Effect of Shock Waves on Tunnel Traffic Flow

LESLIE C. EDIE AND ROBERT S. FOOTE
The Port of New York Authority

• TRAFFIC flowing through the south tube of the Holland Tunnel frequently shows an accordion-like action when there is more traffic than the tube can handle. This happens nearly every day. At these times, a motorist driving through the tunnel is forced to slow down drastically, and then after approximately one minute is allowed to proceed for a few thousand feet before a new shock wave in the traffic stream forces him to stop again.

Experimental work to understand this process and evaluate its effect on traffic flow is described in this paper. A traffic control procedure designed to prevent shock waves has been tested and found effective. When applied to a lane of the south tube during peak periods, this procedure results in a 6 percent increase in hourly flow and provides more rapid, more comfortable and safer traffic movement. Based on these and other experiments, the authors describe the process which may be operating to produce the observed results in single lane traffic flow.

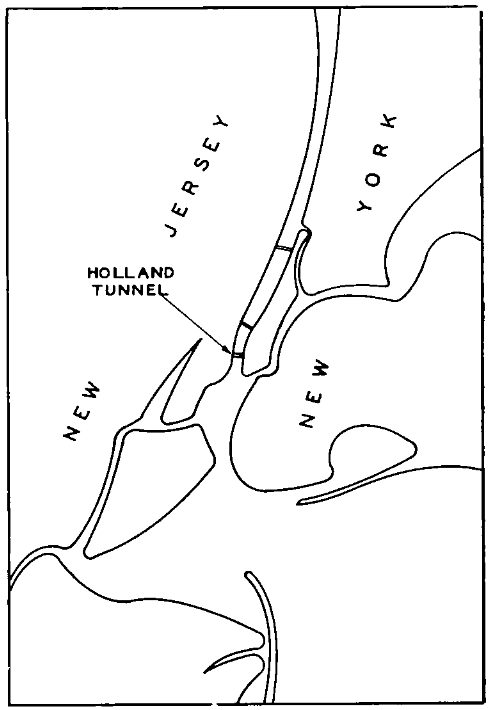


Figure 1. Location of Holland Tunnel.

MEASURING TRAFFIC FLOW

Experiments have concentrated on the south tube because congestion there is more severe and frequent than in other tubes. The Holland Tunnel (Fig. 1) was opened in 1927, and was the first major sub-aqueous tunnel ever built. It has two tubes, each more than 1½ mi long, connecting Jersey City with lower Manhattan at Canal Street. Each tube has two 10-ft wide lanes (Fig. 2). The lane nearest the catwalk is called the near lane; the other, the far lane. Both lanes of the south tube carry traffic to New York.

The Holland Tunnel approaches have required considerable improvement over the years. The most recent major improvement was at the exit from the south tube in New York (Fig. 3) where a new distributor roadway was opened in 1958. This roadway has improved the capacity of the exit.

On the New Jersey side (Fig. 4) the entrance to the south tube had to be fitted in among some large buildings and railroad yards. The toll lanes are located before the entrance, and because of property constrictions had to be offset so that traffic entering the far lane is required to make a relatively sharp jog. This offset does limit the improvement

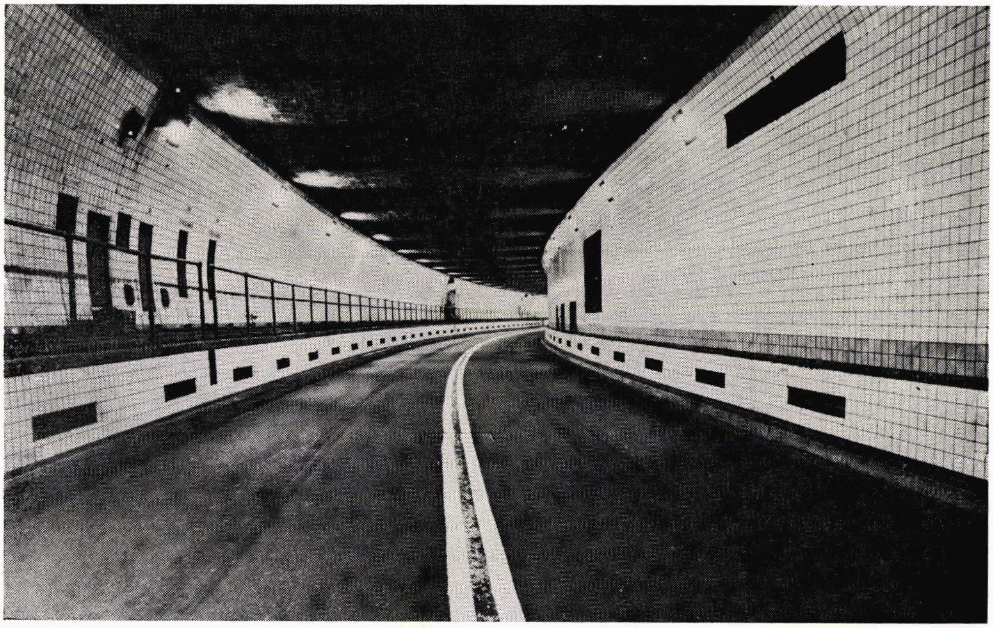


Figure 2. Holland Tunnel south tube.

that can be made in supplying traffic to the tunnel under present property use. As a general matter though, the plaza supplies ample traffic to the tube.

Total traffic through the south tube has been growing steadily (Fig. 5). The Holland Tunnel carries a large volume of commercial traffic, particularly through the south tube in the morning hours. The higher flows generally occur in the afternoon, when there are fewer trucks and tractor trailers.

Using data collection and analysis techniques described previously (*1*), the authors measured traffic flow at various points to locate the bottleneck and to measure the capacity of non-bottleneck sections. The bottleneck for congested flow was found to be at the foot of the upgrade in both lanes (Fig. 6) after analysis of speed and headway samples collected at nine locations in 1954 (*2*) and of a complete speed and headway record collected in 1957, 1958 and 1959 (*3*). These data were analyzed according to the fluid-flow model described by Lighthill and Whitham (*4*) and by Greenberg (*5*). In the near lane, these two independent series of data both indicated bottleneck capacity at the foot of the upgrade of 1,250 veh per hr. In comparison, capacity at the foot of the downgrade was estimated to be 100 vehicles per hour higher. Entrance and exit capacity was estimated to be 1,400 and 1,350 veh per hr, respectively.

Although the concurrence of the capacities indicated by these two independent series of data was encouraging and tended to support the usefulness of the fluid-flow model as a basis for analysis, these experiments also underscored the need for more understanding of the dynamic processes that occur in the traffic stream. Accordingly, two new series of experiments were designed to measure the condition of traffic flow at several points simultaneously throughout the tube.

Optimum Speed Platoons

The first experiments were derived from the concept of an optimum speed. This suggests there is one speed for any roadway section at which drivers will

Figure 3. South tube exit.

tend to maintain a spacing that will bring about a minimum time headway between cars. At either lower or higher speeds, drivers will space themselves so as to bring about a higher time headway, and thus lower flow. Using this concept, it was proposed that if a platoon of drivers was assembled at random and required to drive at an average speed close to optimum, the length of the platoon at any point would indicate roadway capacity. In traversing roads of high capacity at this optimum speed, drivers would drive quite close together and bring about a very low time headway and high maximum flow. In passing through a bottleneck, the drivers would have a longer spacing and somewhat longer time headway, indicating lower capacity of the bottleneck section.

The results of these experiments are shown in Figure 7. Although the capacity pattern is generally similar to that derived by the speed-headway data analyzed according to the fluid flow model, the values of maximum flow are much higher. This curve is the mean of 135 individual time headways. In each run, a Port Authority car was instructed to drive at optimum speed (between 20 and 25 mph) and was fed into the tunnel near lane at times when general flow was low and average speeds were much higher. Accordingly a large gap opened before this driver and he was able to maintain optimum speeds throughout the tunnel. Behind this lead car were fed 9 patron cars at random as they arrived and then, 10 headways after the first, a second Port Authority car was intro-

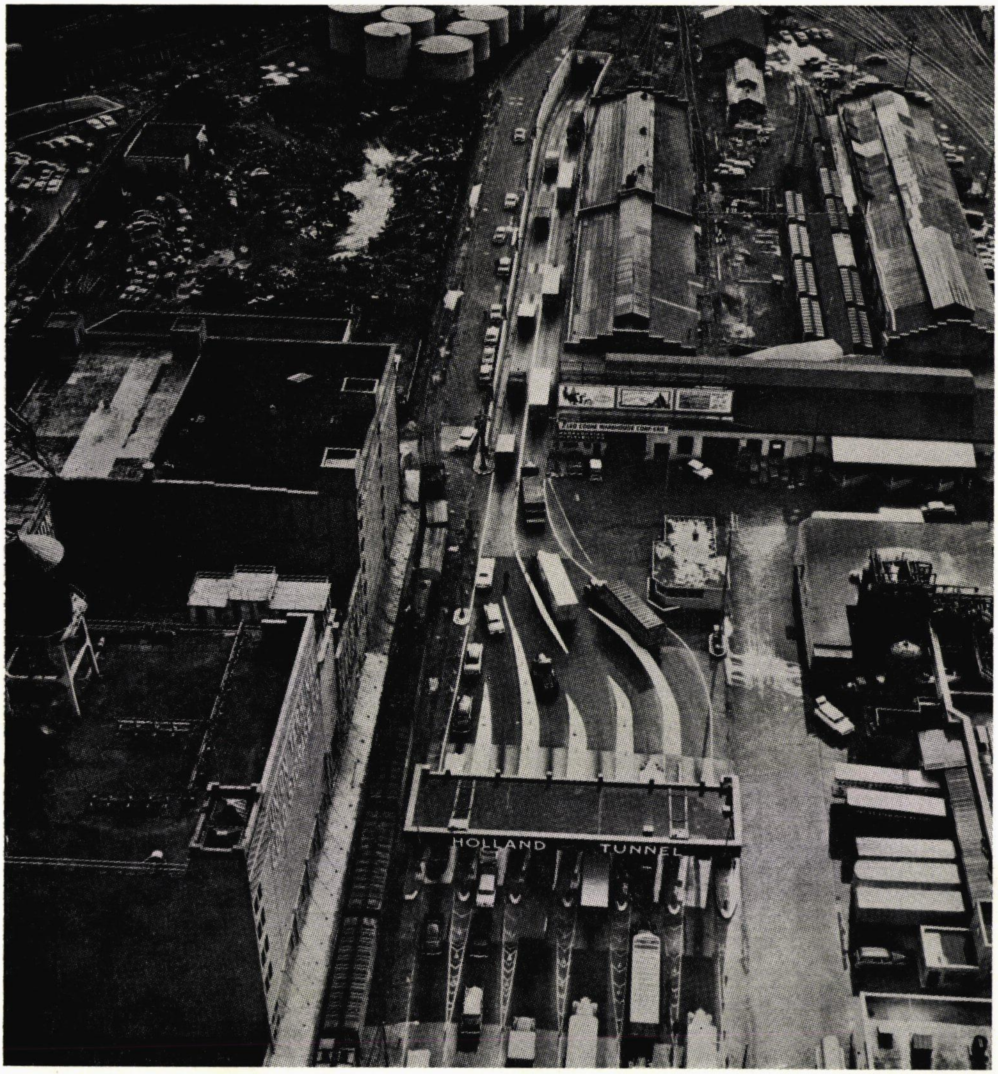


Figure 4. South tube entrance.

duced. In each Port Authority car there were two men, a driver and a timer-recorder. As each Port Authority car passed pre-designated stations approximately 500 ft apart, the driver would state "Mark" and the recorder would note the exact time his vehicle passed that mark. By dividing by ten the time elapsed between the two Authority cars in passing any station, the average time headway being maintained at that point by the random drivers at optimum speeds was determined. Furthermore, by determining the time required by the two Authority cars to travel the known distance between stations, the average speed of these drivers could be determined.

The maximum flow profile derived by this method indicates a minimum following a change in grade, and the bottleneck appears somewhat farther beyond the foot of the upgrade than indicated in

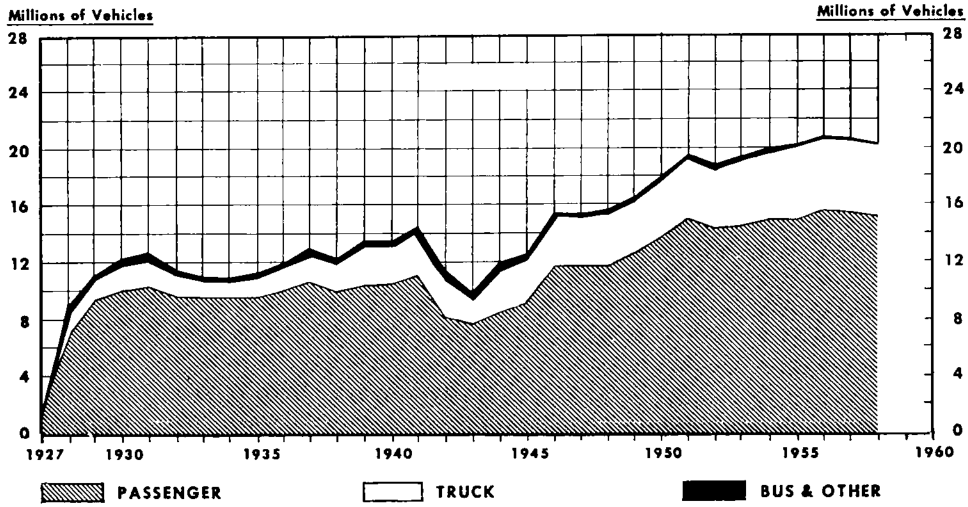


Figure 5. Holland Tunnel traffic.

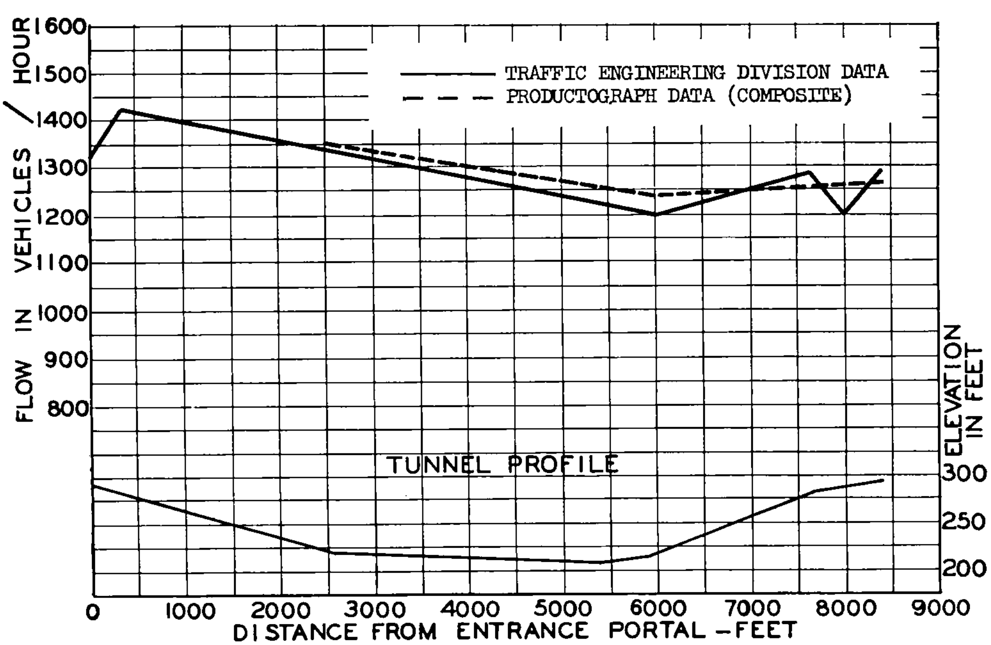


Figure 6. Flow profiles for south tube near lane.

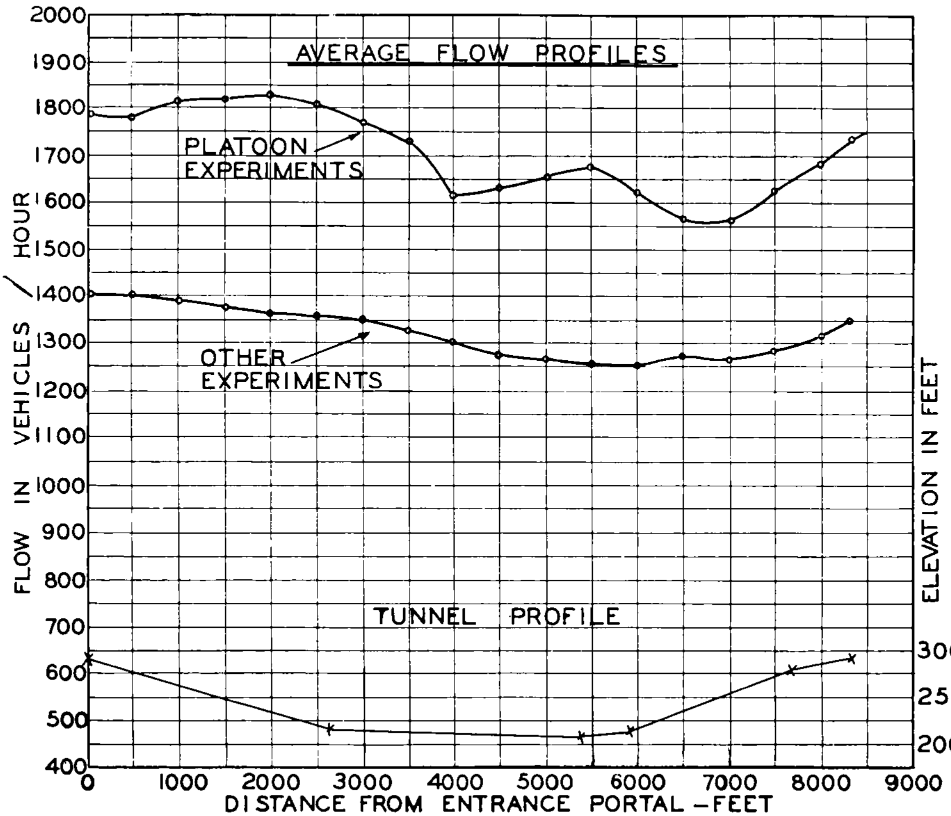


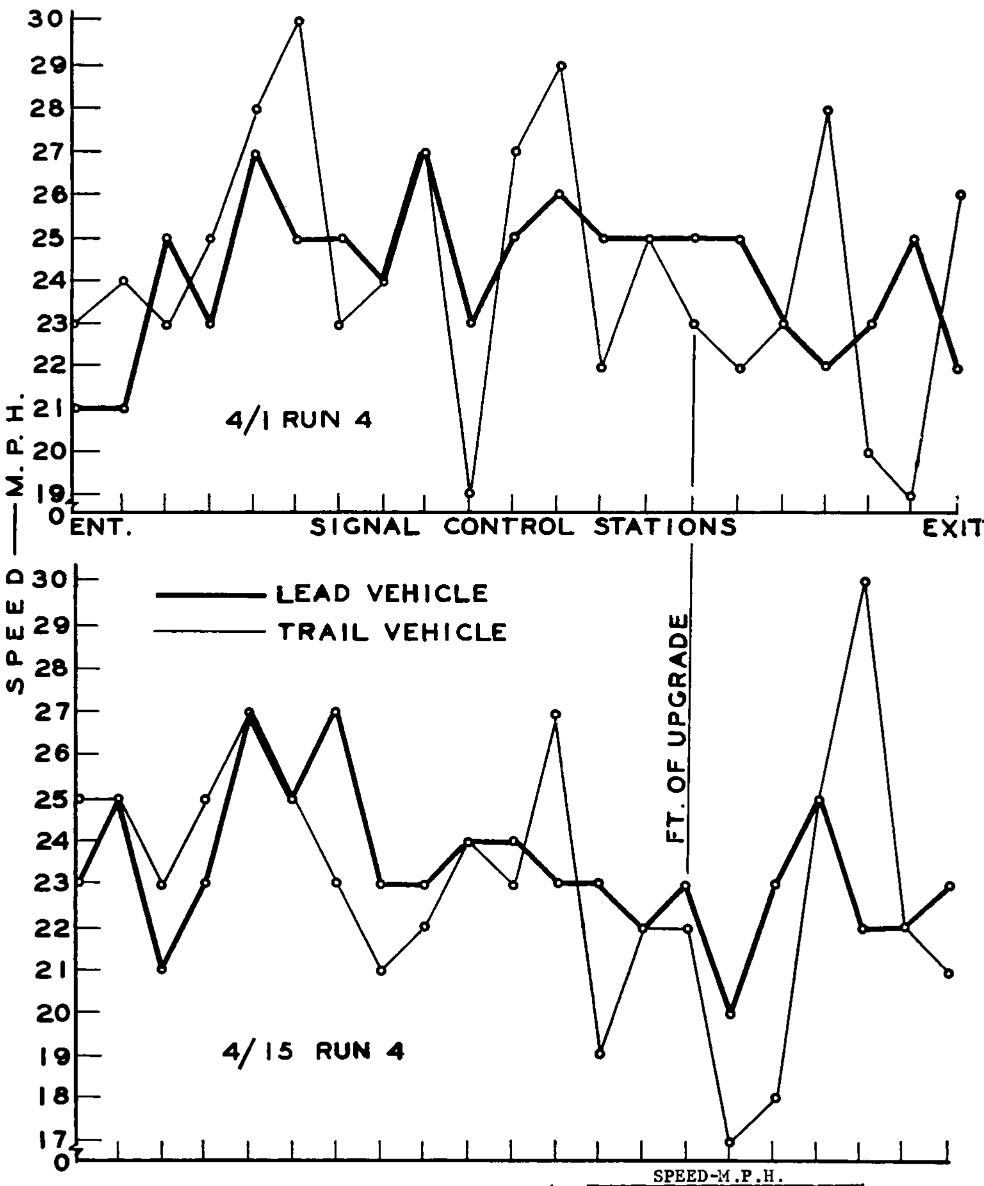
Figure 7. Average flow profiles by platoons, south tube near lane.

previous curves. This offset is approximately one platoon length beyond the grade change and indicates the last Port Authority car is just starting to accelerate with respect to the lead car. The last car normally would accelerate on entering a steeper grade. This apparent offset in bottleneck location is an interesting phenomenon which will be discussed subsequently.

Since the flow pattern produced by these experiments conforms generally with that developed by previous measurements (which would indicate the platoon experiments are realistic and significant) the relatively high flow values become of great interest. With the optimum speed platoon, flow through the bottleneck was 1,550 veh per hr compared with a normal peak flow of only 1,250 veh per hr through the bottleneck. One major difference in this experimental flow from that normally experienced during peak periods is the length of the platoons. During the experiments the last Port Authority car was observed to undergo significant speed changes, although the lead car was attempting to maintain a constant speed (Fig. 8). In the regular traffic stream, these speed changes may be transmitted to a twelfth, thirteenth, etc., car back through the stream.

Timed Sequence Observations

To investigate the wave action within the regular peak traffic stream, a second series of experiments was conducted. These were designed to record traffic flow in the normal peak-period stream at many points simultaneously, using minimum manpower and instrumentation. To



DATE	RUN	VEH.	SPEED-M.P.H. -2σ	MEAN	+2σ
4/1	#4	LEAD	20.6	24.1	27.6
		TRAIL	18.1	24.3	30.5
4/15	#4	LEAD	20.0	23.4	26.8
		TRAIL	16.9	23.1	29.3
4/1 & 4/15	Ave. of all 9 runs	LEAD	20.3	24.1	27.9
		TRAIL	17.3	23.6	29.9

Figure 8. Comparison of lead and trail car speeds.

HOLLAND TUNNEL
SOUTH TUBE

LANE NEAR

DATE: 10/14/59

TIME Hour	TIME Min.	0-14"	15-29"	30-44"	45-59"	Cars	Trucks	Buses	Total
		OBSERVATIONS							
4	0	CCTC	CCBCC	CCCCT	CCBCCC				
	1	CCCCT	CCCBC	CCCCC	CBCCCT				
	2	BCCCT	CCCCTC	CTCCC					
	3								
	4								
	5								
	6								
	7								
	8								
	9								
	10								
	11								
	12								
	13								
	14								

REMARKS:

SHEET No. 1

STATION No. 30

RECORDER Jones

Figure 9. Sample record for timed sequence measurements.

accomplish this, several men were used and each man was assigned to a different station. Each man recorded the vehicles passing him according to vehicle type (autos, trucks, buses, tractor-trailers) and according to the 15-sec time interval in which they passed (Fig. 9). Since the particular sequence in which any mix of vehicle types passes an observer is maintained throughout the tunnel, it is possible to determine the number of vehicles between any pair of observers at any 15-sec interval. Knowing the distance between the pair of observers permits converting the quantity of vehicles into a density value. Since the flow is known from the number of vehicles which passed an observer in 15 sec, it is possible to determine the average speed of segments of the traffic stream between any two observers.

These data were shown on vehicles versus time coordinates (Fig. 10), and the slopes of the lines indicate flow at

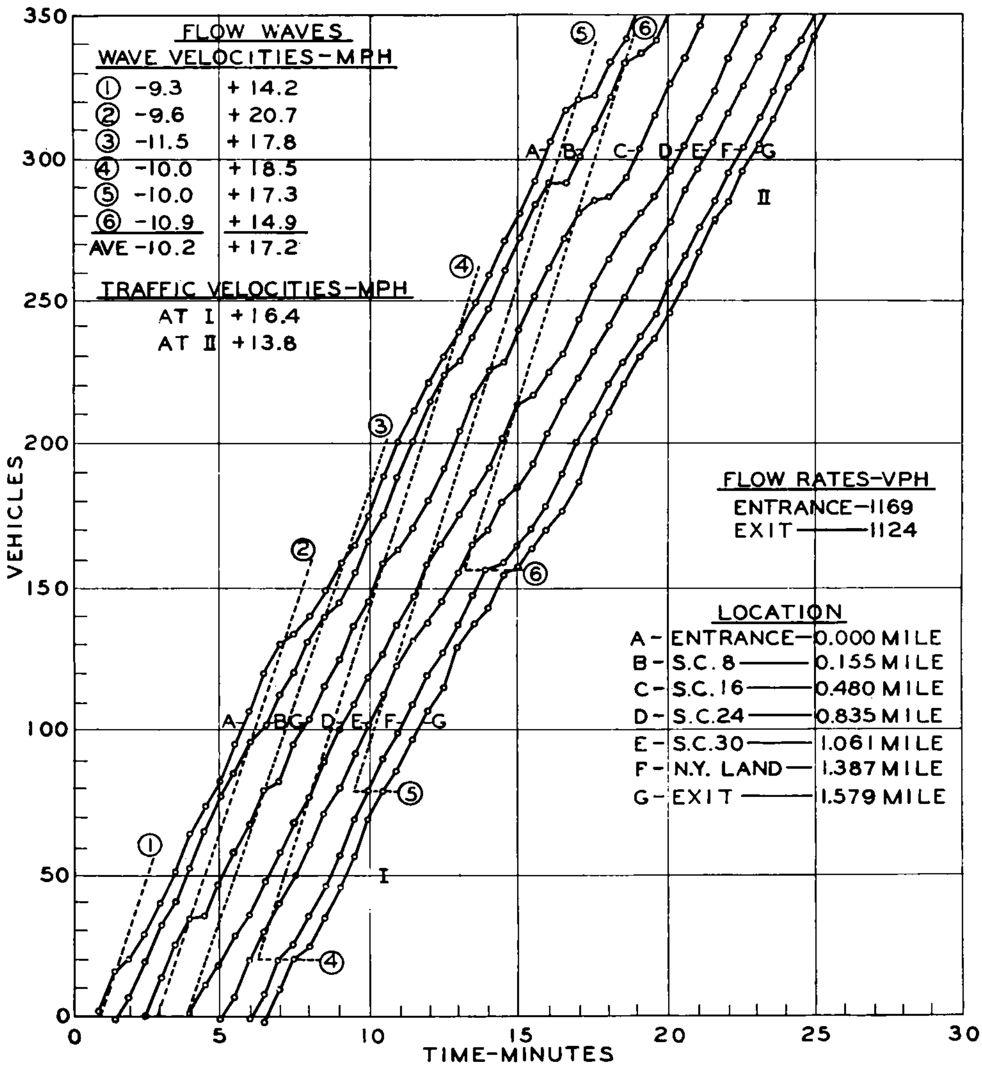


Figure 10. Timed sequence observations.

each station. This plot permits analysis of the flow throughout the length of the tunnel roadway. When this is done for peak flow, the accordion-like action is clearly revealed.

There appear to be three different types of flow at various sections of the Holland Tunnel south tube near lane. Near the foot of the upgrade, previously shown to be the bottleneck section, flow appears quite constant. Toward the tunnel entrance there are severe fluctuations in flow at more or less regular intervals—the accordion action. Periods of flow at a rate higher than is being processed through the bottleneck section are punctuated by periods when flow is negligible. Furthermore, these periods of low flow emanate near the bottleneck section and travel back along the roadway to the tunnel entrance. In effect this section of the tunnel delivers more traffic than the bottleneck can pass, and the excess is reflected back by shock waves in which traffic is forced to come to a standstill. The third type of flow is downstream from the bottleneck along the upgrade to the exit and is marked again with periods of low flow. In this case, however, the low flow wave moves with the traffic out the exit and is a gap.

In working with these data Greenberg (*6*) and other members of the Port Authority staff noted a distinct tendency for flow to be higher after there was a gap in the stream. This observation was consistent with the high flow levels observed in the optimum speed platoons, which also in effect were following a gap. After measuring the rate at which flow diminished from the high values observed immediately following a gap, Greenberg predicted an over-all increase in flow through the bottleneck could be attained if gaps were introduced so as to artificially structure traffic flowing through the bottleneck in platoons of 20 to 40 vehicles.

EXPERIMENTS TO INCREASE TRAFFIC FLOW

The experiments to verify Greenberg's prediction required limiting flow entering the near lane so as to avoid overloading the bottleneck and causing the speed of the traffic stream to drop below optimum. This was accomplished by stationing an observer at the entrance to the near lane to count traffic arriving each 2 min. When 44 vehicles arrived before 2 min expired, a police officer held traffic until the 2 min were up. This introduced a gap in the stream, usually of about 10-sec duration. This gap would probably lose its identity as the traffic stream approached bottleneck area, but the important point was to keep flow at a level that would not overload the bottleneck.

The results of an extensive series of tests showed hourly flow in the near lane increased approximately six per cent when the special procedure was used. These tests were conducted on 12 weekdays (Table 1) between 4:00 P.M. and 5:00 P.M. and days when the procedure was used were alternated with 13 other days when measurements were made without introducing gaps. Average hourly flow during the gaps was 1,248 vehicles, compared with only 1,176 when the control procedure was not used. Possibly more striking is the fact that only on 1 of the 12 days when gaps were introduced was hourly flow less than 1,200. Conversely, on only 4 of the 13 uncontrolled days did hourly flow exceed 1,200.

This improvement in bottleneck productivity would alone justify regular use of the special procedure, but there appear to be other benefits as well. This procedure is aimed at maintaining freely moving traffic through the tunnel, by preventing a higher flow from entering the tube than can be processed through the bottleneck. With the resulting free movement of traffic, motorists can traverse the tunnel more rapidly. Furthermore, waves do not form upstream from the bottleneck, and without these periodic sharp decelerations traffic flow is smoother and safer. One other advantage is the reduced exposure to vehicle breakdowns achieved through having fewer motorists in the tunnel at any one time, through having each motorist spend a shorter time in the tunnel, and through permitting motorists to maintain speed without having to stop for shock waves. Since vehicle breakdowns account for major losses in tunnel capacity, their reduction by this means may well account for further significant increases in tunnel productivity. (In the experiments previously discussed the effect of stoppages is excluded in the analysis.)

A system of control equipment has been devised and tested to space entering traffic on a day-to-day basis to maintain higher flow through the bottleneck. The relative simplicity of this system is considered desirable at a stage when knowledge about traffic flow is expanding so rapidly. It is becoming increasingly clear that ultimately an extensive system of communication and control equipment will improve tunnel traffic operation, and work along these lines is under way at the Port Authority. Until the main lines of an ultimate system can be determined,

TABLE 1

COMPARISON OF CONTROLLED VS. UNCONTROLLED FLOWS
HOLLAND TUNNEL, SOUTH TUBE, NEAR LANE, 4 TO 5 P.M.

Date, 1959	Day	Flow Type[1]	Elapsed Time (Min)	Stoppage Time (Min)	Hourly Flow adjusted for Stoppages	
					C	*U*
6/16	T	C	60	0	1164	—
6/17	W	U	60	5	—	1270
6/18	Th	C	48	0	1302	—
6/19	F	U	55	5	—	1196
6/22	M	C	61	1.5	1247	—
6/23	T	U	58	0	—	1147
6/24	W	C	59½	0	1285	—
6/25	Th	U	60	0	—	1268
6/26	F	C	43	0	1247	—
6/29	M	U	60	8.5	—	1089
6/30	T	U	60	4.5	—	1183
7/1	W	U	60	0	—	1154
7/2	Th	U	60	0	—	1173
7/13	M	C	58	0	1243	—
7/14	T	C	52	0	1237	—
7/15	W	U	60	0	—	1202
7/16	Th	U	70	8.5	—	1086
7/17	F	C	53	0	1275	—
7/20	M	U	60	0	—	1141
7/21	T	C	60	0	1225	—
7/22	W	C	60	5.5	1229	—
7/23	Th	U	60	2.5	—	1081
7/27	M	C	63	4.5	1244	—
7/29	W	U	60	0.0	—	1294
7/30	Th	C	57	0.0	1276	—
				Total	14,974	15,284
				Average	1248	1176
				Difference	(C − U) = 72	

[1] C = Controlled, U = Uncontrolled.

however, low cost and relatively expendable equipment systems are especially attractive.

The present equipment system for spacing entering traffic has three components: a vehicle detector at the entrance to the near lane; a computer circuit consisting of a stepping switch and a timer, which generates an alarm when 22 vehicles enter the lane in less than 53 sec; and signals at the lane entrance to stop traffic for the short time interval between the arrival of the 22nd vehicle in less than 53 sec and the expiration of that minute.

This system has been tested, and it is found successful in maintaining free moving traffic at a high rate of flow. The next step is a 30-day test program to determine the most effective system of signals for stopping entering traffic flow for 5 to 10 sec and to determine the best way to integrate this procedure with other operations which must be performed on the entrance plaza. This test will begin as soon as the necessary automatic recording devices for evaluation have been installed, and as soon as appropriate information has been prepared to inform the public of the purpose of this new procedure.

This last step is especially important in this case, because the first impact of this procedure on the motorist is to delay him for no apparent purpose. Furthermore, at first glance, the expressed purpose of the delay is illogical. "How can you get more traffic through the tunnel by not letting as much in?"

DISCUSSION

It has been suggested that flow would be improved by preventing the overloading of the roadway (*7, 8*). The work done by John Barker in designing the Automatic Signal Division's monitor equipment is aimed at the same problem. However, it is believed that the Port Authority project provides the first extensive controlled experimental verification of the concept that flow can be improved by being restricted.

The reasons for the delay in effecting such an improvement probably arise in part from the lack of a definitive understanding of why, under certain circumstances, flow should be improved by being restricted. The Port Authority has attempted twice in previous years to test this concept, with negative results. One attempt, which periodically would allow the tunnel largely to clear out, resulted in increased accidents due to the decelerations of fast moving newly introduced traffic when it caught up with slow moving traffic previously in the tunnel near the exit. The other experiments, which sought to maintain a fixed distance spacing of 75 ft between vehicles, were not effective.

On the contrary, as previously reported by Strickland (*9*) and subsequently confirmed by statistical analysis (*10*), inauguration of self-feeding at the Lincoln Tunnel ostensibly to avoid gaps inherent in feeding traffic under police officer control resulted in increasing tunnel production by 73 veh per hr. It now appears that at the Lincoln Tunnel the right procedure may have been inaugurated for the wrong reasons. It is possible the officer control resulted in an over-all increase of flow despite the gaps occasioned when traffic in one line was stopped and another line started. Removal of the officer control, under this interpretation, would have been beneficial in reducing the rate of entering traffic rather than increasing it.

Further Questions

These instances have been cited to underscore the need for a definitive understanding of traffic flow. It is hoped the experiments reported here will contribute to the development of such an understanding and, indeed, several questions have arisen during these experiments. Some of these are discussed hereinafter, together with some of the considerations which may bear on the answers.

Why does not traffic naturally make the maximum use of available capacity? One consideration which seems pertinent here is the tendency of vehicles in a platoon passing through a bottleneck to be traveling more slowly the more remote they are from the platoon leader. This was reported by Palmer (*11*) in his study of traffic flowing over a temporary bridge on the Merritt Parkway. A similar phenomenon has been observed by Greenberg in flow through the Holland Tunnel south tube (*6*). A similar mechanism was derived by Helly in his simulation of single lane traffic flowing through a bottleneck (*12*). At maximum flow, such as was observed in the optimum speed platoon experiments, the platoons would be very long and thus, the speeds of vehicles passing through the bottleneck would drop so low eventually that headway times would start to increase. One cause for headway time to increase as speeds decrease is probably just the additional time required by the vehicle itself to pass a point as it travels more slowly.

Several authors have recognized the rapid changes in flow which occur when speeds drop below optimum, and Palmer (*11*) has described them in detail. As headway times increase, the bottleneck is no longer processing vehicles as frequently as they are arriving, and the need arises for individual drivers to delay arriving at the bottleneck until they can be accommodated. Thus there is a sharp decrease in speed and a queue of vehicles is suddenly formed. This queue grows in proportion to the margin by which the rate of arriving vehicles exceeds the rate the bottleneck is processing vehicles.

Why should this speed reduction continue to limit flow? The apparent offset in bottleneck location between that indicated by the optimum speed platoons and that indicated by the measurements of regular traffic flow tends to support an interpretation that the downstream end of the queue then becomes the bottleneck, rather than the environmental or random factor which might have been responsible for the initial speed reductions. This interpretation is further supported by the findings of Forbes (*13*) and others that the time used by motorists in reacting to an acceleration by the vehicle ahead is twice as long or even longer than that used in reacting to a deceleration ahead. The combined effect of slow acceleration reaction and the change in grade apparently acts so that each vehicle starts accelerating at approximately the same point on the roadway. The balance between acceleration reaction time and headway time is of course not exact, and there is some movement in the downstream end of the queue. However, it has been observed this acceleration maneuver tends to localize in the general vicinity of the grade change point in the Holland Tunnel south tube.

Why is traffic flow increased when input is restricted? In view of these considerations, it would appear the reason that flow is improved when input is restricted so as not to overload bottleneck capacity is that this procedure precludes formation of a slow speed queue. It does this by interrupting platoons going through the bottleneck. This interruption tends to limit the drop in speed between the platoon leader and trail vehicle, so the trail vehicle speed is not less than optimum. Once the slow speed queue has been formed, as indicated by vehicle speeds less than optimum (17 mph in the south tube), flow is then constrained by the longer headway times present in the slow speed queue. Furthermore, because these headway times are approximately equal to the acceleration reaction times, the slow speed queue tends to stagnate within the tunnel and continue to constrict flow.

How do shock waves enter this picture? The shock waves would be a symptom of the breakdown in flow rather than the immediate cause of the lesser flow. These waves might be generated by the growth of the slow speed queue, caused by the excess of traffic arriving at the upstream end of the queue over that being processed through the standing speed and acceleration wave at the downstream end of the queue. As the queue grows, traffic approaching it is forced to decelerate to queue speed at a point moving back along the roadway towards the entrance. This may cause, in some drivers, a sharp deceleration in which the vehicles come to a stop. When this occurs, flow approaching the upstream end of the queue would drop to zero for a short period, while flow at the downstream end would continue at a steady rate through the acceleration wave. The queue would thereby decrease in size. Thus a gap would open between the upstream end of the queue and the downstream end of the shock wave. As vehicles start from the shock wave into this gap, the starting wave continues to move back to the entrance. As the starting wave moves upstream to environments of higher capacity, the flow following passage of the starting wave rises quickly to levels above bottleneck flow, and the queue will therefore again start to grow. When this flow increases above the amount being processed through the standing acceleration wave at the downstream end of the queue, a new cycle might commence generating a new shock wave.

In conclusion, the need for definitive understanding of traffic flow is again emphasized. The gains that can be derived by such an understanding in realizing greater productivity from the huge public investments represented by the country's arterial highway network justify redoubled efforts to achieve this understanding.

REFERENCES

1. Edie, L. C. and Foote, R. S., "Traffic Flow in Tunnels." *HRB Proc.*, 37:334-344 (1958).
2. "Preliminary Report, Holland and Lincoln Tunnel Traffic Survey, April 16-23, 1954." Traffic Eng. Div., The Port of New York Authority (Unpubl.).
3. "Vehicle Speed and Headway Data by Simplex Productograph, 1956, 1957, 1958 and 1959." Project

and Planning Div., The Port of New York Authority (Unpubl.).

4. LIGHTHILL, M. J. AND WHITHAM, G. B., "On Kinematic Waves, A Theory of Traffic Flow on Long Crowded Roads." *Proc. Royal Soc.* A 229:No. 1178, 316-345 (1955).
5. GREENBERG, H., "An Analysis of Traffic Flow." *Operations Research, 7*:79-85 (1959).
6. GREENBERG, H. AND DAOU, A., "Limiting Traffic Flow to Increase Flow." *Operations Research* (in press).
7. NORMANN, O. K., "Highway Capacity Manual." U. S. Dept. of Commerce, Bureau of Public Roads, U.S. Gov't Printing Office (1950).
8. BARNETT, J., "Operation of Urban Expressways." *Proc. ASCE,* Paper 1374 (Sept. 1957).
9. STRICKLAND, R. I., "Traffic Operation at Vehicular Tunnels," *HRB Proc.,* 33:395-404 (1954).
10. MILLER, D. W., "The Effect of the Change to Self-Feeding at the Lincoln Tunnel South Tube." Tunnel Traffic Capacity Study Report II, The Port of New York Authority, Oct. 1956. (Unpubl.)
11. PALMER, M. R., "The Development of Traffic Congestion." Yale Univ. Bureau of Highway Traffic (May 1959).
12. HELLY, W., "Dynamics of Single-Lane Vehicular Traffic Flow." Mass. Instit. of Tech., Center for Operations Research.
13. FORBES, T. W., ZAGORSKI, H. J., HOLSHOUSER, E. L., AND DETERLINE, W. A., "Measurement of Driver Reactions to Tunnel Conditions," *HRB Proc.,* 37:345-357 (1958).