, in electro-mechanical and electronic equipment. To determine whether such equipment can be used to improve tunnel traffic operation, the Port Authority has been actively developing and testing new systems and equipment in the past few years.

There are two main areas in which it now seems possible to bring about significant improvements through use of new equipment. One area deals with clearing disabled vehicles from active roadways at less cost and more rapidly, thereby minimizing the congestion and delay which usually is precipitated by them. The second area is concerned with maintaining the higher traffic production and the lessened occurrence of disabled vehicles which are characteristics of fluid traffic flow. Prototype automatic equipment systems have been developed which will perform operating jobs in both of these areas, and full-scale field tests are under way now.

Both of these areas involve installing vehicle detecting and other equipment on or near the roadway. Also, both systems are aimed at eliminating or reducing the loss in roadway productivity which occurs when the traffic stream breaks down, either due to a disabled vehicle or to congestion. In view of these similarities, it is likely that the two systems will be integrated eventually into one comprehensive traffic flow monitor and control system.

However, the immediate aim of the studies is to evaluate and improve the functional and performance aspects of each system, and this work can be done best by treating the two systems separately. Accordingly, each system is discussed separately in this report.

Although these two systems are designed for tunnel operation, they might be adapted at least in part to benefit traffic operations on any congested roadway system. Tunnels do differ greatly in many important respects from freeways, but so far as traffic control is concerned the difference is more in degree than in substance. Because tunnels are so expensive to construct and operate, comprehensive traffic equipment systems are likely to find their first application in them, possibly followed by more widespread use on other congested roadways. This is true also because tunnels offer a more controllable test situation in which the effect of equipment systems can be measured.

TUNNEL POLICING

Disabled vehicles on active roadways are the most direct cause of congestion and lost capacity, and their consequences are especially harmful in tunnels. A vehicle which breaks down during rush hours causes traffic tie-ups which not only can be of major proportions, but also occur at unpredictable times. The importance of rapidly detecting and removing disabled vehicles in tunnels is underscored by the extent of the police coverage provided now to do these jobs.

During peak traffic flow there are five police officers in each of the five tubes stationed along the catwalks which run throughout the approximately 8,000 foot-long tubes. At other times, the number of police is reduced to four men in certain tubes. Late at night, tunnel roadways are patrolled by officers in vehicles. With allowances for reliefs, regular days off, etc., it is necessary to have nearly six officers on the payroll for each post manned full time.

However, events requiring policing action are fortunately not very frequent, and these officers spend the greater portion of their time observing the flow of traffic. A system which would save or reduce the cost of this observation time and direct it to more effective tunnel policing would be a definite step forward.

The most important single measure of the effectiveness of any roadway policing system is considered to be the amount of time required to handle any incident. The incident might be, for example, a fire or serious accident, a disabled vehicle, or just a slow moving driver. This time can be divided into three main components—the time needed to detect the incident, the time needed to respond, and the time needed to restore normal operations.

Reducing the man-hours that are now spent observing, can be accomplished most directly by reducing the number of men who are observing. However, this would result in a less effective policing system—that is, more time would be needed to detect and respond to incidents and restore normal operation—unless the policing effectiveness of each remaining officer can be magnified by new equipment.

Therefore, the aim of the system the Port Authority is developing is to magnify the ability of an individual officer to police roadways, by providing him with equipment to detect, respond, and restore normal operations more rapidly. His ability to detect incidents is now largely limited to the length of roadway in his direct view, and it is expected that this range will be extended radically by means of an automatic alarm system and closed circuit television. His ability to respond is now limited to a walking speed of 3 mph, and this speed will be multiplied by a factor of ten through unique catwalk transportation system. His ability to restore normal operations depends in large measure on his effectiveness in controlling tunnel traffic so as to expedite the tow truck or emergency tractor on its way to the disabled vehicle. His control is limited now to traffic in his immediate area, and it is planned to extend his effectiveness by providing several sets of remotely operated signs, signals, barriers, loudspeakers, and other devices which he can control from a central point equipped with television for surveillance of the remote traffic control areas. To summarize this projected system, the present and possible new systems are compared directly in Figures 1 and 2.

Figure 2 shows a possible system of policing tunnels with only one man rather than the five men used in the present system. However, this minimum manpower has been assumed only for study purposes, and is not at this time a serious proposal. The purpose of this study is to develop equipment which will increase the policing effectiveness of individual officers to a maximum, and therefore, it is desirable in the study to assume that only a minimum of manpower is available. But the number of men that would actually be used by the Port Authority to police tunnels under a system such as this will depend on the judgment of operating management, which will be based in part on the actual performance of the equipment described in the following paragraphs.

Extending the Officers' Ability to Detect

In view of the direct applicability of closed circuit television for this function, the question may airse as to why any developmental work is considered necessary. There are two general reasons why television alone is not considered likely to provide the best solution.

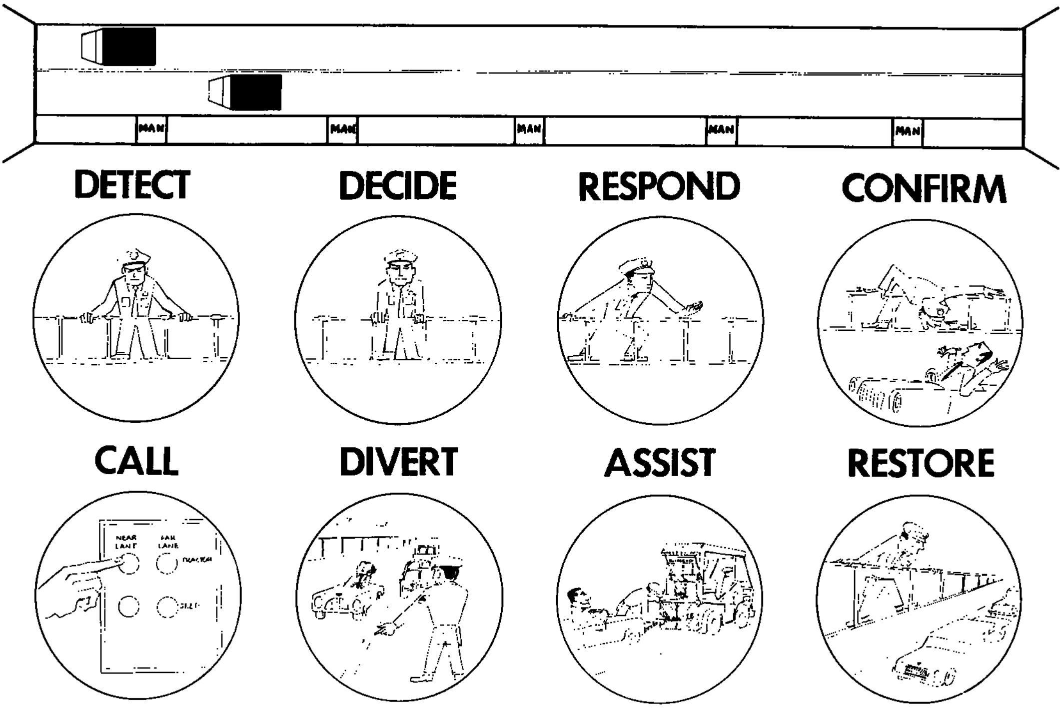


Figure 1. Present system.

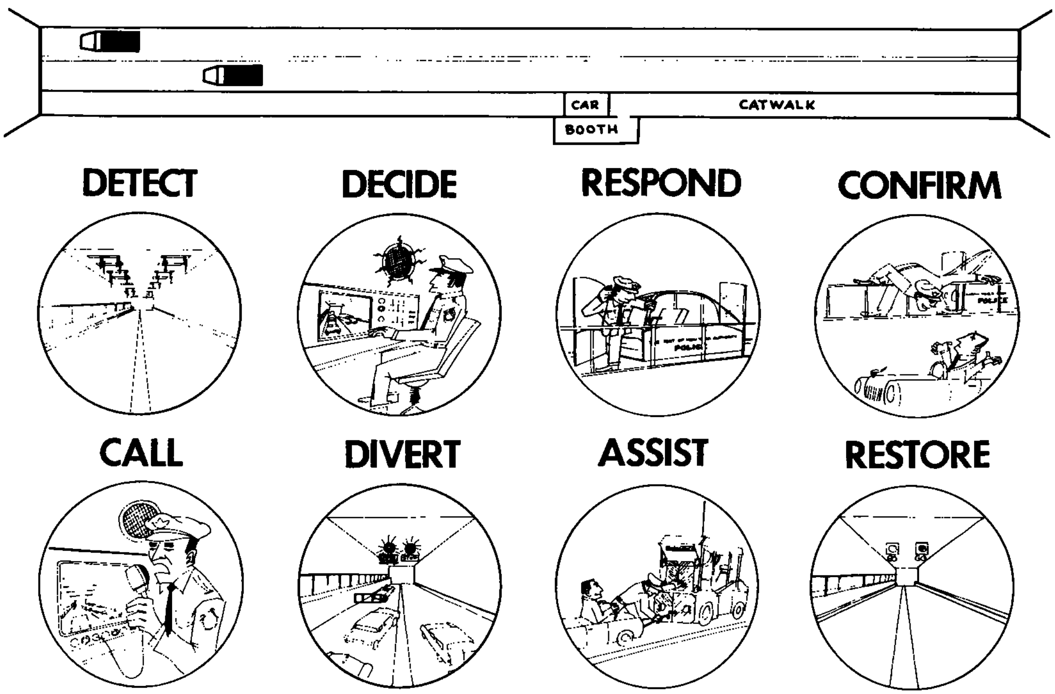


Figure 2. Possible system.

The first reason is the tunnel environment which, because of low light levels, handicaps the performance of television. The 1 to 3 foot-candles of light present inside the tunnel is the minimum level at which television can operate. Nevertheless, through extended testing, it has been found that the performance of closed circuit television is remarkably good. Although the low light level does result in a marginal picture, police observing the picture screen have been able to determine the general condition of traffic movement up to distances of 500 ft from the camera. It is not possible, however, to gain detailed information on any vehicles which might become disabled within the camera's view.

A more serious environmental limitation on television in tunnels arises from the impossibility of placing the camera far enough away from the traffic stream to cover a significant length of roadway. However, one relatively minor modification which appears promising, is to place a mirror at the focal length of the lens so that the television monitor displays on one-half the screen the view seen directly by the camera, and on the other one-half of the screen the view reflected from the opposite direction by the mirror. By a system such as this it is expected that a camera may be able to provide traffic information through a section of roadway up to 1,000 ft in length.

These environmental limits on television performance would not apply on freeways, and it seems likely that television will be more effective in those applications. However, the second general reason the Port Authority has, at this early stage, tentatively decided against using television as the front line component does apply on freeways. Inasmuch as a man can effectively monitor only one picture at one time, television is basically a means of transporting a man's vision rather than duplicating it. Thus, a detection system which depended on many television cameras monitored by one man, would still be relying basically on the attentiveness of one man rather than at present, on five men. And the problem of assuring attentiveness over a period of hours seems likely to be major.

Because of these limitations on television, the Port Authority is developing a system which will automatically generate a signal when and where traffic flow is not normal. The proposed automatic alarm system uses vehicle or axle detectors located along each tunnel lane (Fig. 3). Each detector is connected to a "stoppage computer" which

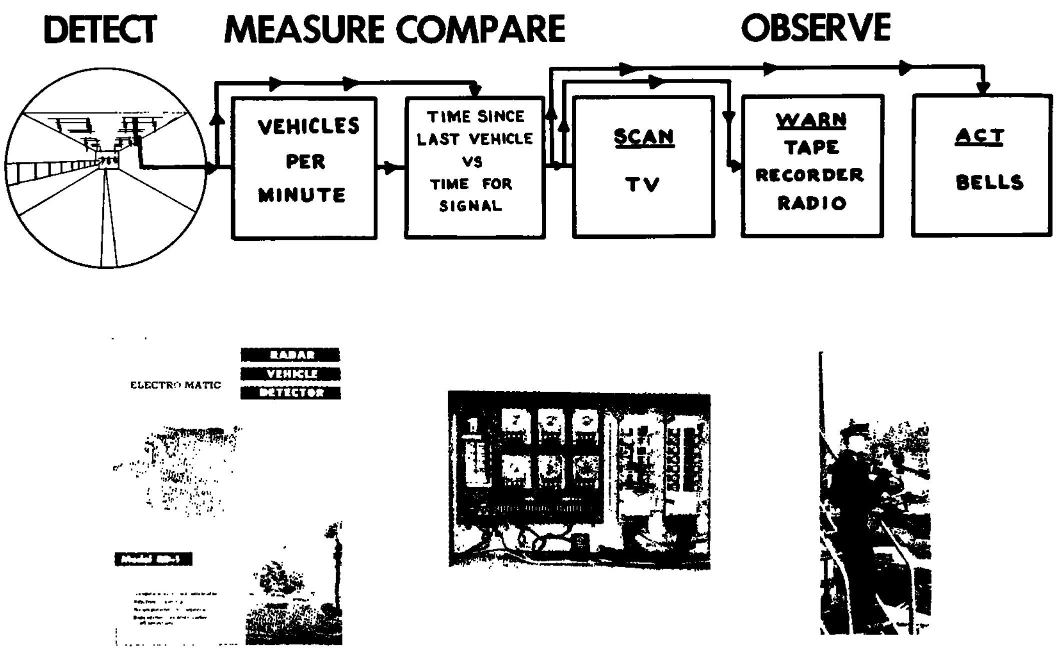


Figure 3. Monitor system.

measures the rate of traffic flow past the detector and determines when, for that level of flow, an excessive amount of time has elapsed without a vehicle passing the detector. When that occurs, the stoppage computer starts a chain of alarms which continue either until a vehicle does pass the detector, or a police officer acknowledges the alarm and resets the system.

Vehicle detectors are available commercially in increasing variety, and there is little question of the feasibility of accomplishing this part of the operation. Detectors are likely to be the front line component in any automatic traffic system. Because of their importance, it might be helpful to review the Port Authority's experience with detectors.

For the past two years the Port Authority has been testing radar vehicle detectors, ultra-sonic vehicle detectors, and induction loop detectors. The first two are especially suited for tunnel use because they can be installed in the ceiling with a minimum of difficulty. The induction loop is also simple to install by cutting a slot in the form of a loop in the roadway. Each of these three detectors is generally comparable in price. In the Authority's experience the ultra-sonic detector has been the most accurate of the three although the induction loop now appears to have been developed to a point of comparable accuracy. Circuitry required for the induction loop appears to be the most simple of the three.

Another vehicle detector which is currently being tested establishes a beam of ultra-sonic energy. This detector cost only about one-third the amount of the three commercial units described earlier, but is more difficult to install because two separate units, a transmitter and a receiver, are required. Because of the geometrics of the tunnel design, one unit has been installed under the roadway in the fresh air supply duct, and the other unit on the tunnel ceiling. These units have not been tested long enough at this time to state their accuracy and maintenance requirements. Another commercial product, which is by far the least expensive detector being tested, is a tape treadle. Although it is hoped that this unit will function satisfactorily, experience to date has been too limited to permit any conclusions.

In addition to these detectors, the Port Authority is testing two other units. Photocells offer a relatively inexpensive device, although maintenance costs will doubtless be higher than with some of the other detectors mentioned. Because of the fresh air

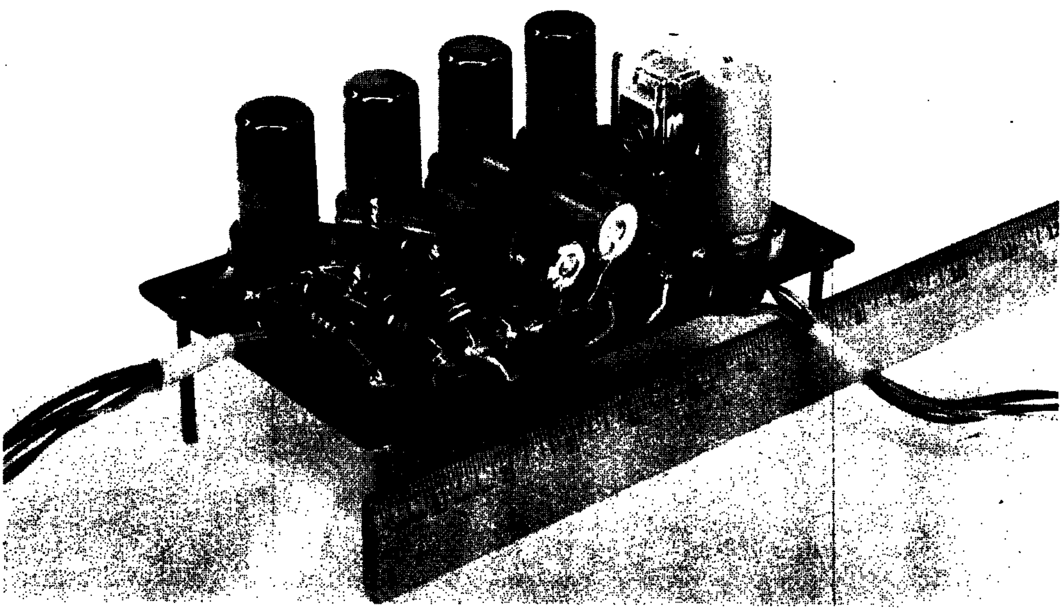


Figure 4.

which must continually be supplied to a tunnel, it is possible to mount the photocell light source in such a way that it will remain cleaner than would be expected in the usual roadside environment.

After studying several types of treadles, the Port Authority staff has devised a carbon pile unit which consists of a steel plate resting on piles of carbon disks. This unit may offer long life and low maintenance. Another prototype commercial vehicle detector being tested also uses a metal plate in the roadway and a strain gage. Maintenance cost of this unit is also expected to be low. However, both of these treadles are still untested and their performance is not known yet.

The stoppage computer is the heart of the automatic alarm system. These units have been developed entirely by the Port Authority staff, as a canvass of possible manufacturers failed to find commercial unit or system which could be easily adapted at a reasonable cost for this purpose. The computer appears to offer a relatively simple and low-cost method of automatically monitoring traffic flow for the occurrence of disabled vehicles. An electro-mechanical version is shown in Figure 3, and a much simpler prototype using vacuum tubes is shown in Figure 4. This unit might be transistorized and made even more compact.

In operation, the computer does two jobs simultaneously. First, by remembering the number of pulses it has received in the past few minutes, the computer establishes a flow rate. Secondly, the computer measures the time that has elapsed since the preceding vehicle has passed the detector with which it is associated. When flow is heavy past the detector a large number of pulses will be received in the few minutes. Then the computer will recognize that the passage of a relatively small amount of time (about 30 sec) without a vehicle passing the detector might be cause for an alarm. On the other hand, when traffic flow is light and few pulses are received, the computer would not generate an alarm until a much longer time (about 2 min) passes with no vehicle passing the detector. One significant advantage of this system is that it fails safe. That is, unless the system continues to operate and vehicles pass the detector, an alarm is generated.

The alarm circuitry has various outputs to provide for alarms of increasing urgency as time passes without a vehicle being detected. This gradation in alarm severity is desirable to match the increasing certainty that the lack of flow is due to a disabled vehicle. If the amount of time the computer waits after the passage of each vehicle before generating an alarm is relatively small in relation to the average headway time between vehicles, a relatively large proportion of false alarms will be generated. On the other hand, if the computer were to wait in all cases until there was a strong probability that the failure of a vehicle to pass its detector indicated a disabled vehicle, then there would be an excessive delay in detecting that stoppage. It is planned to compromise this dilemma by generating alarms of limited scope when the ratio of false alarms is high, but increasing the severity of alarms as time continues to pass without a vehicle detection. The earliest alarm might consist of automatically turning a television camera on to view that section of the roadway in which the alarm is generated. If an officer is observing the television and there is a stoppage, it would be detected very quickly. If the officer is engaged in some other duty and not observing television, then the next step in the alarm process might be to broadcast a prerecorded voice signal. If still no action is taken to investigate the cause of the alarm, bells might be sounded. At any point in this alarm process, when it has been conclusively determined that there has been a stoppage and that response is on the way, or that the alarm is false, the train of alarms can be interrupted.

As a complement to the automatic alarm system, it is planned to test closed circuit television for several purposes in the new system of policing tunnels, including:

1. To verify alarms from the automatic alarm system and indicate the probable types of emergency equipment that will be needed.
2. To assist a police officer outside the tunnel in manipulating the signs, signals and other special devices that will be provided as part of the remotely operated traffic control system.
3. To allow this same police officer to observe vehicles throughout the tunnel during periods when there is a disabled vehicle and normal flow has been suspended.

4. To periodically inspect the condition of roadways to detect large foreign objects which might have been dropped by traffic.
5. To detect violations of traffic regulations.

Several alternate plans for using television are being considered. Decisions as to the disposition of cameras, picture screens and the flexibility of interconnections between these components, will depend in part on the usefulness and performance of television, and in part on the job done by other components of the proposed system.

As an adjunct to these alarm and visual communication systems, voice communication systems are also being studied. The usefulness of radio in traffic police work has been well established, but there is no system presently in use which meets all the requirements for a tunnel application. It is desirable that the officers on tunnel duty be equipped with pocket-sized radio transmitters and receivers which would interfere as little as possible with their freedom of action. A special antenna system is needed and, although the necessary antenna systems and radios are commercially available, they have not been used in environments with the high ambient noise present inside tunnels.

The remote components of this system to extend the officer's range of detection are located in a booth adjacent to the catwalk in which the officer will normally be stationed. When an alarm is received and verified, the officer next needs a rapid means of reaching the scene. Other monitor points will also be equipped outside the tunnel for backup.

Extending the Officers' Ability to Respond

In the two-lane tunnels, as in any roadway where there are no shoulders or other spaces that can be used in an emergency, the problem of supplying police rapidly to a scene requires a specialized solution. In the tunnel the most feasible way of accomplishing this is to use a vehicle on the narrow catwalk along which police officers are presently stationed. Because a man requires 18 in., the 22-in. wide catwalk allows only 2 in. of space on each side of the man to accommodate the vehicle in which he is traveling and the inevitable sway produced as the vehicle moves along the catwalk.

To provide for rapid response to any point in the tunnel, a vehicle was desired that an officer would elect to drive at speeds up to 30 mph along the catwalk. To provide this system, the Port Authority retained Battelle Memorial Institute of Columbus, Ohio.

The vehicle they have conceived is unique (Figs. 5 and 6). There are only three points of contact and only one wheel in the conventional sense. The rubber-tired pneumatic wheel, located near the center of the vehicle, supports most of the vehicle weight and provides the propelling and decelerating force. At each end of the vehicle on the side next to the tunnel wall there is mounted a three-wheel trolley which is firmly clamped to run along a special Z section guide rail. Lateral placement of the vehicle on the catwalk is controlled by a V section welded to the underside of the Z rail. A grooved wheel rides on this rail (Fig. 7). In addition, these wheels are affixed to a member of the trolley assembly which is shaped to slide along the rail in the event of any failure of the trolley wheels. Motive power is supplied by a 7.95 HP gasoline engine, acting through a planetary transmission similar to those used on the Model T Fords. There are duplicate controls at each end of the vehicle which permit travel equally well in either direction.

The 20-in. wide, single-wheel vehicle has fully demonstrated its ability to operate at speeds in excess of 30 mph along a special guide rail which has been attached to the catwalk. Of critical importance is the fact that the vehicle feels both stable and safe when it is operated on the 22-in. wide catwalk at these high speeds.

Extending the Officers' Ability to Restore Traffic

Restoring traffic for normal operation requires clearing one of the two lanes between the disabled vehicle and the tunnel exit so that emergency equipment, which enters the tunnel from the exit portal and proceeds against traffic, can reach the disabled vehicle. Under the present system of tunnel policing, officers on the catwalk between the disabled vehicle and the tunnel exit, stop traffic in both lanes and then move all traffic in the lane nearest to the catwalk over to the other lane. In a system which makes extensive use of equipment it will be necessary to provide remotely operated traffic control devices to accomplish this function.

A possible system to accomplish this would use signs, signals, barrier gates, and other devices operated by an officer possibly located in a traffic control center outside the tunnel (Fig. 8). That officer would be observing the effect of his actions over

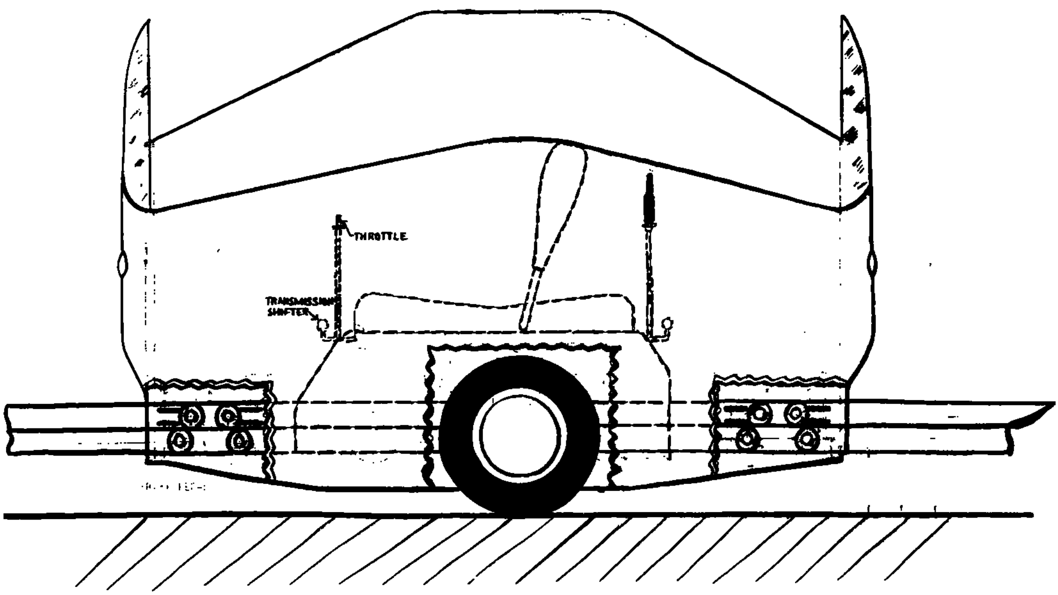


Figure 5. Catwalk vehicle diagram.

Figure 6.

television, and might also have a voice link to motorists in the affected area via loudspeaker.

One of the problems in such a system is to provide a legible sign with good impact, but not reduce ceiling clearance more than 3 in. To accomplish this, the Port Authority designed a sign 8 ft x 10 ft x 3 in. for mounting on the ceiling, using the elongated letters which are standard for pavement marking. This sign is shown in Figure 9 at a distance of 100 ft. It has been found to provide ample legibility and impact, but is not sufficient by itself to assure that traffic will stop. Other devices, including retractable lane delineators, will be used.

When assembled as a system, these three types of equipment—detection, transport and control—can provide considerable flexibility and backup. Monitoring will be performed at several points, and spare catwalk vehicles will be stationed at tunnel portals in the system presently conceived to increase reliability and effectiveness.

FLOW CONTROL

Although it is clear that more expeditious handling of disabled vehicles and other interruptions in normal traffic operation will improve traffic service, it is not immediately clear that controlling the character of traffic flow can also significantly improve traffic operations.

Through study of traffic flow characteristics in the near lane of the Holland Tunnel South Tube conducted in 1959, a pattern of shock waves was found to exist during peak traffic flow. The shock waves are periodic reductions in the flow and speed of traffic.

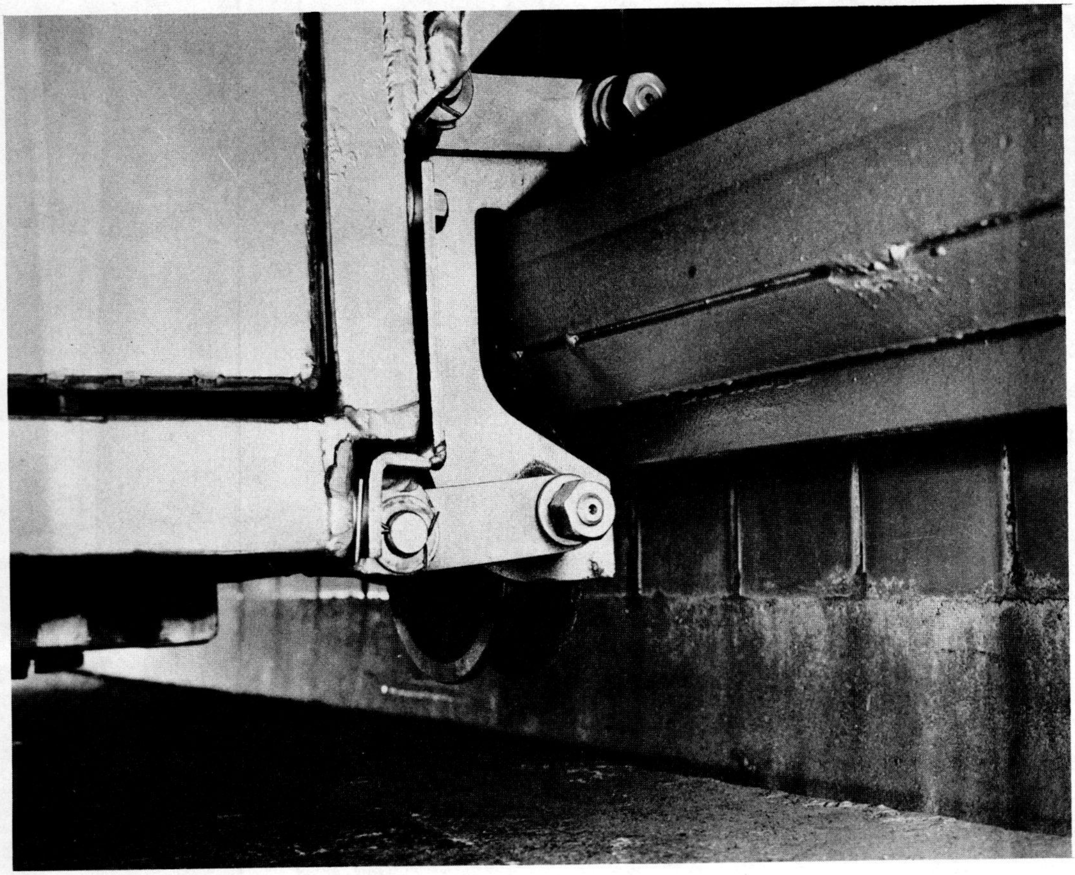


Figure 7.

They are caused by the inability of that section in the tunnel which has the least capacity (that is, the bottleneck), to handle all of the traffic being supplied to that section. Shock waves start at the bottleneck and move back through the traffic stream to the tunnel entrance. On the other end, between the bottleneck and the tunnel exit, gaps appear in the traffic stream because the bottleneck cannot furnish enough traffic to saturate that section.

Because of this behavior of shock waves and gaps, it is possible to locate the bottleneck by observing the progression of shock waves and gaps in the traffic stream flowing through the tunnel lane. Measurements made in the Holland Tunnel South Tube near lane showed that the bottleneck is located near the foot of the upgrade.

Further study showed that several improvements in the traffic flow through that lane could be achieved if shock waves were prevented. This could be accomplished by limiting traffic entering the tunnel to the maximum amount which could be handled at the bottleneck. Experiments have confirmed this expectation.

To understand how these improvements are gained it is necessary to understand two processes which occur in vehicular traffic flow. One process is the decrease in speeds of successive vehicles in platoons. This decrease is caused by the fact that, because the vehicles are in platoons (and hence driving relatively close to each other), the fluctuation of speeds from one vehicle to the next will generally be such as to result in slower speeds. Fluctuations which would be on the side of having the successive vehicles speed up are not likely because accidents would follow due to vehicles becoming too closely spaced.

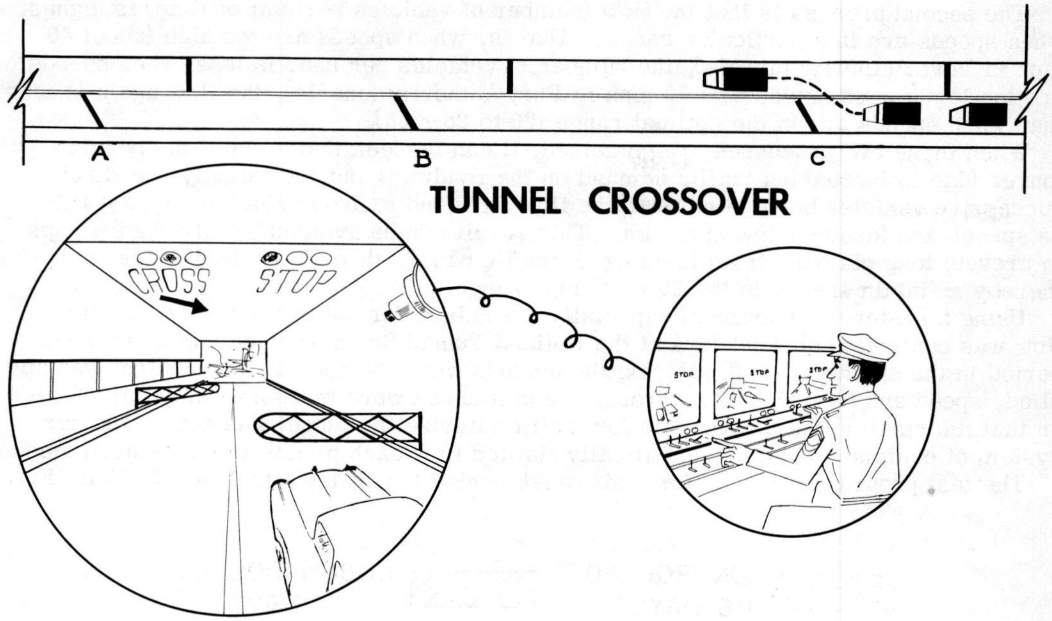


Figure 8. Diversion system.

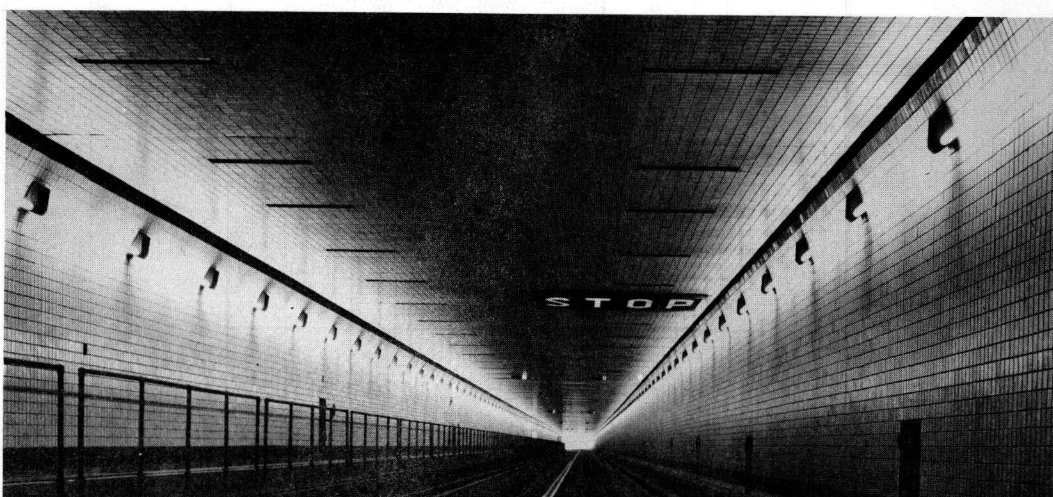


Figure 9.

The second process is that the flow (number of vehicles per unit of time) is highest when speeds are in a particular range. That is, when speeds are too high (about 40 mph in Port Authority tunnels), the number of vehicles per hour is less; when speeds are too low (for example, 5 to 10 mph in Port Authority tunnels), the flow again is less than when speeds are in the optimal range (20 to 25 mph).

When these two processes are combined, it can be seen that as platoons become longer (due to increasing traffic demand on the roadway) and accordingly speeds of successive vehicles become slower, the flow will tend to drop below its highest rate as speeds are forced below optimum. This result can be avoided by introducing gaps to prevent long platoons from forming as traffic passes through the bottleneck, and thereby maintain speeds in the 20 to 25 mph range.

Using a system of equipment especially assembled for the experiments, traffic flow was controlled on weekdays at the Holland Tunnel South Tube during a six-week period in the spring of 1960. During the periods when the special flow control was applied, speed and flow of traffic through the bottleneck were measured in detail. Based on that information the proper rate for traffic entering the tunnel was set on another system of equipment which automatically limited flow each minute to the desired amount.

The test program extended for a six-week period from May 4 to June 17, 1960 (Fig.

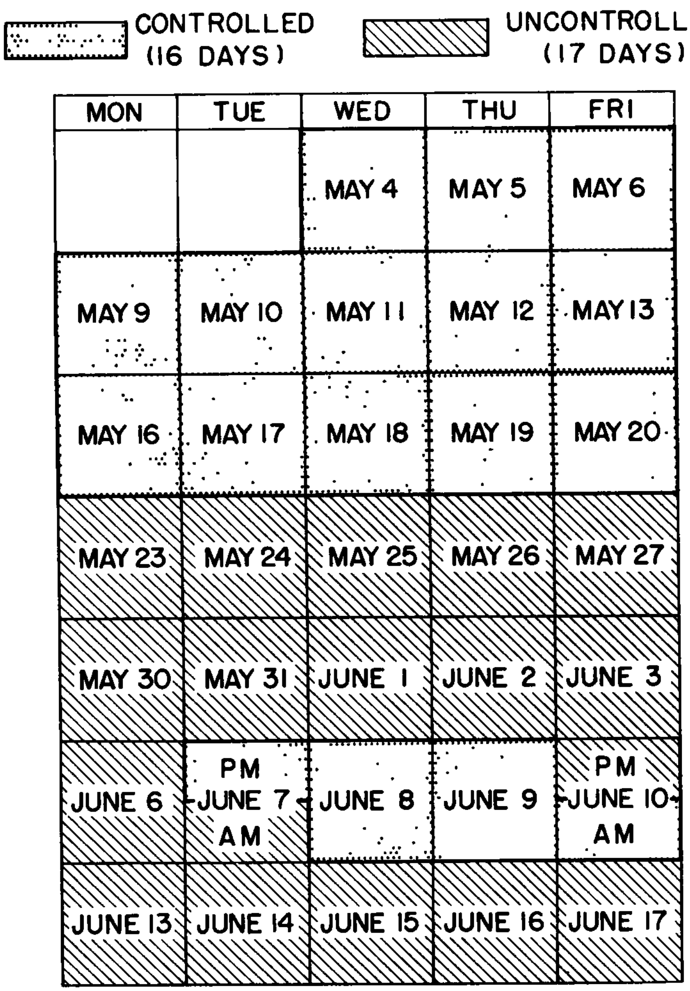


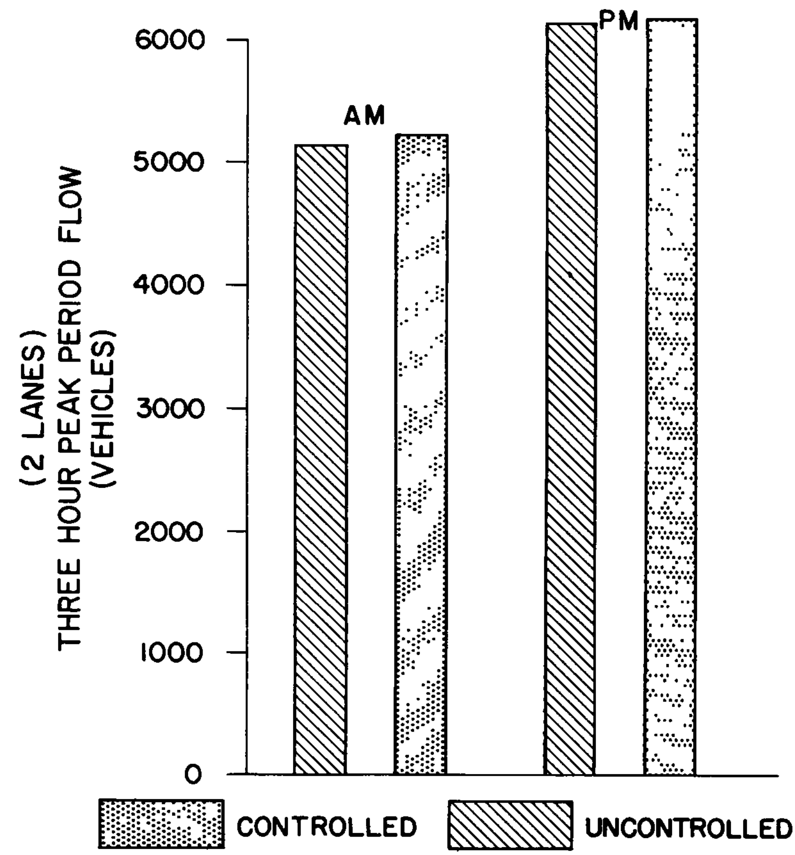
Figure 10. Calendar of controlled vs uncontrolled survey days.

10). During the first two weeks, from May 4 to May 20, the control procedure was followed. From May 23 to June 6, the traffic flowed without control but with the major indices of tunnel operation being measured. June 7, 8, 9 and the morning of June 10 were periods when the traffic was controlled. From June 10 until June 17 uncontrolled traffic production was measured.

The average 3-hr peak period traffic demand comparison for the controlled and uncontrolled days during either the morning (7-10 a.m.) or evening (4-7p.m.) rush, indicates that there is no significant difference in the demand, and hence no difference in the volume handled (Fig. 11); nor was there any significant difference in the weather conditions during the two periods. In other words, the tunnel had to do essentially the same job under essentially the same conditions. The basic question is: how was the traffic served when the control procedure was used, in comparison with when no control was applied?

Test Results

A detailed analysis of tunnel production in 15-min intervals clearly shows a consistent difference in production (Figs. 12 and 13). During the evening peak period the



	AVG TEMP		σ TEMP		AVG HUM		σ HUM	
	AM	PM	AM	PM	AM	PM	AM	PM
CONT	59	66	4.6	18.4	64	63	5.8	16.2
UNCONT	63	70	4.8	11.0	75	62	6.5	19.4

Figure 11. Average traffic demand and weather conditions during survey.

average demand was less than tube capacity until 4:15 p.m., and there was no difference in the controlled versus uncontrolled flow. From 4:15 and 6:15 p.m. however, the control procedure maintained a consistently higher average production level than did the uncontrolled operation. During the critical hour the increase was 5 percent in the total tunnel flow. From 6:15 to 6:45 p.m. the uncontrolled 15-min volumes were higher than the controlled volumes. The apparent reason for this reversal at 6:15 p.m. in the production pattern is that the demand under the control procedure was satisfied earlier.

A similar production analysis of the morning peak period also showed an increase in production of 5 percent in the critical hour from 7:45 to 8:45 a.m. However, in the 15-min periods before and after this hour, there was no significant difference in controlled and uncontrolled flow. It is believed this record reflects the high proportion of trucks present in both lanes, except in the 7:45 to 8:45 a.m. period when passenger cars are present. The flow control procedure did not appear to benefit truck traffic, because these vehicles generally would not take advantage of gaps to maintain higher speed.

Whereas the significance of this production increase lies more in its consistency than in its magnitude, the relatively modest 5 percent increase in the production during

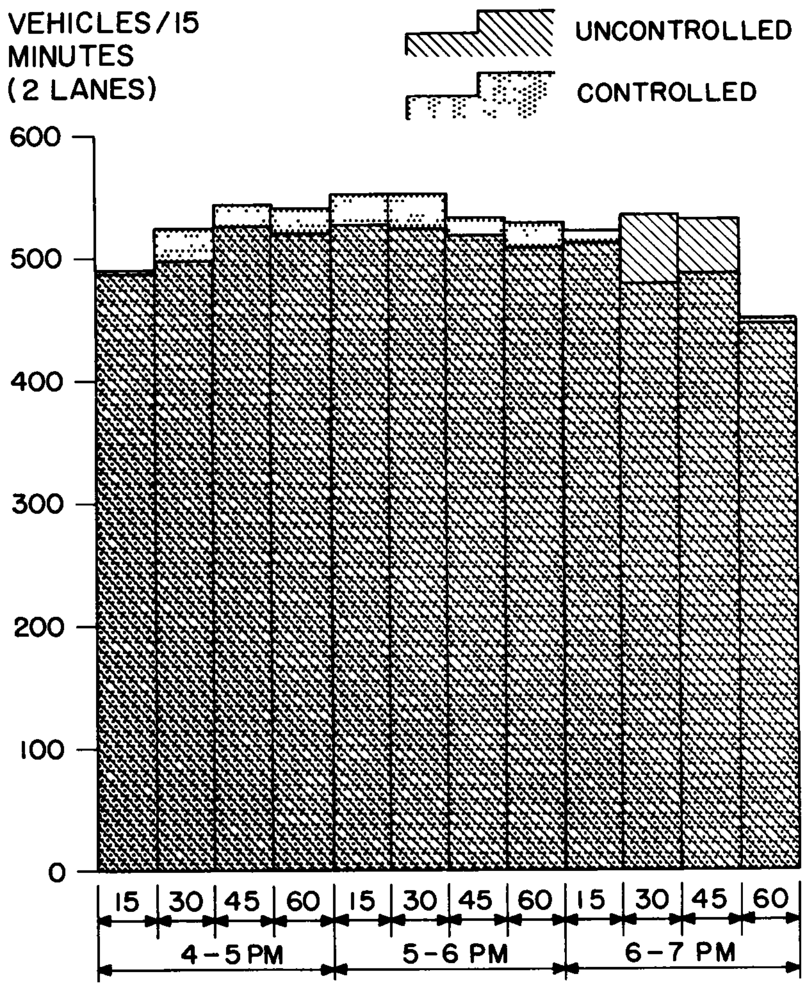


Figure 12. Average volume for 15-min intervals during PM peak period.

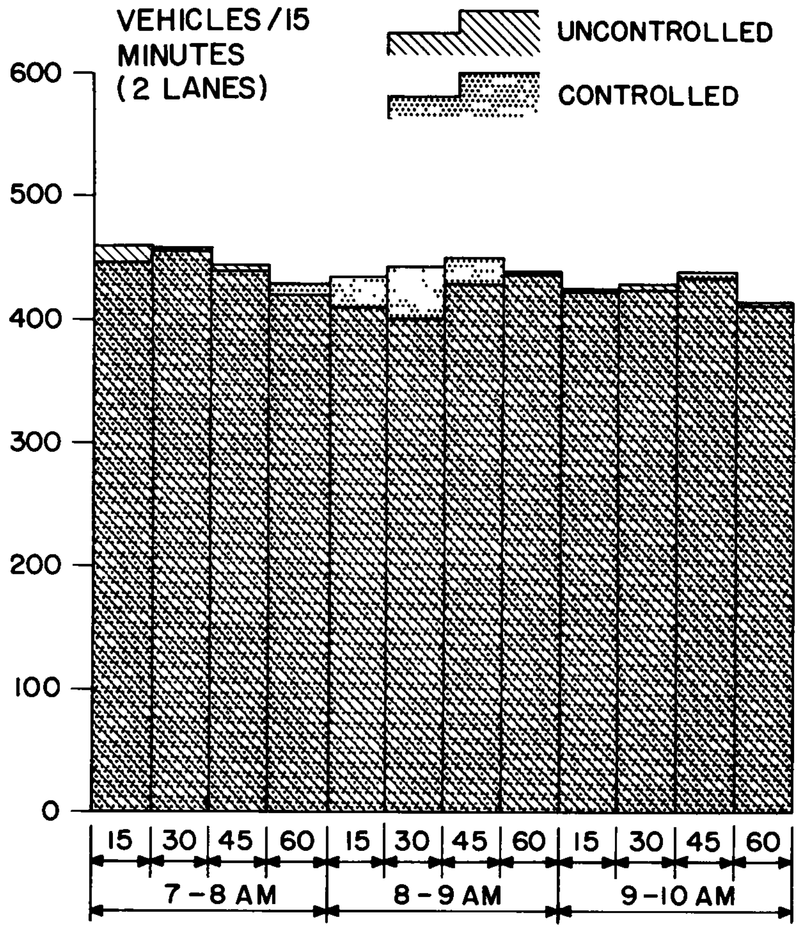


Figure 13. Average volume for 15-min intervals during AM peak period.

the critical hours from 4:15 to 5:15 p.m. produced a very marked reduction of 33 percent in the duration of congestion on the approaches in the evening peak period (Fig. 14). The average congestion during the "uncontrolled" evening period was 3 hours 2 minutes, whereas the "controlled" period had a congestion duration of only 2 hours 2 minutes. Analysis of congestion in the morning period showed no significant reduction in the length of congestion during the controlled period, and this probably can be attributed to the fact that morning congestion is made up largely of truck traffic that was not amenable to improvement by flow control methods.

The improvement in tunnel production recorded in these tests when the input control was used can be attributed to two general factors: a significant reduction in the occurrence of disabled vehicles, and an improvement in the speed-headway relationships maintained by traffic passing through the bottleneck.

In a 3-hr peak period two disabled vehicles will occur on the average in each tube. By maintaining free-moving traffic flow through the tube, the flow control procedure was expected to reduce the occurrence of vehicle failures caused by overheating, motor trouble, stalling, vapor lock, and other failures increased by frequent stopping and slow speeds. The test experience confirmed this expectation.

Analysis of the disabled vehicles in the controlled versus uncontrolled periods showed a total of 60 vehicular breakdowns during the uncontrolled a.m. and p.m. peak periods, compared with 44 disabled vehicles in the controlled periods (Fig. 15). The reduction in stoppages occurred in the classification of motor trouble (which covers stalled vehicles, vapor locked vehicles, and overheated vehicles), and was from 43 during uncontrolled flow to 16 in the controlled period. Other classifications (such as out of gas) were not reduced by the flow control.

To determine whether an improvement in the speed and headway relationships of traffic passing through the bottleneck had occurred, a random sample of near lane speeds and volumes at the foot of the upgrade was plotted for both the controlled and uncontrolled periods (Fig. 16). For each speed, the mean volume was computed. The flow versus speed curve for the controlled flow depicts a clear relationship, with maximum flow of approximately 1,290 vehicles per hour occurring in the optimal speed range between 20 and 25 mph. For the uncontrolled flow, no single flow-speed relationship is evident. However, the points do suggest two flow-speed curves, with one extending through the optimal speed range and having a maximum flow of 1,235 vehicles per hour.

Another result of these tests that is particularly important for tunnels, and may have some importance in urban areas generally, was a significant reduction in tunnel

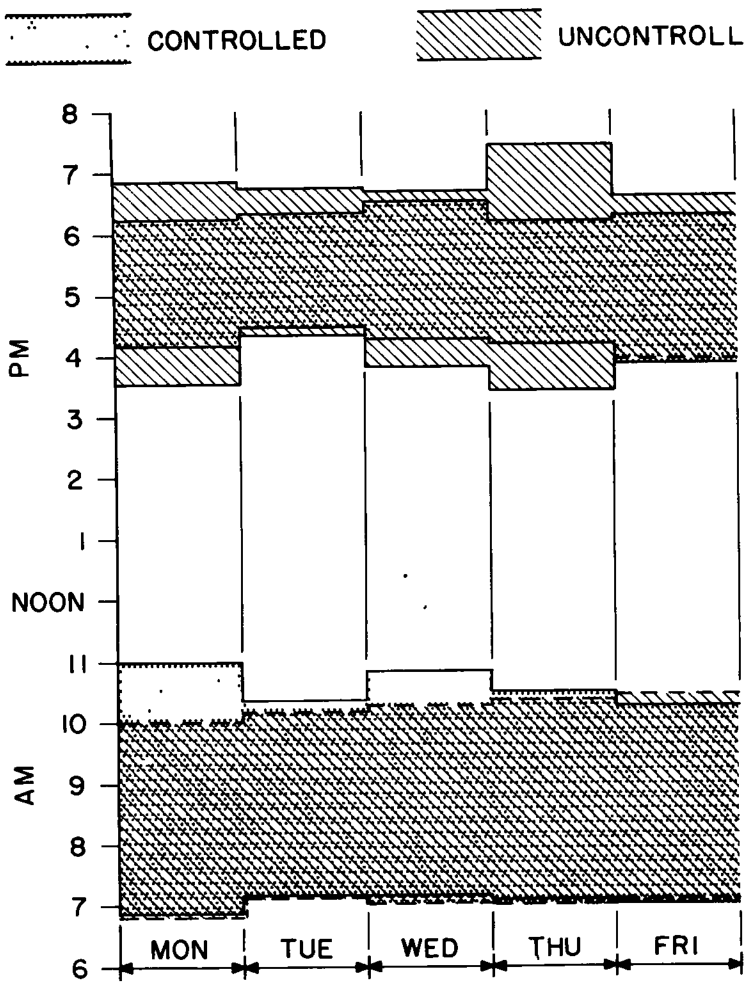


Figure 14. Congestion on approaches.

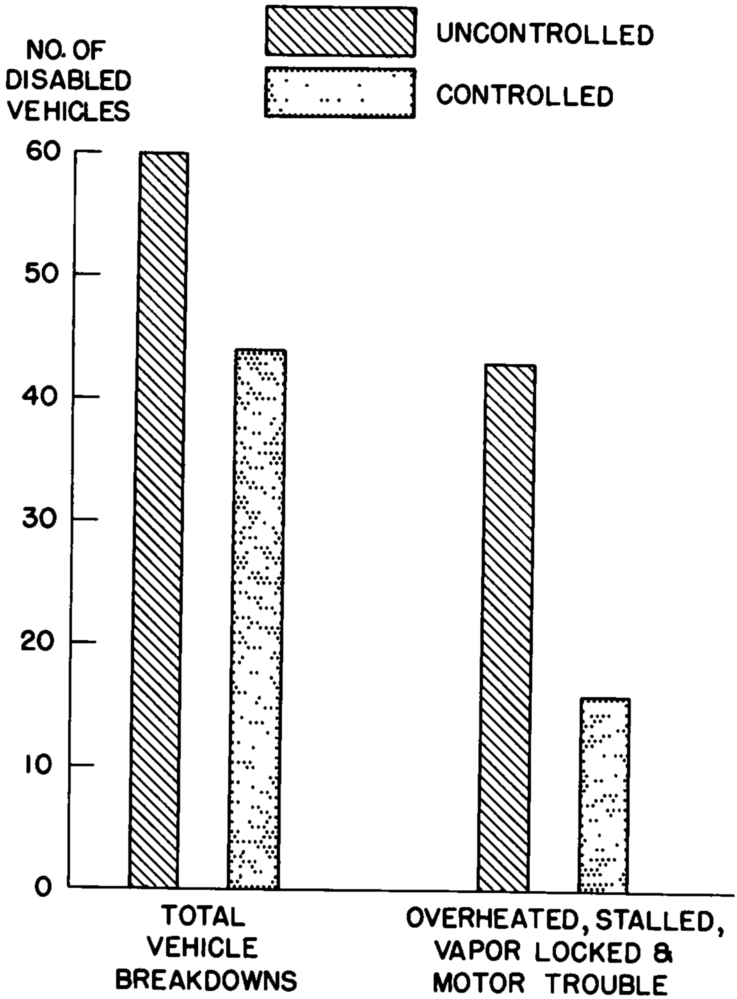


Figure 15. Vehicle breakdown comparison.

ventilation required during controlled flow. Even though the power consumed in ventilating the tube was decreased by 28 percent, the air in the tunnel at the same time was 20 percent cleaner (Fig. 17).

Equipment

The system of flow control equipment tested in these experiments had two general components. First, devices to limit traffic entering the tunnel were designed so that entering flows could be set as low as 15 vehicles per minute through a range in 1 vehicle per minute increments to a maximum of 24 vehicles per minute. The proper setting for this first component was to be determined continually in peak periods by a man observing the speeds and flows of vehicles approaching and through the bottleneck. Equipment to provide the speed information formed the second component. The equipment used in this system is shown in Figure 18.

The first main component of the system—devices to automatically limit the number of vehicles entering the tunnel to any desired level—was installed at the entrance to the South Tube, and consisted of:

1. Overhead signals, flashing stop signs and a bell, located where traffic starts on the downgrade to enter the tunnel (Fig. 19).

2. These entrance signals were actuated by a traffic spacing computer located in the tolls sergeant's building (Fig. 20). This device consisted essentially of a timer and a stepping switch. The computer turned on the entrance signals whenever more vehicles than the preset amount entered the near lane in less than the proper time.

3. In this system the number of vehicles entering the near lane of the tunnel is provided to the computer by vehicle detectors located at the point where traffic has been merged into two lanes and starts its descent to the tunnel entrance portal.

4. Controls for the system were all installed at the New Jersey tolls sergeant's desk at a point where the entire entrance plaza was in view.

The second component of this system—devices to measure the speed and flow of traffic at critical points in the tunnel—consisted primarily of equipment loaned to the Port Authority for this test by the Automatic Signal Division of Eastern Industries, Inc., and was located inside this tunnel as follows:

5. A radar speed sensor was mounted over the near lane at the foot of the upgrade.

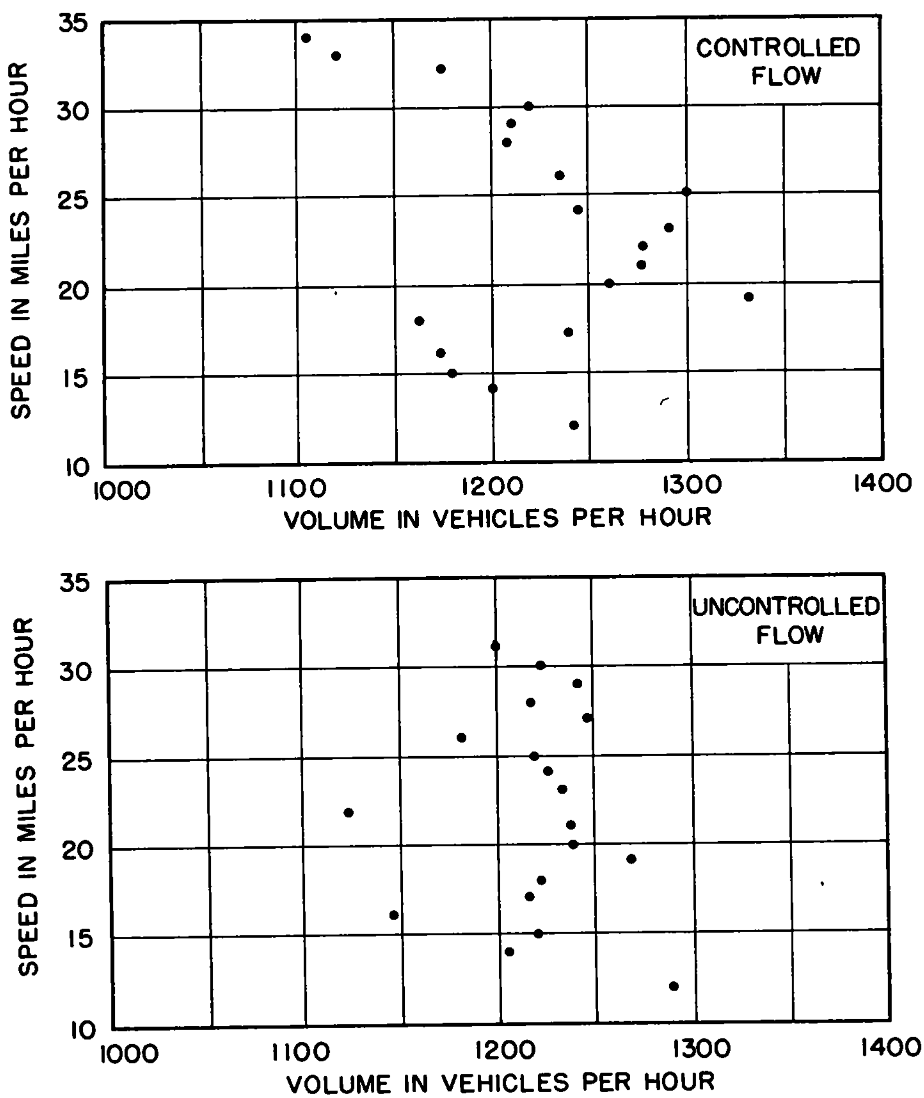


Figure 16. Bottleneck volume—speed relationship.

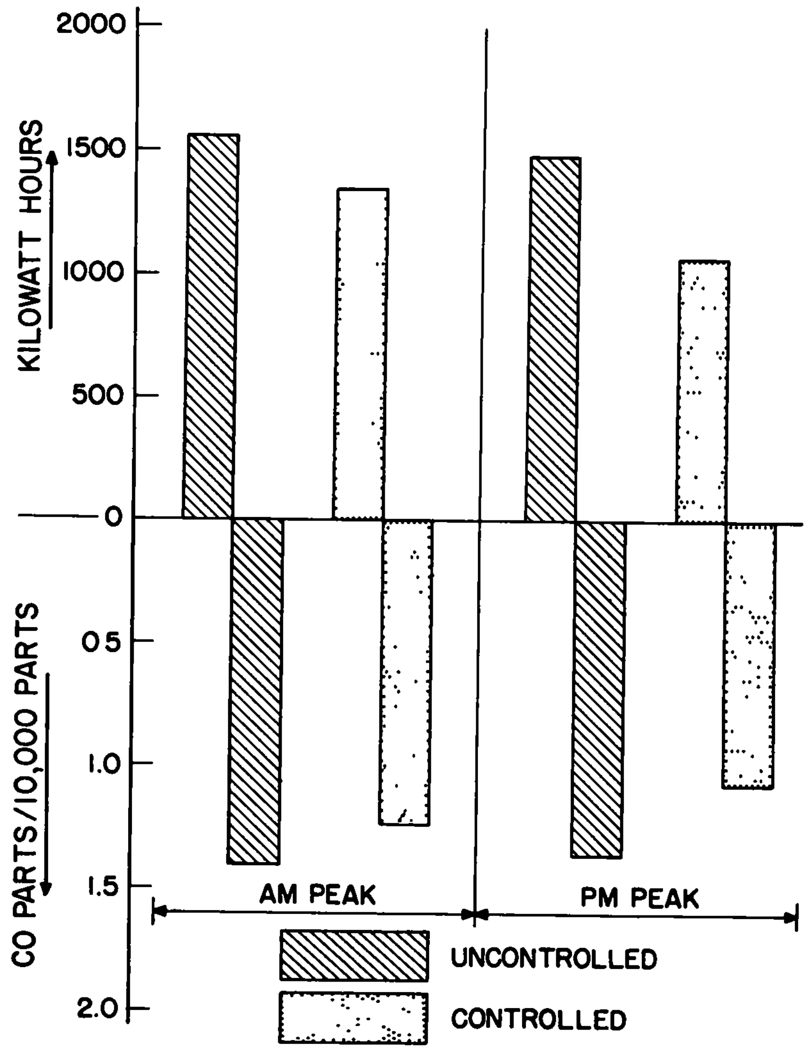


Figure 17. Power and carbon monoxide comparison.

6. A second radar speed sensor similar to the first was mounted 2,500 ft upstream (back toward the entrance) from the bottleneck.

7. Two systems of ASD Monitor equipment were provided (Fig. 21) in the Traffic Flow Monitor Center established for this test near the tunnel upgrade. This location is where the controller responsible for determining the proper setting for the input flow rate each minute was stationed. There, the staff member continuously "played" tunnel traffic, seeking to adjust the rate of traffic entering the tunnel to a level which would result in fluid, high rate flow through the bottleneck more than a mile inside the tunnel from the entrance portal. When the entering level was set too high, tunnel traffic became congested. When the entering level was set too low, the tunnel became starved for traffic and again, traffic production through the bottleneck would drop.

8. A one-camera, one-monitor closed circuit television system was installed to provide qualitative information on traffic flow conditions at the bottleneck.

Although this system did perform effectively during the test, it was evident to the experimenters that their control could be more effective. Analysis of the causes of

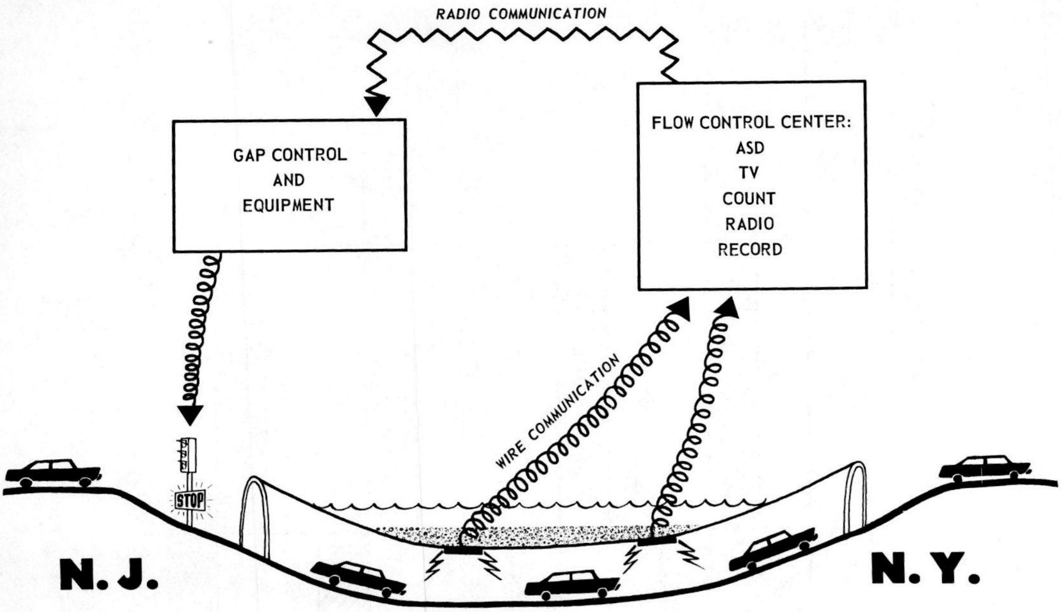


Figure 18. Traffic flow control cycle.

Figure 19. Entrance traffic signals.

production loss (Fig. 22) shows that in 39 percent of the cases when flow at the bottleneck was below average, the reason was inadequate control.

It became evident that measuring the speed and flow of traffic at the bottleneck alone was not enough to guarantee fully effective operation of the flow control system. As a general rule, the effectiveness of the flow control operation depended directly on the amount of information available to the controller. The more known about the current state of traffic flow through the tunnel, the more effective was the strategy followed by the controller in maintaining optimal flow.

The need for more information first arose as the effect of the time lag built into the initial system became clear. Observing flow and speed 6,000 ft downstream from the entrance portal, the controller acted on a situation over which he had no control until the traffic in the "pipeline" between the entrance and the bottleneck at the time of his decision passed through the bottleneck. This would require from 4 min to much longer times, depending on the amount of traffic in the pipeline. If the controller had observed traffic speeds below optimum at the bottleneck and decided that entering flow should be reduced, his decision would be wrong if there turned out to be relatively little traffic in the pipeline. In that case the bottleneck would soon lack traffic, and speeds would rise above optimum.

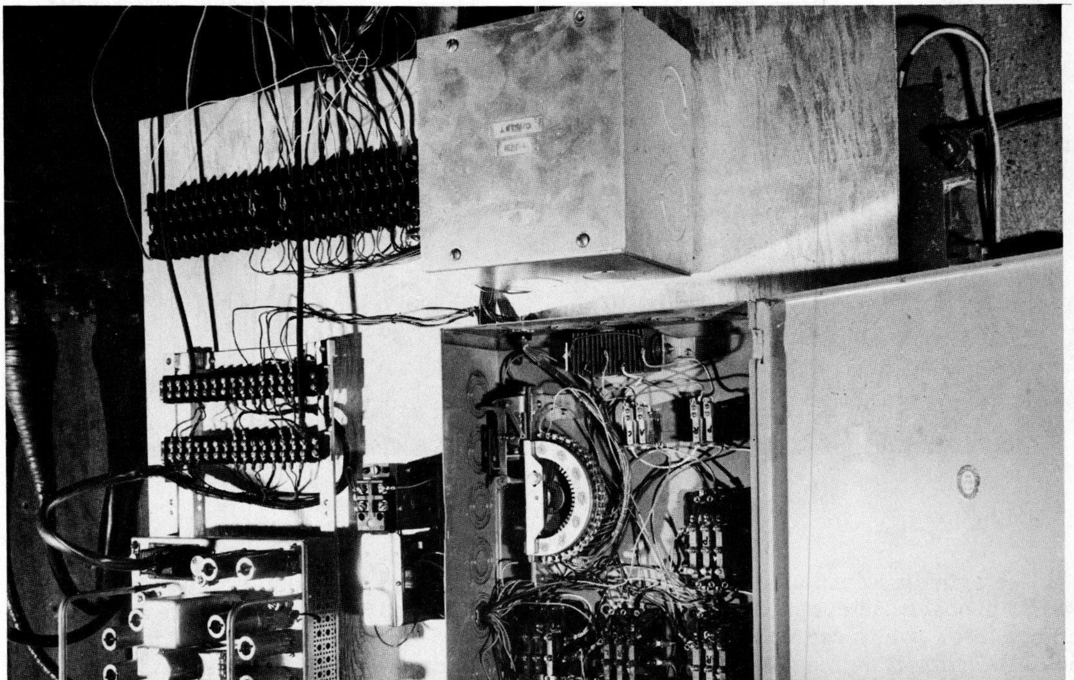


Figure 20. Traffic spacing computer.

Figure 21. Traffic flow monitoring center.

The principal conclusion drawn from this test was that the most effective system would probably be completely automatic. With an automatic system a large number of information points can be monitored continuously and consistent action strategies can be followed with immediate feedback of information on the effect of the strategy.

The test was not long under way before it became apparent that the least accurate piece of equipment in the system was the observer. Trying to exercise continuous control of stream flow for long periods of time was found to be extremely demanding on the individual. It required intense and uninterrupted concentration. The controller had to regularly evaluate information being received from several sources as well as consider the probable effects of his decisions on the traffic stream.

In view of the frequency and rapidity with which the state of traffic flow changes in the tunnel it was not possible for a man to provide the frequent and regular alterations in the entering flow needed to maintain a fluid high volume stream of traffic through the bottleneck.

Automatic Equipment

Based on these experiments, the Port Authority has now developed what might be

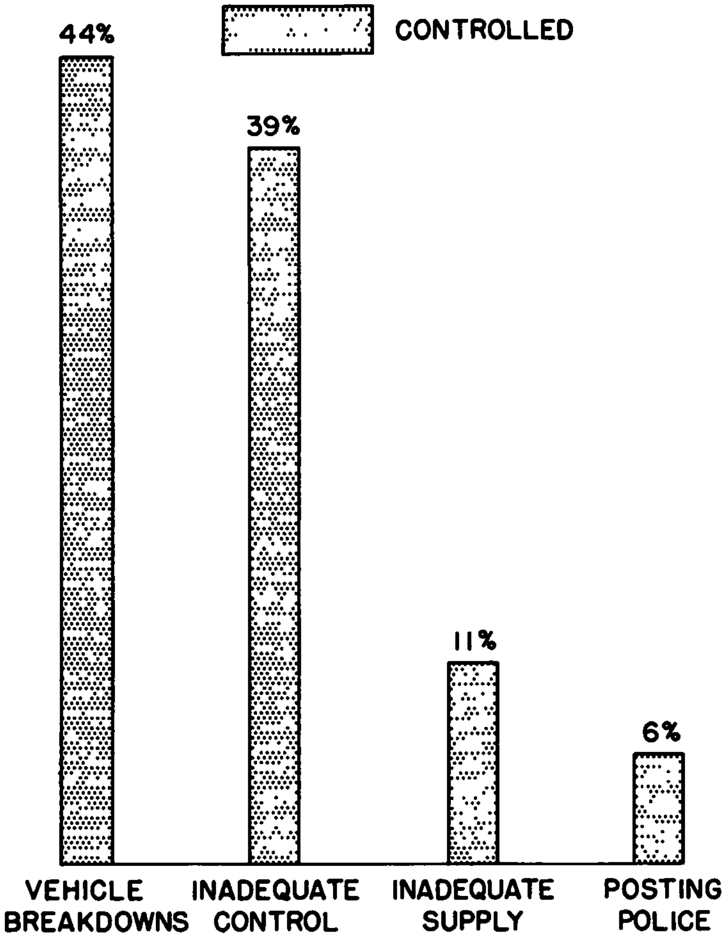


Figure 22. Causes of production loss.

described as a "first generation" prototype automatic system for controlling traffic flow.

The prototype system consists of three main elements:

1. Two sets of photocells—each set bounding a 13-ft zone for continually measuring the speed and flow of traffic through the zone. One set will be placed at the bottleneck (foot of the upgrade), and the second set will be 1,500 ft upstream. These two sets of photocells will be connected to the primary component of the new system, the flow computer.

2. The flow computer (Fig. 23)—located at the entrance to the Holland Tunnel South Tube. Each minute this computer will consider the number of vehicles which passed through the bottleneck in the preceding minute and then, by next considering the speeds of traffic approaching and at the bottleneck, establish a maximum number of vehicles which should enter the tunnel in the next minute. The prototype computer will not measure the speeds of vehicles exactly, but rather will determine when an excessive number of vehicles are going too slow or too fast to achieve the highest flow. This system has been entirely conceived, designed and built by Port Authority staff. Despite the relative simplicity of its design, the computer contains more than 70 relays. One of the most important features is the flexibility that has been built into the prototype computer, which will make it simple to change the action of the computer to improve its effectiveness as test operating experience is gained. After deciding each minute

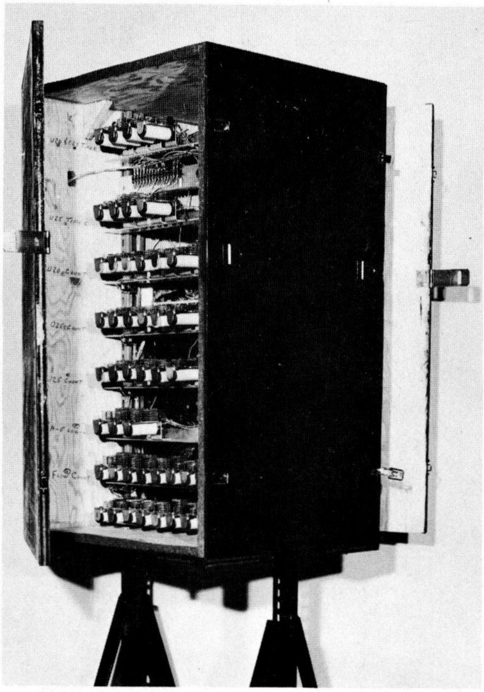


Figure 23. Prototype automatic flow computer.

the number of vehicles which should enter the tunnel in the next minute, the computer automatically adjusts a traffic spacer.

3. The traffic spacer—also located at the entrance to the Holland Tunnel South Tube. This element will perform essentially the same functions as the equipment shown in Figures 22 and 23, but will be compatible with the new flow computer. From an ultrasonic or induction vehicle detector placed at the tunnel near lane entrance, this traffic spacer will count the number of vehicles entering the tunnel. When the amount which has entered in less than a minute is equal to the amount predetermined by the flow computer, the traffic spacer will automatically turn the entrance signals red in both lanes for the remainder of that minute.

In testing this total system the Port Authority will use several recording devices to analyze the system operation. The main analytical tool is new Monitor equipment purchased from Automatic Signal Division.

It is most likely that this relatively straightforward flow control system will require a considerable amount of improvement both in functional design and in hardware. This system is the first prototype for accomplishing a job which is new in the field of traffic control, and one of the main values of this test will come in gaining new knowledge about traffic flow as the system is developed further.

Some of the specific points which will be considered are:

1. What is the effect on various types of traffic flow of various settings for the flow computer? What settings are best? What periodic or seasonal adjustments are desirable?

2. Are the very general speed divisions in this first prototype sensitive enough, or is it desirable to measure speeds in greater detail?

3. Should additional speed measurement points be added, and if so, where?

4. Are speed and flow the best traffic characteristics to measure, or should the system measure density, speed variance, or other characteristics? If density should

be measured, can this be done best by measuring flow at the entrance for a 3-, 4- or 5-min period?

5. Should the flow computer also consider the amount of traffic which actually entered the tunnel, and adjust its traffic spacing decisions up or down depending on the discrepancy between planned and actual traffic input?

6. How well does the far lane operate under this proposed system where input decisions are based entirely on the near lane? Should this near lane system be augmented with speed, flow or other sensors at critical locations in the far lane? Would a separate flow computer system for the far lane be desirable?

These questions show the extent of the study that will be needed to evaluate functional aspects of the flow control system. The answers will determine the design of a system likely to be most effective, and hence will strongly influence further development of the hardware aspects of this system. Here, the questions that may have to be considered are equipment reliability, whether relays are the best counting and timing devices for this type of circuitry (they probably are not, but at this stage they are easiest to work with), whether the Port Authority should construct a more advanced prototype, and when consultants and/or commercial manufacturers should be used to build more units.

Based on studies conducted to date, it seems likely that flow control systems of this type can be a significant help to engineers and roadway operators in gaining more effective traffic service from congested roadways. As these tests and developments are carried forward, the Port Authority will be pleased to make its findings available.

ACKNOWLEDGMENTS

The work reported in this paper is being carried forward through the active support and endeavors of many staff members of The Port of New York Authority. All major decisions relating to the development of the tunnel policing system are made by the Director of Tunnels and Bridges, Charles H. Taylor, after review by a special group of top Tunnel and Bridge management consisting of August Z. Schneider (Deputy Director of Tunnels and Bridges), Leslie C. Edie (Chief, Project and Planning Division), George E. Stickle (General Manager), J. Douglas Maynard (Manager of the Holland Tunnel) and Arthur Tate (Manager of the Lincoln Tunnel).

The traffic flow work is carried on under the primary influence and stimulus of Mr. Edie. Traffic flow experiments recorded in this paper were conducted under the immediate supervision of Kenneth W. Crowley and Alan T. Gonseth, who have also played a primary role in developing a functional specification for the automatic flow control system. Robert A. Hauslen and Carroll F. White have contributed to the design of this automatic flow control system. Tunnel management, especially Mr. Maynard and his staff at the Holland Tunnel, have been of great assistance in this work. Credit for successful performance of the flow control system is due Charles Kneeter and Daniel Cook under whose supervision the equipment has been assembled.

John D. Barbieri is of great assistance in coordinating the tunnel policing work, and Messrs. Hauslen and White have contributed much to the development of the electro-mechanical systems. Henry Wenson and Mr. Kneeter have played major roles in developing essential components for the tunnel policing system. The Port Authority's Traffic Engineer, Louis E. Bender, and his staff are participating in development of the traffic diversion system.

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