Developing Density Controls for Improved Traffic Operations

ROBERT S. FOOTE and KENNETH W. CROWLEY
The Port of New York Authority, Tunnels and Bridges Department

Traffic through a single-lane road section with a bottleneck at output is considered as a system involving input flow, section density, output speed, and output flow. Effects of output flow on output speed, output speed on section density, and section density on input flow are shown.

Four case studies are described, each with different patterns and levels of traffic production. Consistent relations among section density, output speed, and output flow are observed. Flow is at a maximum when output speeds are in midrange; output speeds are a delayed inverse function of section density. The effect of an early automatic system for controlling section density by limiting input flow based on measuring output speeds is described. Use of direct measures of section density to stabilize the control system is planned.

•AN INTENSIVE study is being made of traffic flowing through the Holland and Lincoln Tunnels to determine reasons for the significant fluctuations observed in peak traffic production through these expensive roadways, and to enable controlling pertinent variables to raise the overall level of peak traffic production. These studies have shown that increases of a few percentage points in peak traffic production can have a dramatic effect in reducing the duration of congestion (1). An increase of 4 percent in traffic production can result in a 33 percent cut in the duration of congestion (1, 2).

Peak hourly traffic figures in each tunnel lane regularly vary more than 4 percent. Traffic production through these tunnels differs by as much as 50 percent from the capacity of other similar tunnel lanes and by as much as 100 percent from the capacity of open expressway lanes.

One consequence of this research has been to demonstrate that controlling tunnel traffic to maintain fluid movement and prevent congestion can increase traffic production by approximately 5 percent. An automatic system controlling input flow based on traffic conditions inside the tunnel has been found to cause an overall improvement of 2 percent, but significant oscillations in tunnel traffic conditions were evident. The need for an improved control logic led to undertaking more detailed measurements of tunnel traffic behavior over a length of roadway.

This paper reports the conditions observed as a result of these measurements. Four different types of output flow are described. Consistent relations among density, speed and flow are observed indicating that a more stable and effective control logic can be obtained.

EXPERIMENTAL CONDITIONS

The traffic system consists of a 6,000-ft single tunnel lane having a bottleneck at the output end and changing from 3 percent downgrade to level 3,100 ft from the entrance. In addition to measuring traffic at both the entrance and output points, measurements

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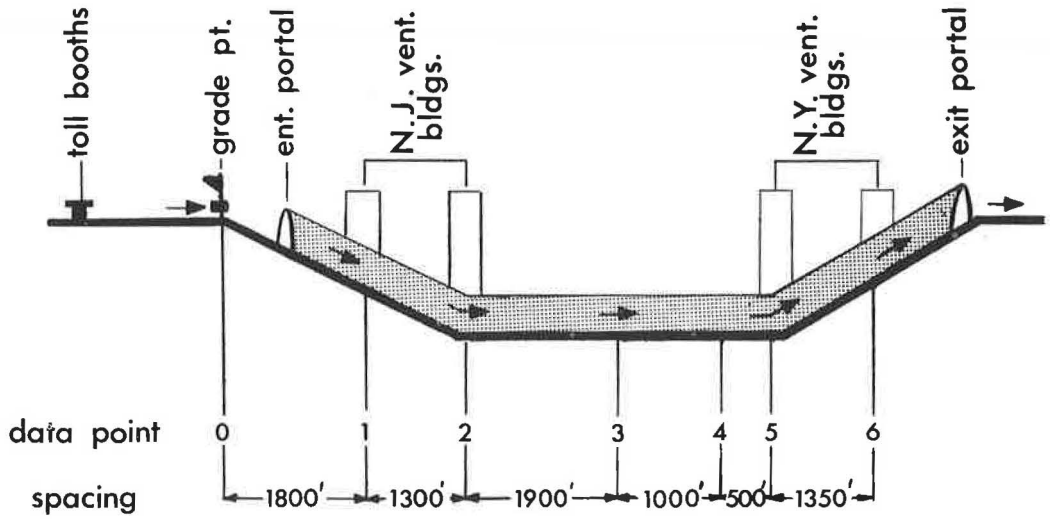

Figure 1. Location of data points: Holland Tunnel, south tube.

were also taken at the intermediate point on the downgrade section, at the grade change point, and on the level section (Fig. 1). Additional data were collected beyond the output section, but with one exception, data from those points are not used.

Data were collected at each tunnel point by a pair of photocells spaced 13 ft apart under the tunnel roadway, completely out of view of passing motorists. As a vehicle passed each pair, four events occurred: (a) the light beam to the upstream photocell was broken, (b) the light beam to the downstream photocell was broken, (c) the light beam to the upstream photocell was re-established, and (d) the light beam to the downstream cell was re-established. The sequence of the second and third events depends on the vehicle length. The occurrence of each event at each pair of cells was recorded on one channel of a stereo-magnetic tape recorder. Data were collected concurrently and multiplexed on the one channel from each of the four tunnel points. Simultaneously, on the other channel a 100-cps time tone was recorded. Therefore, for an hourly traffic flow of 1,200 vehicles, a total of 1,200 times four points times four events—or a total of 19,200 units of information—was recorded. Each of the four cases is based on at least one hour of data, and in one case, on two hours of data.

Data reduction was handled automatically, two cells at a time, by converting magnetic tape information to punched paper tape using the traffic data reduction system developed by the Port of New York Authority (1), based on a similar system developed by General Motors Research Laboratories (3). Punched paper tape was converted to IBM cards and the data were then processed through various error correcting and computational programs, using the IBM 7070 computer.

For traffic passing each point, the computer output states for each vehicle:

1. Time (to the nearest hundredth of a second) at which it entered the trap;
2. Headway time between it and the vehicle ahead;
3. Headway in feet to the vehicle ahead;
4. Velocity in feet per second;
5. Velocity of that vehicle relative to the vehicle ahead in feet per second;
6. Length of the vehicle; and
7. Whether the vehicle was accelerating, decelerating, or maintaining constant speed.

The IBM output also provides a number of computed parameters for each vehicle or group of vehicles, including virtual density, virtual flow, average speed, average density, and average flow.

Measurement of the length of each vehicle passing a detection point is a particularly important element of this system. Observing the sequence of vehicle lengths passing one point and matching with the same sequence of vehicle lengths passing a point downstream later in time, it is possible to state exactly the number of vehicles between the two points at any instant. This measure of section density differs from other measures also labeled "density," which are computed by dividing the number of vehicles passing a point during a fixed time interval by the average speed of that traffic passing that same point. The latter measure indicates the number of vehicles passing over a length of roadway downstream from the measurement point only so long as the vehicles continue to maintain the same speeds as were observed at the measurement point. For control purposes, it is the fact that speeds lessen as traffic passes through the bottleneck section which is of most interest. It is possible to estimate section density through analysis of point densities so long as traffic conditions are fluid, but the method of deriving and averaging speed and flow measures to compute an accurate density measure requires the section measurements as a control (4).

Consideration of the number of vehicles present over the length of roadway used is an important element in distinguishing this study from others (e.g. 5), which have used point density measures. It was of particular interest to evaluate the extent to which section density could be used as a control parameter leading to more stable and higher peak traffic production through the output bottleneck.

OUTPUT FLOW CONDITIONS

Figure 2 summarizes the four output flow conditions; 5-min moving averages of output flow are plotted against a reference value of 21 veh/min. In Case 1, a morning peak period with 19.8 percent commercial traffic, there is considerable fluctuation above and below the reference value of 21 veh/min. In Case 2, with 0.9 percent commercial traffic (an afternoon peak period), the output flow is remarkably consistent. For 30 min (from 10 min to 40 min after the beginning of the experiment), the output flow was consistently 20 veh/min. At no time did the flow average more than 22 veh/min, and in general, this consistent flow is relatively low.

Much higher output flow was observed in Case 3, also an afternoon peak period with similar composition of traffic as in Case 2 (only 0.4 percent commercial). For most of the time during the 90 min of the experiment, output flow was consistently higher than 22 veh/min. However, during the last 30 min, output flow decreased considerably, breaking the 22 veh/min barrier only for 6 min.

Case 4 (with 1.7 percent commercial traffic) demonstrates the operation of an early automatic system limiting input flow based on output speeds. Severe oscillations in output flow are evident. While the level of output flow at the high values usually exceeded 22 veh/min, the low values were considerably more frequent, and in this particular example the average output flow was quite low.

While the output flow is seen to vary considerably in each of these four cases, analysis was made to determine the extent to which these four different patterns could be explained by a consistent relationship of section density and output speed, as discussed in detail for each of the following cases.

Case 1: Uncongested Flow

Figure 3 shows Case 1—AM uncontrolled 5-min moving averages of input flow, output flow, section density and output speed. Input flow fluctuates considerably between 17 and 23 veh/min, with no apparent regularity. The trace of output flow shows a pattern very similar to that of the input flow, but occurring 3 to 4 min later. This suggests that traffic conditions are fluid, and therefore, section density will be less than critical.

Section density on a 5-min moving average is at all times less than 50 veh/mi, at some times dropping to 35 veh/mi (Fig. 3). Most of the time the 5-min moving average of output speed was above 30 fps, and on some occasions rose above 45 fps. There also appears to be a tendency for output speed to be an inverse function of section density, displaced by 2 to 3 min.

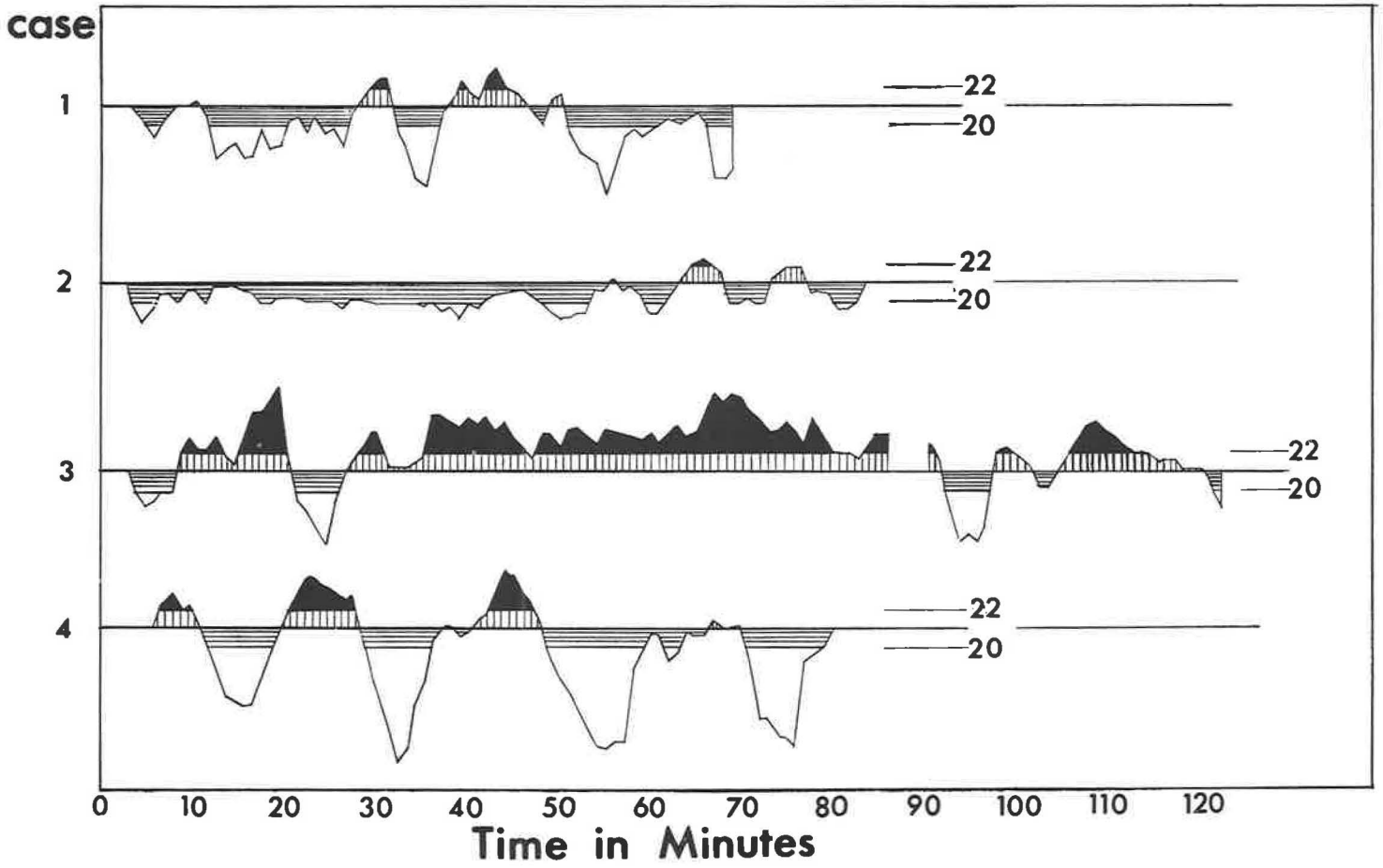

Figure 2. Output flow comparison, 4 cases.

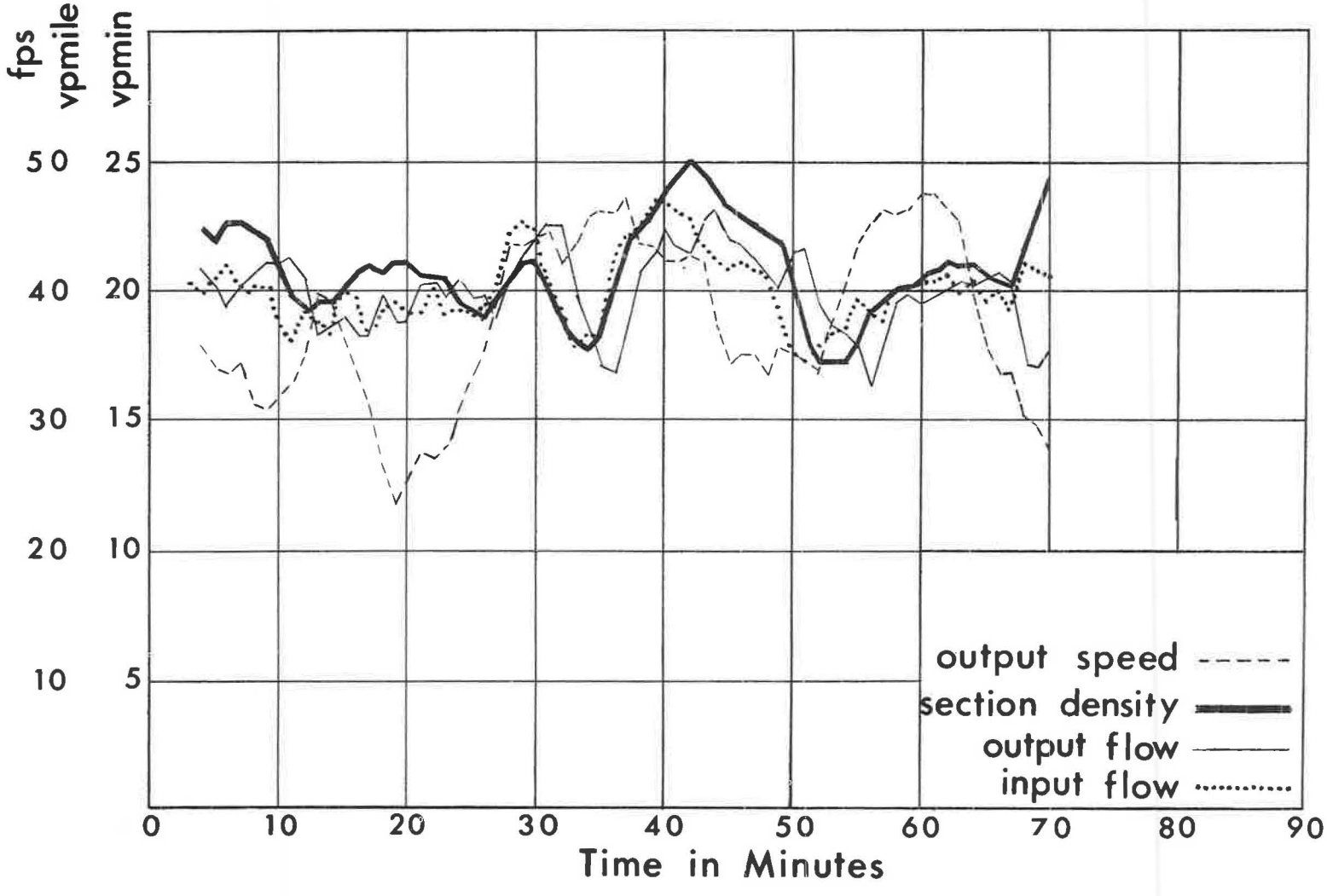

Figure 3. Case 1—AM uncontrolled 5-min moving averages: input flow, output flow, section density, and output speed.

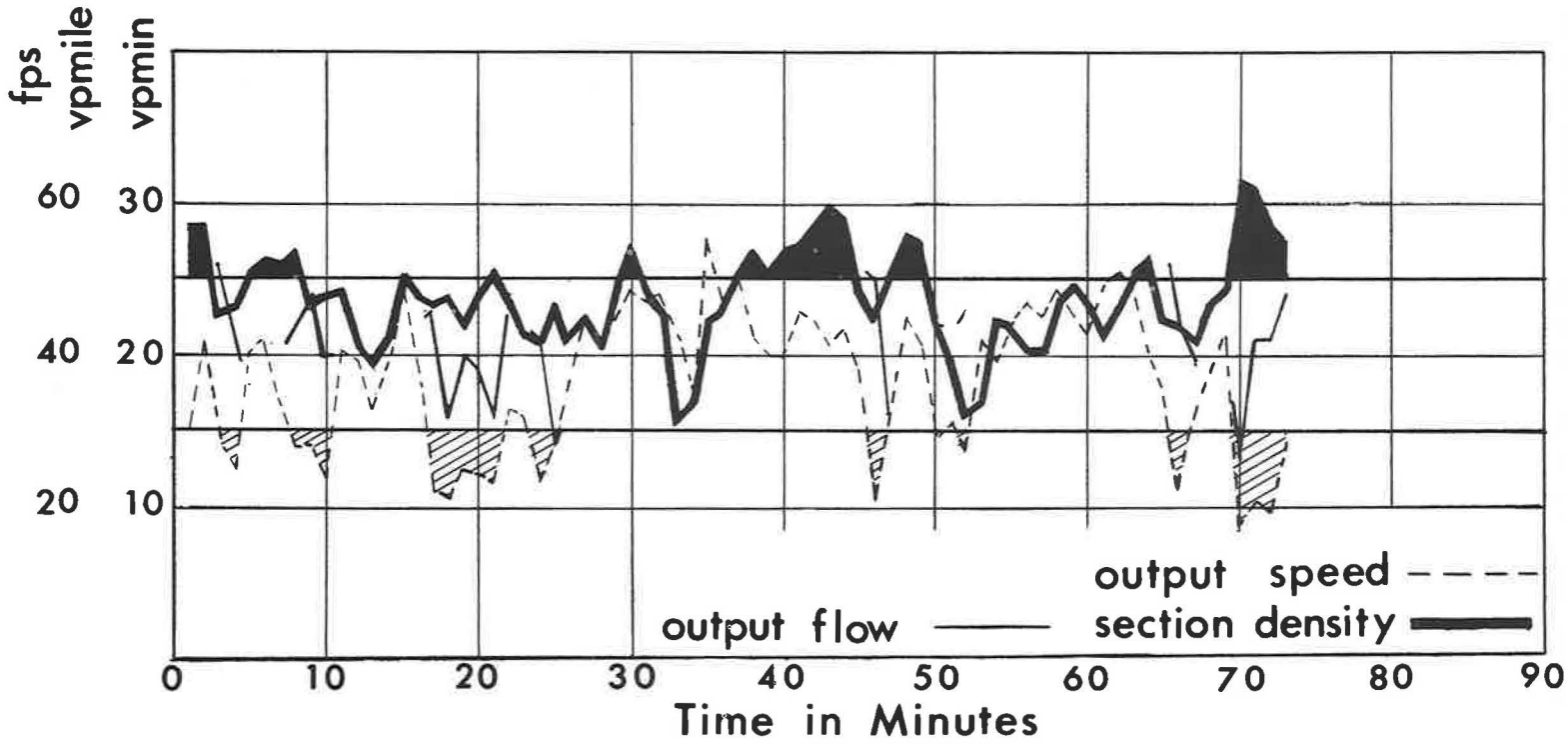

Figure 4. Case 1—AM uncontrolled 1-min data: section density plus output speed, density over critical—velocity below critical, and pattern of output flow.

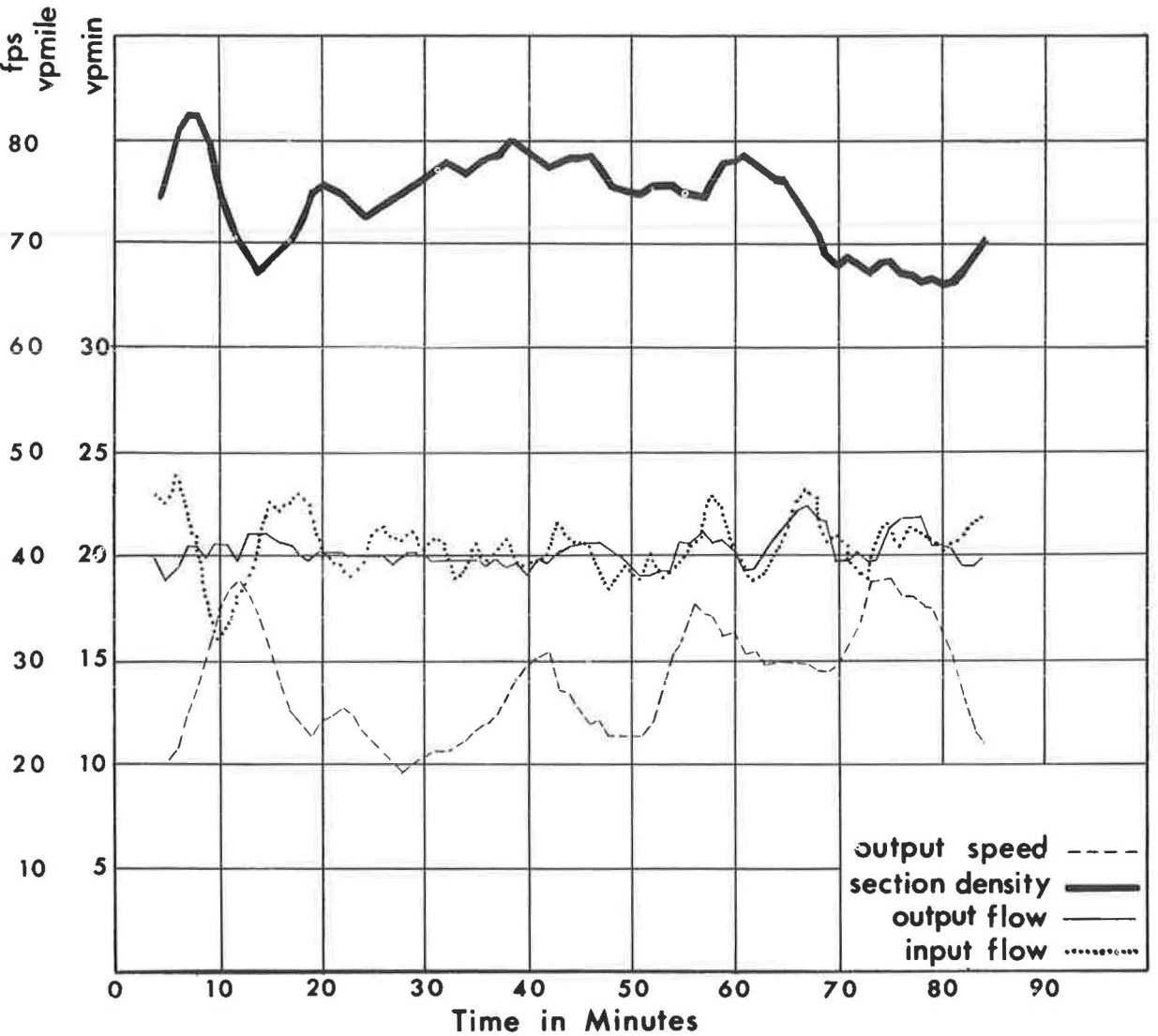

Figure 5. Case 2—PM uncontrolled, high density 5-min moving averages: input flow, output flow, section density, and output speed.

The four traces typify conditions when the tunnel is processing all the traffic entering it without congestion. In terms of vehicles per minute handled throughout the study period, this first case ranks third among the four considered. However, when the comparison is based on the number of vehicle-feet handled rather than the absolute number of vehicles, this case becomes the second most productive. This may or may not be an optimum adjustment for the commercial traffic handled in this example, but it indicates that relatively high flows can be achieved when tunnel traffic conditions are fluid.

Despite the general fluidity of traffic during this example, however, examination of the output speeds averaged over 1-min intervals shows (Fig. 4) several occasions when output speeds drop below 30 fps. Section densities on a minute-by-minute basis were remarkably consistent, but several instances were observed where the 1-min densities exceed 50 veh/mi. Since in previous studies (6, 7) these two levels of 30 fps and 50 veh/mi have been identified as levels at which traffic production might begin to decrease,

the time relationship between these apparently critical density and speed levels was examined next. The shaded and solid areas of Figure 4 emphasize the relationship between high densities and low speeds; in virtually every case a density of about 50 veh/mi was followed in a few minutes by an output speed less than 30 fps.

Considering only those times when output speeds drop below 30 fps, the pattern of output flow can be seen in Figure 4. In nearly every case, output flow decreases while speeds are below 30 fps. However, the pattern occurring at 70 min shows that this is not a completely regular phenomenon since, despite the low output speeds occurring then, section densities were sufficiently high as to provide an increase in output flow.

Case 2: Congested Flow

What probably would have happened in Case 1 if input flow had remained high enough following the end of the experiment to keep section densities above 50 veh/mi is shown in Case 2.

Figure 5 shows an input flow pattern with fluctuations generally between 17 and 23 veh/min, similar to the range in Case 1. However, output flow exhibits none of the fluctuations observed in the input flow. There is remarkable consistency at 20 veh/min, with nearly every flow contained in a band between 19 and 21 veh/min. This consistency in output flow suggests that the road section is operating under pressure—an ample supply of traffic is being processed through the output bottleneck at a uniform and relatively low rate.

The trace of section density (Fig. 5) confirms that there is a high number of vehicles in the tunnel—nearly always above 70 veh/mi. This affects output speeds which are nearly always less than 30 fps, and never reach 40 fps.

To determine whether these high density levels were accompanied by shockwaves as found in previous studies (8), the pattern of speeds throughout the tunnel was examined. Figure 6 shows the 1-min averages of speed at each of the tunnel points, including station 5 just beyond the bottleneck. Zero speed reference is plotted on the ordinate at a location analogous to the geographic location in the tunnel. While the speeds at station 4 are generally in the 20 to 40 fps range, speeds at station 3 drop below 20 fps on several occasions. Similarly, speeds below 20 fps are observed periodically at station 2; at station 1, speeds dropped below 10 fps on some occasions. Furthermore, it is apparent that the low speeds at each of these stations are related to low speeds at the other stations by straight lines of similar and negative slope. Therefore, Figure 6 demonstrates that the congested conditions shown in Case 2 were accompanied by shockwaves generating from the bottleneck section, between stations 4 and 5 at frequent intervals and reflecting back to the tunnel entrance.

Case 3: High Production, Fluid Flow

Exceptionally high flow through this tunnel roadway section is exhibited in Case 3. For 90 min, flow averaged 22.6 veh/min or 1,356 veh per lane hour, compared with the usual output of 1,150. The highest hour flow recorded for this lane in the last two years is 1,402 vehicles—less than 50 vehicles higher than the flow shown in Figure 7.

The pattern of input flow (Fig. 7) exhibits the fluctuation typical of the input flow patterns shown in Cases 1 and 2, but at a generally higher level and exceeding 25 veh/min on several occasions. The output flow pattern appears to follow the input flow pattern generally for the first 40 min, but then becomes more consistent than the input flow pattern. After the first 60 min of the experiment, the input flow pattern exhibited several peaks which were not matched by the output flow pattern. After the first 90 min, the output flow pattern dropped markedly for 5 to 6 min and then returned to the above 20-veh/min level. However, in contrast to the average output flow of 22.6 veh/min for the first 90 min, the last 30 min of this experiment had an average output flow of only 21 veh/min, or 6 percent below the previous flow.

Section densities exhibit a particularly interesting pattern during this experiment (Fig. 7); they were generally below 50 and averaged near 40 veh/mi for the first 60 min of the experiment. Then, however, as input flow consistently exceeded output flow, densities climbed rapidly above the 50 veh/mi critical level and up to a level of 80.

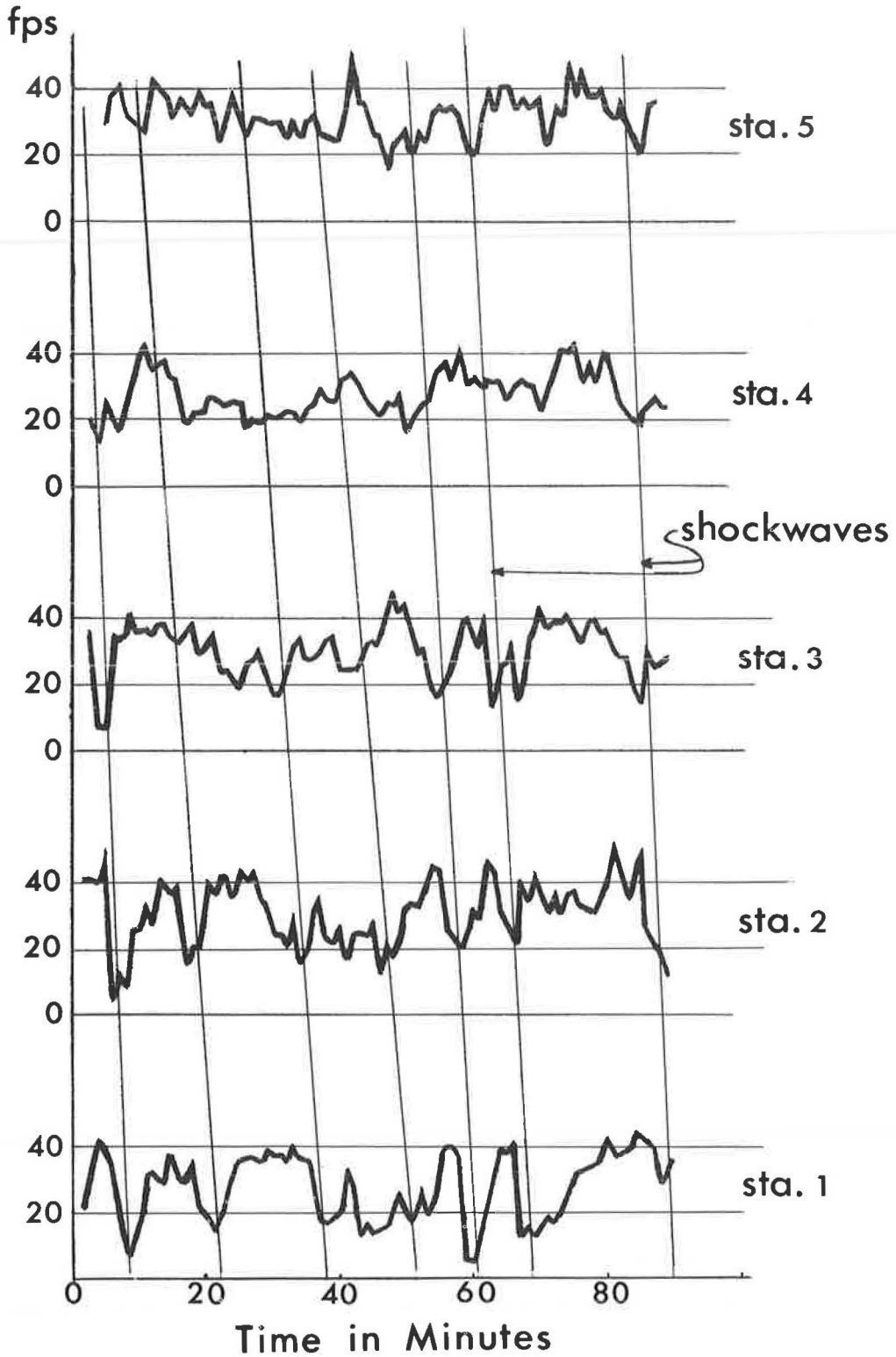

Figure 6. Case 2—PM uncontrolled, high density 1-min data: shockwave occurrence.

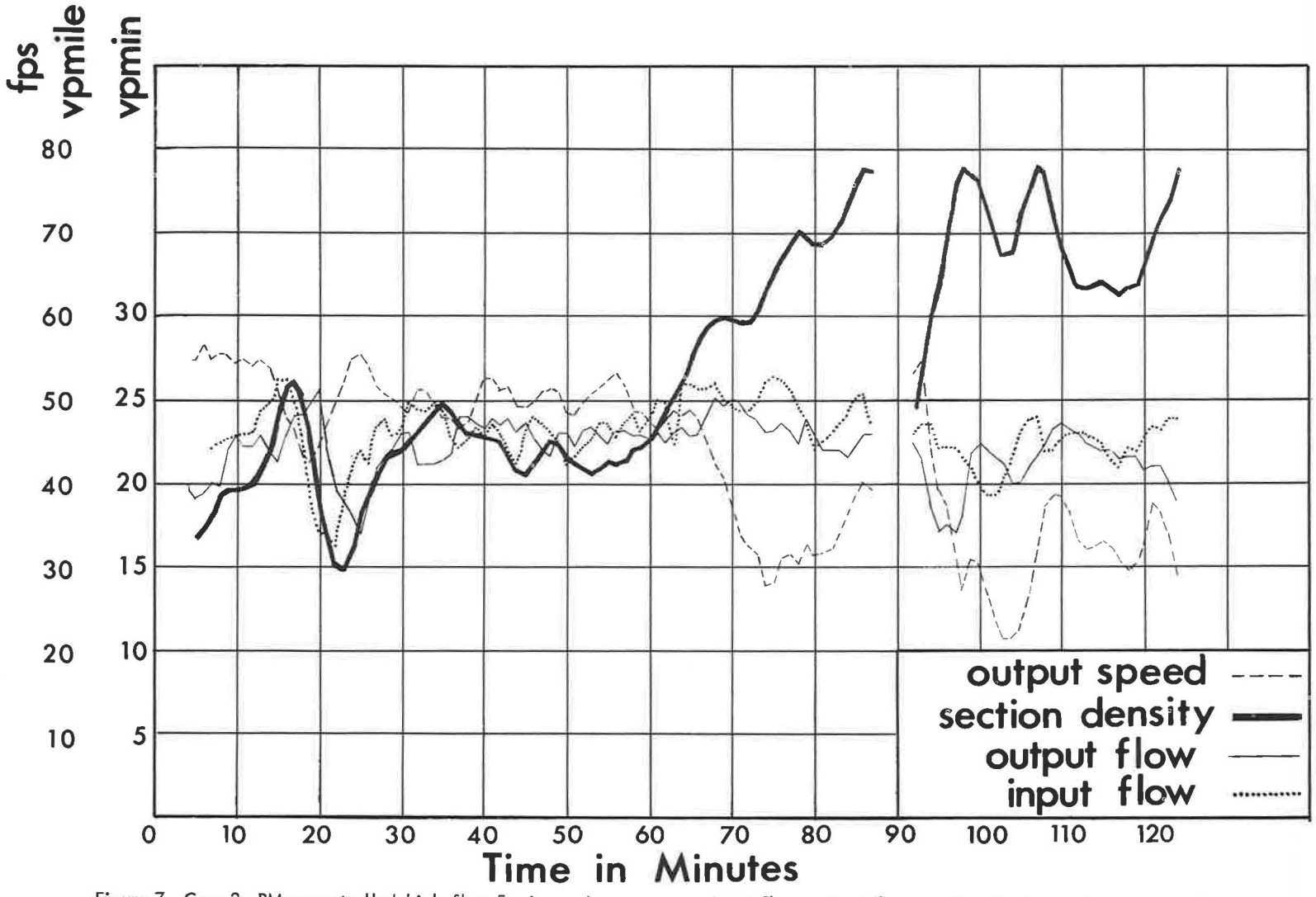

Figure 7. Case 3—PM uncontrolled, high-flow 5-min moving averages: input flow, output flow, section density, and output speed.

The need to change the magnetic recording tape caused a loss of data for the 5-min interval from 87 to 92 min after the start of the experiment. When the measurements resumed there had been a sharp drop in section density. This had to be caused by a drop of input flow relative to output flow. Examining the pattern of densities at the several stations within the tunnel in these critical minutes between 80 and 86, Figure 4 of Crowley and Greenberg (6) shows that a shockwave had generated and was moving back to the entrance. Apparently then, the shockwave caused a sharp drop in input flow during the missing minutes from 87 to 92. But also, when the measurements were resumed, output flow dropped markedly again causing a sharp rise in section density. For the remainder of the experiment, section density remained above 50 and generally near 70 veh/mi.

The pattern of output speeds (Fig. 7) sheds more light on the condition of the tunnel during the missing data. But first, it should be noted that all through the first 60 min of the experiment when output flow was high, output speeds were also high, averaging 50 fps. Then, during minutes 60 through 90 when density climbed from below critical to more than 75, output speeds dropped rapidly and went below the critical level of 30 fps when density went over 60 veh/mi.

Immediately after the measurements were resumed at minute 92, the output speeds were again quite high—more than 50 fps. This suggests that in addition to the shockwave causing a depression on input flow, there may have been some other event which interrupted input flow and allowed densities inside the tunnel to drop below the 50-veh/mi level when data were not being gathered. In any case, the high output speed dropped very rapidly, and for the 10 min between minutes 96 and 106, output speeds were below critical. Output flow was also low, and remained generally lower than during the first 90 min of the measurements.

Case 4: Controlled Flow

The first three cases generally confirmed the findings of earlier tunnel experiments (1), which showed that output flows could be improved by limiting input flows as necessary to keep output speeds above 30 fps. As described by Foote (1), a control device was built to limit input flow automatically when output speeds drop below 30 fps. On the basis of measurements over several weeks, it was found that the computer did raise the level of output flow, but only by about 2 percent rather than the 5 percent found when control was exercised directly by the experimenters. To study the action of the control device on the traffic stream, measurements of the same type described in Cases 1, 2 and 3 were taken. They showed clearly that the computer during this particular experiment was maintaining an excessively fluid traffic movement through the tunnel.

Of greater immediate interest, however, is the clear demonstration in Figure 8 of the systematic relationship among the four parameters being analyzed. The control system caused oscillations among input and output flows, section densities and speeds, with an approximately 20-min cycle period. Four cycles are observed during 80 min. While these four parameters varied in nearly identical period and amplitude, they were not in phase. Taking minimum output speed at t = 0 min, minimum input flow generally occurs at t = 1.5 min; minimum section density occurs at t = 2.25 min; and minimum output flow occurs at t = 6 min. In each case where output speed dropped below 30 fps, output flow decreased.

Input flow fluctuated in a cyclical pattern between highs of 22 to 24 veh/min and lows of 13 to 15 veh/min (Fig. 8). Output flow indicated the same pattern as input flow, generally 4 to 5 min later. Section densities fluctuate on the same cycle, between highs of 52 to 58 veh/mi and lows of 29 to 32 veh/mi. And, output speeds also fluctuate on the same cycle between highs of 53 to 57 fps and lows of 18 to 30 fps.

In this automatic control system, input flow is limited whenever six or more vehicles are observed in any minute traveling through the output section at speeds less than 30 fps. The minutes in which input flow is limited because of low output speeds are shown in Figure 8 along the 10 fps coordinate. It is of special interest that the uncontrolled input flow is in every case high enough, when combined with the reduced output flow caused by the excessively fluid traffic, to bring densities rapidly above the critical 50-veh/mi level and cause output speeds to drop rapidly. Stated differently, clearing the tunnel out by excessively limiting the input did not result in a generally stable state with

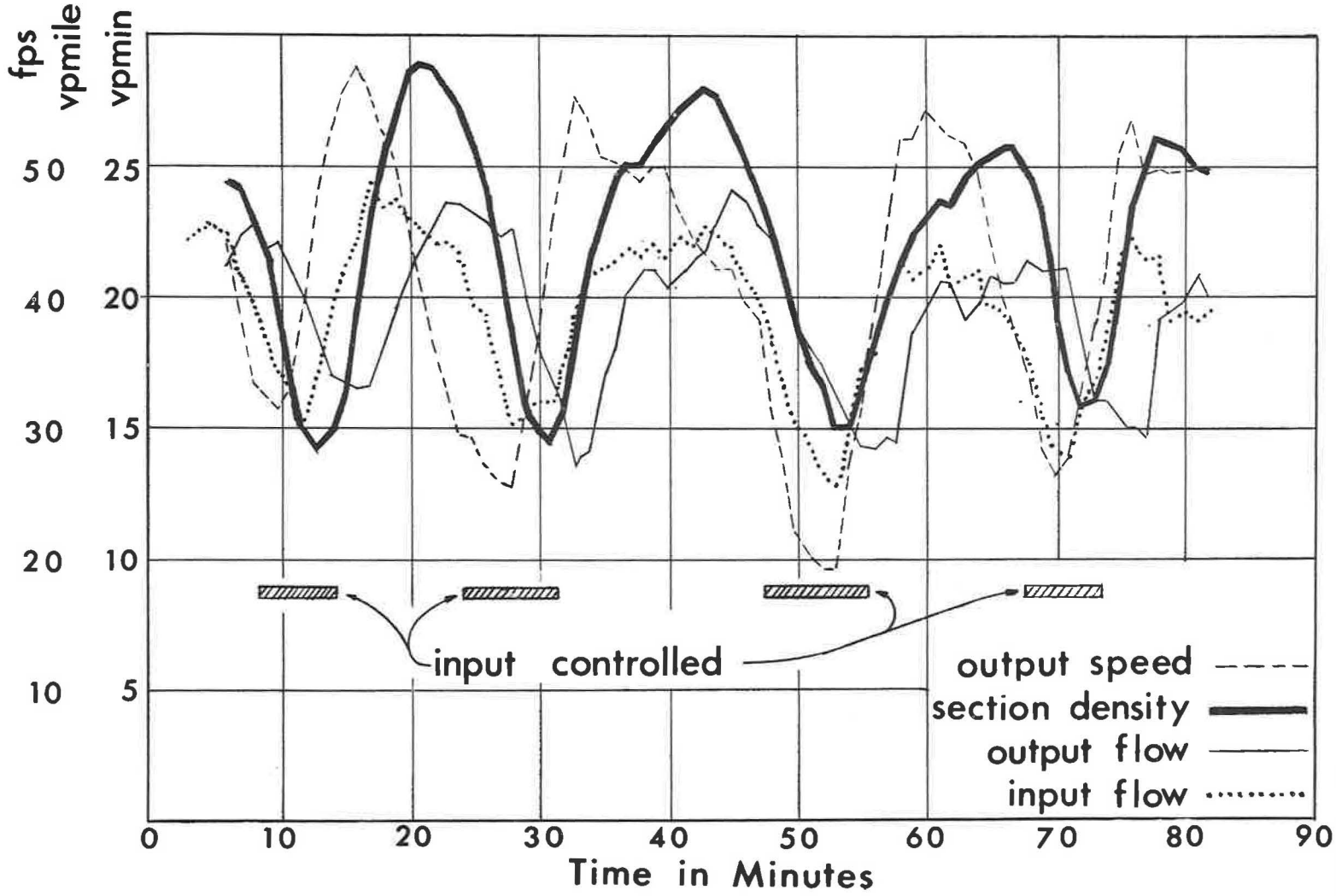

Figure 8. Case 4—PM controlled 5-min moving averages: input flow, output flow, section density, and output speed.

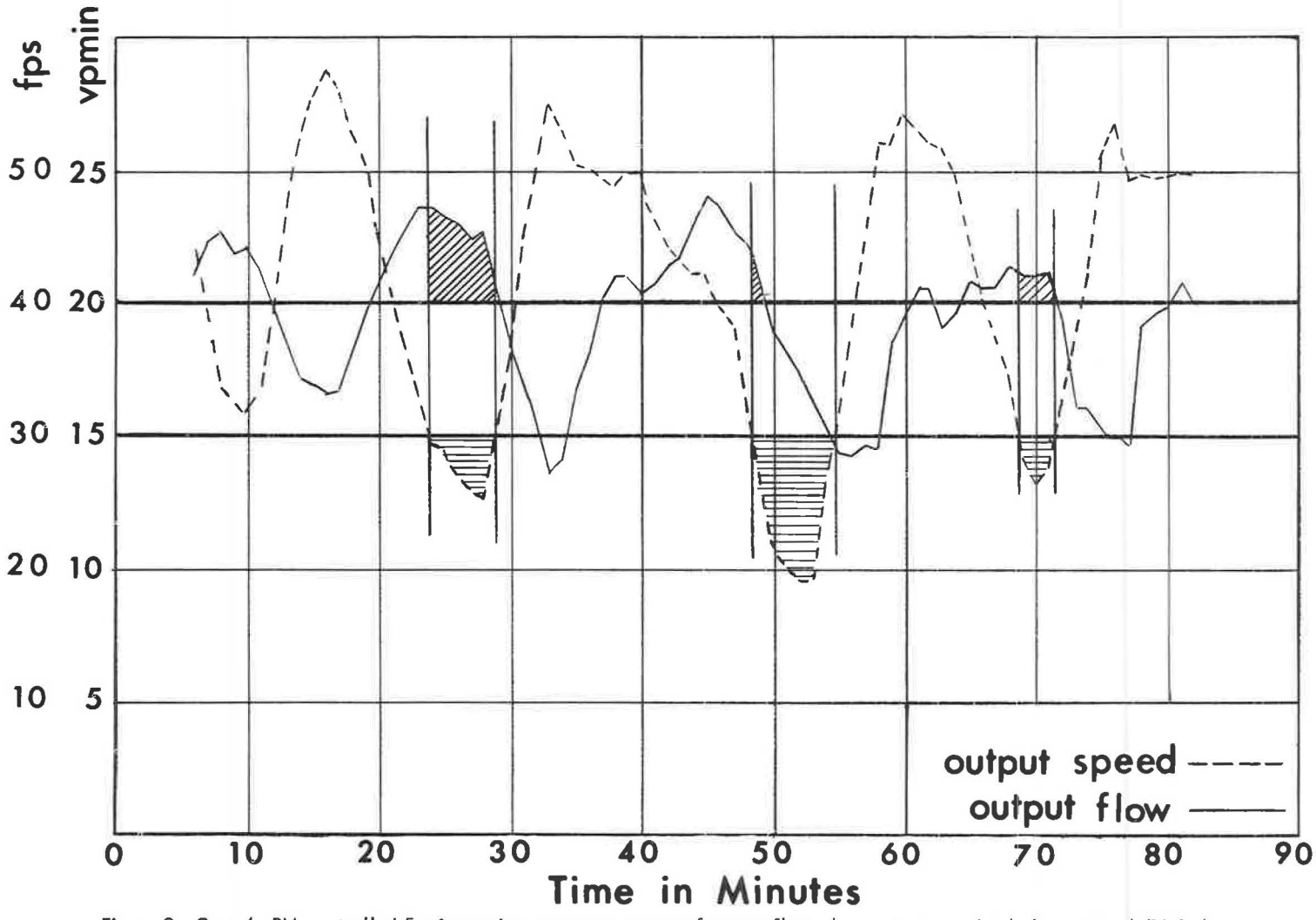

Figure 9. Case 4—PM controlled 5-min moving averages: status of output flow when output speed is below critical (30 fps).

subsequent gradual buildup of densities. Rather, it resulted repeatedly in quite a rapid decay of tunnel conditions and the need generally within a 15-min interval to limit input flow again.

These measurements make clear that the control device was too late in beginning its action on the tunnel traffic stream, and that it continued to restrict traffic for too long a period of time.

The relation between output flow and output speed is of particular interest, since the control of flow is based on the previous finding that output flow is reduced by low output speeds. Figure 9 shows the relationship between these two parameters, and it is clear that in this experiment most of the drop in output flow occurred when speeds were rising rapidly because there was too little traffic reaching the output section. However, the start of the drop in output flow in every case occurred when output speeds dropped below the critical level. At minute 8, output flow is at a high of 23 veh/min, while speed is approaching a low. By minute 11, while speed is passing through the low point, output flow has definitely begun to drop. At minute 24, when output speed dropped again below 30 fps, output flow was at a high of 24. But by minute 30, when the output flow again rose above 30 fps, output flow had dropped to 20 veh/min. At minute 48, when output speed next went below 30 fps, output flow was at 22 veh/min. But, by minute 55, when output speed regained the 30 fps level, output flow had dropped to 15 veh/min. On the last cycle beginning at minute 68, when output speed dropped below 30, output flow was 21 veh/min. By minute 72, when output speeds began to rise, output flow was dropping again.

CONTROL IMPROVEMENTS

These four cases confirm the desirability of maintaining fluid traffic movement, with speeds above 30 fps and densities below 50 veh/mi, in order to obtain good output flow levels and prevent shockwaves. The cases also show consistently high section densities are followed by low output speeds and a decrease in output flow; therefore, it is clear that a direct measure of section density can be used to predict output speeds. With the ability to predict output speeds, it would be possible to initiate input flow restrictions sooner, and also to end them more quickly when densities have been restored to optimum levels. These steps should eliminate or, at least, greatly reduce the period and amplitude of the oscillations observed in Case 4, and permit maintaining tunnel traffic at near optimum conditions with more stability.

Modifications to the existing controller to limit restrictions on input when speeds midway between the entrance and the bottleneck become too high are discussed by Duckstein (4). Of more fundamental importance however, a device to measure section density continuously as an on-line control parameter is now being developed by the Port of New York Authority staff, and experiments using this control device will be undertaken.

REFERENCES

1. Foote, R. S. Single Lane Traffic Flow Control. Proc. Second International Symposium on Theory of Traffic Flow, 1963.
2. Foote, R. S., Crowley, K. W., Gonseth, A. T. Instrumentation for Improved Traffic Flow. ITE Proc., 1960.
3. Edie, L. C., Foote, R. S., Herman, R., and Rothery, R. Analysis of Single Lane Traffic Flow. Traffic Engineering, Jan. 1963.
4. Duckstein, L. Control of Traffic in Tunnels to Maximize Flow. Highway Research Record 154, 1966.
5. Weinberg, M. Traffic Surveillance and Means of Communicating with Drivers. NCHRP Report No. 9, HRB, 1965.
6. Crowley, K., and Greenberg, I. Holland Tunnel Study Aids Efficient Increase of Tube's Use. Traffic Engineering, March 1965.
7. Edie, L. C., and Foote, R. S. Experiments in Single Lane Flow in Tunnels. Theory of Traffic Flow, R. Herman, ed., D. Van Nostrand Co., 1961.
8. Edie, L. C., and Foote, R. S. Effect of Shock Waves on Tunnel Traffic Flow. Pub. HRB Proc., Vol. 39, 1960.