Measurement of Driver Reactions to Tunnel Conditions*

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Analyses by the Port of New York Authority staff indicated differences in traffic flow between different tunnels. After discussion of these and because of previous headway studies by the senior author, it was thought that driver reactions to conditions of tunnel traffic might be basic to differences in traffic flow. Accordingly, experiments were designed to simulate the close following of heavy traffic driving to measure effects on driver reactions of different combinations of curve, grade and, in tunnels, of different characteristics in the Pittsburgh area. Analysis of photographic measurements showed that increases of time-headway resulted from experimental decelerations. Variations of time-headways and driver-lags were related to these different highway characteristics. These data are of both practical and theoretical importance since they account for major differences in self-limitation of flow. This has been noted previously but not explained.

On the basis of these measurements, predictions of effects in New York tunnels were made. A short experimental series was run in which each driver drove in each of three tunnels. Time-headway increases resulting from a deceleration would account for the general order of maximum traffic flow recorded.

Measurements indicated that downgrade, right curve, lower illumination, and even psychological constriction tended to reduce flow.

The results furnish basic data for mathematical studies of traffic flow which results in different traffic-volume or traffic-density relationships in different traffic samples. Practical implications for increasing maximum flow with safety are suggested.

• THE STAFF of the Port of New York Authority reported elsewhere (*1*) an investigation of differences in tunnel traffic flow examining relationships between physical factors and the traffic-volume, traffic-density, and speed variables. Differences in the flow in the various New York vehicular tunnels apparently were not directly attributable to physical factors. Discussion of these studies together with a previous study of time-headways by the senior author (*2*) led to the hypothesis that systematic, consistent effects on psychological reactions of drivers to tunnel traffic conditions might be an important factor. These effects would be expected to be in the direction of longer time-headways on the basis of previous psychological and traffic research data.

Accordingly, a series of experiments with a simulated platoon technique was undertaken to measure effects on driver reactions of grade, curve, and illumination. Effects of more psychological influences were to be studied later, but it was found that some of these entered even in the first series. The theoretical expectation was not indicated to any of those involved in the experiments until later to avoid biased results.

In Phase 1 experiments were set up in

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* A summary of research carried on under contract with the Port of New York Authority. All interpretations and conclusions are the responsibility of the senior author and not necessarily those of others or organizations participating.

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the Pittsburgh area to analyze the effects of these factors separately and from them to predict the effect on driver behavior to be expected in the New York tunnels. In Phase 2 a few experimental runs (minimum in extent) were carried out in three of the New York tunnels to check the predictions made. This second series involved both the experimental simulated platoon technique and "floating" runs through the tunnel. In the latter, the attempt was to imitate and record the behavior of the two cars ahead of the photographic vehicle.

TABLE 1

CHARACTERISTICS OF EXPERIMENTAL SITES FOR PHASE 1 [a]

Black Top Highway (2 lane):
1. Straight, down 6 percent
2. Straight and level
3. Straight and level
4. Down 3 percent, right 3 degrees
5. Level, right 6 degrees
Tunnels and Approaches (4 lane):
6. Bridge (straight and level, concrete)
7. Squirrel Hill Tunnel (straight and level, brick)
8. Liberty Bridge (straight and level, black top)
9. Liberty Tunnel (straight and level, black top)
10. Armstrong Tunnel (right 5 degrees northbound, concrete) (left 5 degrees southbound)

[a] Characteristics are approximate. Site 7 includes a 1 percent grade but appeared to drivers as level.

METHOD

Simulated Platoon Technique

The simulated platoon method was as follows: A 3-car caravan was used to simulate close following in heavy traffic. The lead car (car A) was driven by an experimenter, while car B and car C bringing up the rear were driven by experimental subjects. The subjects were young male drivers all with considerable driving experience. They knew only that they were to drive as if in heavy peak hour traffic. They were told to drive closely but safely as if anxious to get home in heavy traffic.

At certain predetermined locations, a severe acceleration or deceleration maneuver was executed without warning by the lead driver while the photographic equipment in the third car recorded time, speed, spacing and certain driver reactions. An increase or decrease of speed of about 10 mph was held for several seconds followed by a sharp return to the cruising speed.

Experimental Sites and Subjects

One series of five experimental locations was on 2-lane, blacktopped road where traffic was very light. Five other locations included three tunnels with different illumination levels and two straight and level sites near the tunnels for comparison purposes. Characteristics of each site are shown in Table 1.

Each driver operated car B and also car C through each series once. They drove the series on the black top (a) in daylight and (b) under dusk conditions, and the tunnel series (c) in daylight. This resulted in 15 determinations for each person as a driver of car C for the complete series and another 15 in which he was the driver of car B.

A total of 19 different subjects served as drivers in Phase 1 resulting in over 200 total determinations. Because of weather and other difficulties, they did not all carry out the complete series on 15 sites or some of the records were not measurable.

On each of 11 subjects, however, a complete series of measurements was usable giving a total of 165 determinations. Since it was important to have each man serve as his own control in order to eliminate differences between people, the analysis of results was restricted to this group of 165 determinations.

Recording Equipment and Procedure

Speed, time, spacing and driver reactions were recorded photographically with a 35-mm movie traffic camera fitted with a built-in speedometer and sweep-second watch. The camera was controlled by an electric release button operated by the experimenter in the right front seat (Plate A).

To this equipment was added a series of 6 signal lights operated by associated electrical equipment to indicate (a) increase, (b) decrease, (c) foot off of accel-

Plate A. Recording equipment and camera mounted in car showing indicator lights on speedometer dial of camera.

erator pedal, (d) foot on brake, (e) brake pressure applied and (f) actuation of the signal light by the camera operator to notify the lead driver of his readiness for recording. The experimenter also recorded on a log sheet the time and conditions under which the photographic record was taken. These records were later keyed to the films for analysis purposes.

Car spacing was determined by measuring in the projected pictures known distances on cars A and B. The known distances were provided by three marker lights on a ski rack on the roof of each vehicle and one light on each side (Plate

B). For the most part, the horizontal lights were measured but on curved locations it was sometimes necessary to use the vertical interval, thus eliminating errors from the angle of the horizontal markers introduced by road curvature.

The scales for determining distance from the marker lights were developed mathematically and then checked by a preliminary series of pictures of a car taken at measured distances.

Accuracy of Determinations

Accuracy of determinations was checked on the known film and proved to be within 2 percent. Two different individuals made a series of spacing determinations between cars from an unmarked film for which distances had been measured. During the routine measurement of records, certain cases were found where there was an apparent aberration of the path of the light beam due to reflection by a curved window surface or confusion of a marker light with a reflection from a car body. For the most part such difficulties were eliminated by selection of directly seen markers. Routine measurement of records was carried out by university students under supervision. They developed considerable skill and reliability in selecting markers and making measurements. A final check was the internal consistency of each set of measurements when plotted.

METHOD OF ANALYSIS

From the projected photographic records, every eighth frame was measured and recorded on a columnar data sheet. This gave a time, speed, and distance measurement for each $1/3$ second (approximate). Actuation of any of the indicator lights was tabulated for assistance in interpreting the record.

Plots of distance against time were then made showing the distance of cars A and B from car C. The speed in feet per second of the photographic vehicle (car C) was also plotted. From these data, determinations were made of average time-headways before and during experimental maneuvers, for example, when the deceleration curves had reached a horizontal phase indicating that the three cars had reached the same velocity. Driver-and-vehicle lags before the ensuing acceleration or deceleration were determined by noting the times of appropriate inflection points of the curves (see Figs. 5 and 6).

Headway-and-lag determinations in

Plate B. Experimental platoons showing marker lights on roof racks.

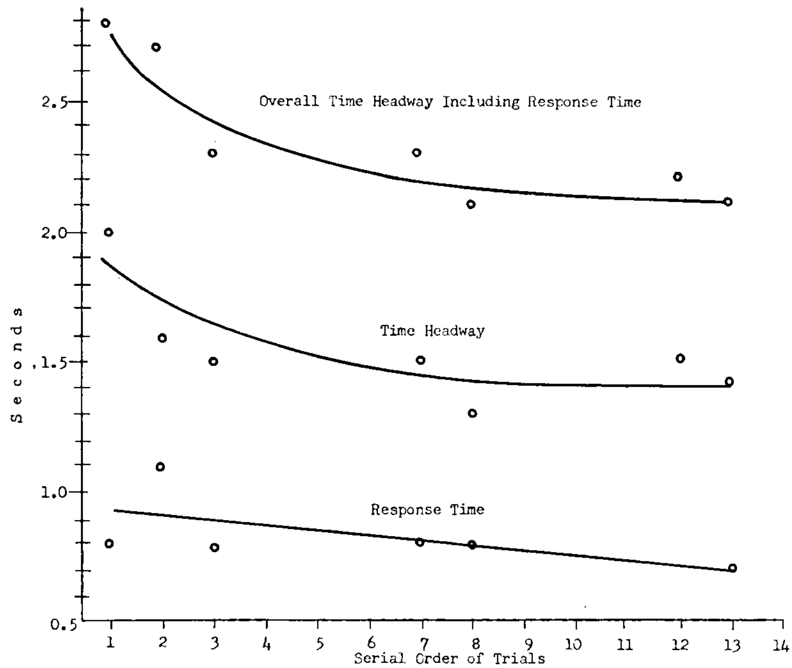

Figure 1. Serial learning effects on time headways and response times, straight-level trials only, daylight and dusk, Phase 1.

the unexpected initial acceleration maneuvers were less definite than those in decelerations and less critical for the object of the experiment. They were, therefore, omitted from consideration in the final analysis but served an important purpose in preventing the experimental drivers from being certain ahead of time what maneuver would occur next. Any such anticipation of the exact maneuver would have made the conditions of the measurements unlike the operation in normal traffic where the driver ahead may perform either maneuver.

The experimental design provided for the subjects to drive the three different series in a different order, that is, some started with dusk, some with daylight and some with the tunnel series.

Learning effects were shown by plotting straight and level site results by serial number of the trial. Figure 1 shows how time headways and lags shortened when the site occurred later in the series. Thus, it was possible to correct for and eliminate most of the effect of such learning.

RESULTS

The corrected results showed that introduction of a deceleration maneuver in itself lengthens the over-all time-headway (time-headway proper plus driver-and-vehicle response lag). This over-all headway increase (including lag) was greater on down grade, right curves, and under low illumination. In addition, lateral constriction even when psychological rather than physical, produced a similar increase of the headway increase. The magnitude of the time-headway increase was sufficient to account for limitations of flow in freeflow samples.

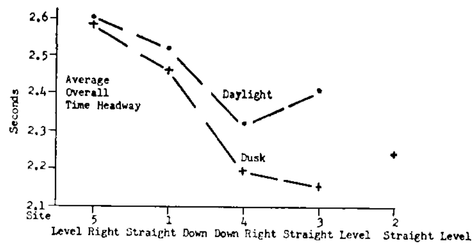

Figure 2. Effects of grade and curve in daylight and dusk on driver behavior, simulated platoon, Phase 1.

TABLE 2
AVERAGE HEADWAY AND SPEED PRIOR TO MANEUVER
PHASE 1

Group	Average Speed (ft per sec)					Average Time Headway (sec)				
	Site 1	Site 2	Site 3	Site 4	Site 5	Site 1	Site 2	Site 3	Site 4	Site 5
(a) All Groups, Daylight										
Day-Dusk-Tunnel	38	33	34	36	30	1.7	1.4	1.3	1.3	1.6
Day-Tunnel-Dusk	19	26	25	31	24	2.4	2.0	1.7	2.0	1.8
Tunnel-Day-Dusk	33	30	31	33	29	1.4	1.1	1.4	1.2	1.5
Means	30	30	30	33	28	1.8	1.5	1.5	1.5	1.6
(b) All Groups, Dusk										
Day-Dusk-Tunnel	37	27	30	39	24	1.7	1.4	1.2	1.2	1.5
Day-Tunnel-Dusk	31	32	35	32	26	1.4	1.1	1.0	1.5	1.4
Tunnel-Day-Dusk	29	30	33	33	30	1.3	1.2	1.1	1.1	1.3
Means	32	30	33	35	27	1.5	1.2	1.1	1.3	1.4
(c) All Groups, Tunnel										
	Site 6	Site 7	Site 8	Site 9	Site 10	Site 6	Site 7	Site 8	Site 9	Site 10
Day-Dusk-Tunnel	34	26	32	32	30	0.9	1.1	1.0	1.1	1.1
Day-Tunnel-Dusk	40	22	28	39	28	1.2	1.7	1.3	1.1	1.2
Tunnel-Day-Dusk	33	36	33	32	32	1.5	1.3	1.3	1.3	1.4
Means	36	28	31	34	30	1.2	1.4	1.2	1.2	1.2

These findings are illustrated in the tables and graphs. Table 2 shows the average speed in feet per second and average running time headway previous to maneuver. These time headways would give a maximum flow of from 2,000 to 3,000 vehicles per lane per hour if no other factor entered.

However, when the sudden deceleration maneuver was introduced, the corrected time-headway plus response-lag produced an effective over-all headway of as high as 2.6 seconds (Table 3). The longest of these headways, therefore, would account for a limiting flow on the order of 1,400 vehicles per lane per hour (about that reported in some tunnels).

Figure 2 shows the relationship between these over-all time-headways which were consistently highest for "level, 6 degrees right" and "6 percent straight down." "Three percent down, 3 degrees right" was intermediate and "straight level" provided the shortest over-all time headways. Unexpectedly these over-all time headways (average) were shorter in the dusk runs than in daylight in most cases.

Decelerations on straight-and-level site 2 gave longer time-headway increases, especially during daylight runs, a result which appeared inconsistent. Investigation of conditions brought out the fact that most runs, scheduled in the late afternoon in fall, occurred while this location was in shadow. Thus drivers were entering a zone of poorer visibility which would be expected to produce an increase.

Figure 3 shows the over-all time-headway relationships for the three tunnels

TABLE 3
AVERAGE HEADWAY AND LAG DETERMINATIONS CORRECTED FOR SERIAL LEARNING EFFECTS — PHASE 1

Group	Time Headway and Response Lag				
	Site 1	Site 2	Site 3	Site 4	Site 5
(a) All Groups, Daylight					
Day-Dusk-Tunnel	2.56	2.31	2.01	2.23	2.23
Day-Tunnel Dusk	2.56	3.26	3.11	2.61	3.01
Tunnel-Day-Dusk	2.44	2.36	2.06	2.09	2.58
Means	2.52	2.64	2.39	2.31	2.61
(b) All Groups, Dusk					
Day-Dusk-Tunnel	2.93	2.21	2.15	2.38	2.61
Day-Tunnel-Dusk	2.40	2.30	2.00	2.15	2.80
Tunnel-Day-Dusk	2.06	2.44	2.28	2.02	2.36
Means	2.46	2.32	2.14	2.18	2.59
(c) All Groups, Tunnel					
	Site 6	Site 7	Site 8	Site 9	Site 10
Day-Dusk-Tunnel	1.70	1.87	1.90	2.22	2.44
Day-Tunnel-Dusk	2.86	2.36	2.01	2.31	2.21
Tunnel-Day-Dusk	2.35	2.29	2.11	2.36	2.45
Means	2.30	2.17	2.01	2.30	2.37

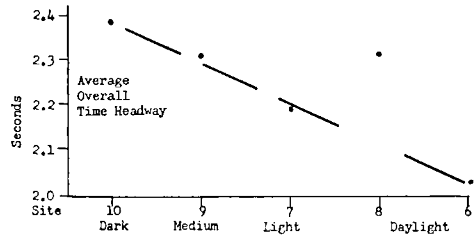

Figure 3. Effects in tunnels and on comparison sites, simulated platoon, Phase 1.

and the two straight and level comparison locations approaching the tunnels. Here, as theoretically expected, the time headway increase was greatest in the darker and less in the better illuminated tunnels. Site 6, on 4-lane concrete open highway with a 10-ft center strip, showed the least increase of over-all time-headways. Site 8, on the other hand, showed longer times. This was a straight and level location but with only a 6-in. center divider, on a bridge with a steel railing separating the roadway from the pedestrian sidewalk. There was, therefore, definitely a psychological effect of constriction here, even though lane width was actually the same.

The relationships of the cars in the simulated platoon are shown in two ways in Figure 4. The left figure is a time-space diagram representing Cars A, B, and C going through a deceleration maneuver. The right hand half of the figure shows an idealized photographic record from Car C and indicates how the average time-headways and driver-and-vehicle lags were computed. Pre-maneuver running time-headways were obtained from the horizontal constant velocity part of the curve on the left. Time-headways at the minimum speed of the maneuver were determined from the lowest horizontal phase of the curves. The letters a, b, and c indicate points determining the driver-and-vehicle lag. In each case, an average of the two headways between the three cars was used.

Figure 5 is a tracing of an actual plot of data from the measured photographs illustrates that inflection points were sometimes difficult to determine. In case of doubt, conservative values of lag were chosen. In this case, the average lag was taken as $\frac{1.0}{2}$ seconds. A second sample is shown in Figure 6.

These two records illustrate an important result also confirmed qualitatively by observation: that drivers learned to

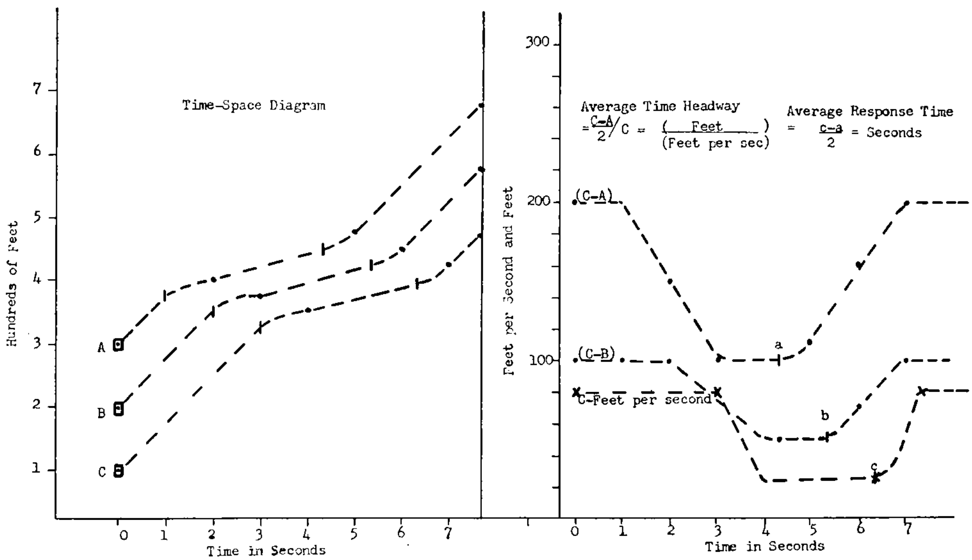

Figure 4. Relation between time-space diagram and relative distance-speed pilots from experimental platoon technique.

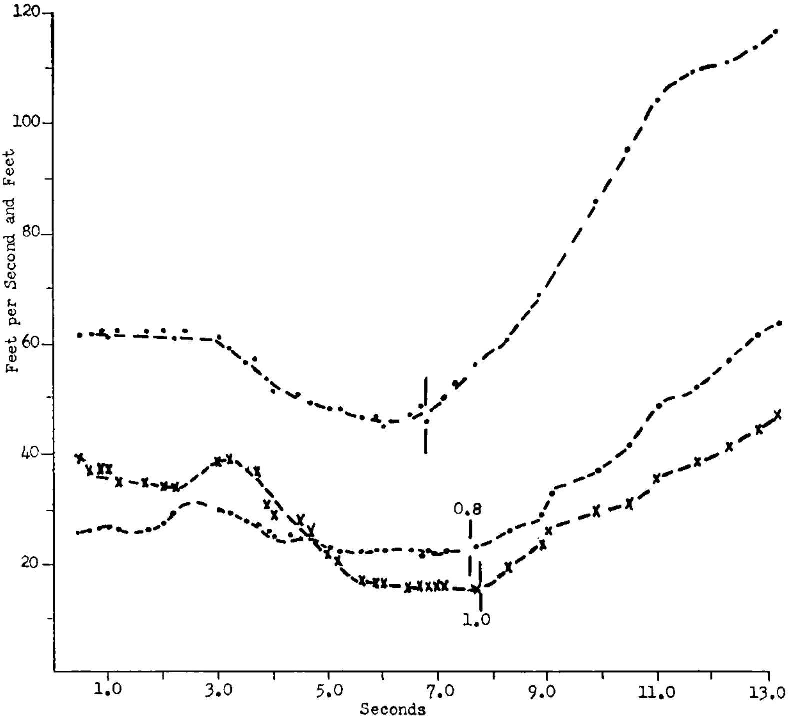

Figure 5. Sample record illustrating response time overlap, site 6, daylight.

base their actions on the second car ahead rather than the car immediately ahead. Thus the response of the third driver after some practice in many cases became almost simultaneous with that of the second. In a few cases the third actually preceded the second, an important point in explaining very short time-headways on a freeway reported previously (*2*).

Results of Phase Two

In phase two the same experimental procedure was used in runs in three New York tunnels. These runs were made during off peak hours between 10:30 A.M. and 3:00 P.M. A police escort protected the rear of the experimental platoon. A complete series of determination in the three tunnels was obtained on each of four drivers. Two others drove in the simulated platoon, but an equipment malfunction resulted in loss of some determinations. Their records were, therefore, not complete on all locations and could not be used.

Table 4 shows the characteristics of the sites, Table 5 gives average values for each tunnel. Figure 7 shows the corrected time headways combining both

TABLE 4

CHARACTERISTICS OF TUNNEL SITES[a] SELECTED, PHASE 2

Site	Eastbound	Westbound
	(*a*) HOLLAND TUNNEL	
1	Straight, downgrade	Straight, downgrade
2	Right and level	Straight and level
3	Straight and level	Straight and level
	(*b*) LINCOLN TUNNEL	
1	Straight, downgrade	Straight, downgrade
2	Straight and level	Straight and level
3	Straight and level	Straight and level
	(*c*) QUEENS MIDTOWN TUNNEL	
1	Right and downgrade	Right and downgrade
2	Straight and level	Straight and level
3	Straight and level	Left and level

[a] Sites in Holland and Lincoln Tunnels approximately 1,500, 2,700 and 4,500 ft from portal entered. Queens Tunnel Sites were similarly spaced.

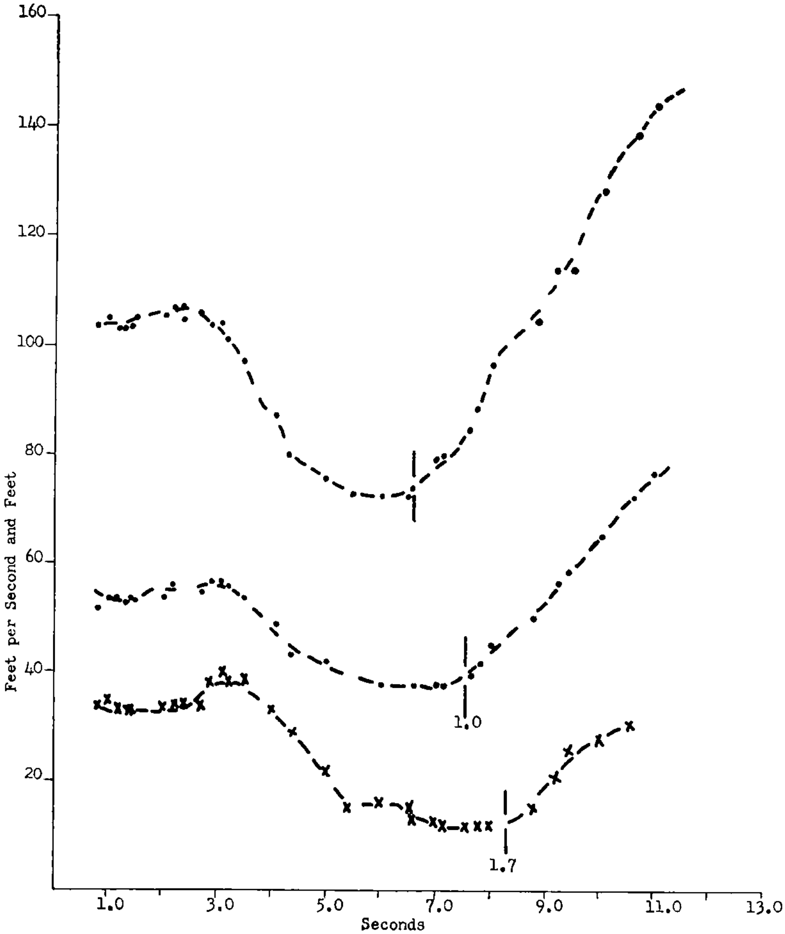

Figure 6. Sample record illustrating long headway and response time, site 6, daylight.

directions in each tunnel. Doubling and tripling of the over-all time-headway were produced as a result of the experimental deceleration maneuver (the top row of figures compared with the middle row). The components of the over-all time-headways appear in the lowest row. Clearly, for statistically reliable determinations, additional determinations would have been desirable if they had been possible. However, there is some indication of longer headway on the downgrade (site 1) in each case and the trend was greater in the Holland Tunnel, which had the lowest illumination level. This was in line with effects shown in Phase 1.

Floating Runs

A series of floating runs in which the driver of the photographic vehicle tried to follow at the same distance as the two cars ahead of him (or in the case of a truck or bus as the car following him). Photographic records were taken at approximately 1-second intervals. They showed decelerations and bottlenecking occurring first on the down-grade and, in some records, other decelerations further on in the tunnel. Very significantly there was consistent free-flow on the up-grade. Therefore, these data also tended to bear out the predictions from the experimental runs and analyses.

TABLE 5

HEADWAY AND RESPONSE LAG TIMES, EXPERIMENTAL PLATOON MEASUREMENTS,[a] PHASE 2

Site	Time Headway and Response Lag (sec)						Mean EB and WB
	Eastbound			Westbound			
	Driver 1	Driver 2	Mean	Driver 3	Driver 4	Mean	
	(a) Holland Tunnel						
1	2.48	4.20	3.34	3.17	2.58	2.88	3.11
2	2.47	3.20	2.84	2.07	3.28	2.68	2.76
3	2.20	2.98	2.59	2.60	2.81	2.71	2.65
	(b) Lincoln Tunnel						
1	1.97	2.44	2.21	2.68	2.45	2.57	2.39
2	2.52	2.48	2.50	2.45	2.07	2.26	2.38
3	2.23	2.70	2.47	2.64	2.76	2.70	2.58
	(c) Queens Midtown Tunnel						
1	2.18	2.87	2.53	2.23	3.16	2.70	2.61
2	2.85	2.90	2.88	2.21	2.37	2.29	2.58
3	2.87	3.04	2.96	1.71	2.30	2.01	2.48

[a] New York, 7-9 May (four drivers).

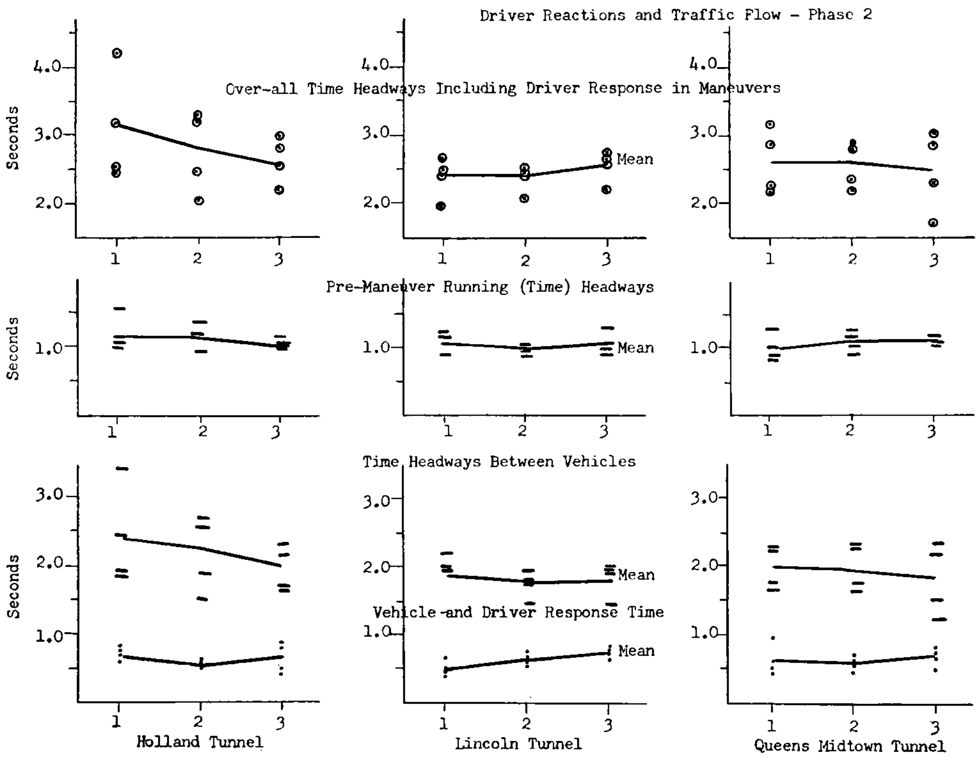

Figure 7. Time headways and driver response times (lag), experimental platoon, eastbound and westbound combined.

Several of the floating runs gave records of not only one but of several complete stoppages during peak-hour traffic. Even then, however, there was free-flow on the up-grade and at the exit. Figure 8 shows records from three such floating runs.

DISCUSSION AND CONCLUSIONS

The determinations in Phase 1 showed (a) that any deceleration maneuver increased over-all time-headways and (b) that right curve, down-grade, and low illumination or conditions interfering with visibility ahead increased the time headways. These factors would, therefore, be expected to produce limitations of flow at lower and lower rates of flow. Site 2, although on straight-and-level in daylight conditions, represented a relatively poor visibility condition. Therefore, the long time headways here actually were consistent, although they did not appear so at first sight.

The lesser increase of time-headway increase under dusk conditions on the outdoor runs of Phase 1 also seemed contradictory at first. However, the experimenter's log noted that in most of these runs it was actually dark rather than dusk by the time the run got underway because of the time required by the preceding series. In the dark, the marker lights were more visible, and the brake lights of the second vehicle ahead could be seen from reflected glow even when not directly seen. Therefore, drivers apparently followed more closely with confidence and judged the actions of the second car ahead better.

In tunnels, on the other hand, the effect of higher illumination in decreasing the time-headway increase (reducing the over-all headway) was clearly shown in Phase 1. As would be expected, the open highway comparison location, site 6, was lowest of all.

However, somewhat longer time-headway values resulted on straight and level site 8, again at first appearing contradictory. These data, however, were especially significant since apparently the effect was from a psychological constriction effect on the driver. This site was on a 4-lane bridge with opposing traffic sep-

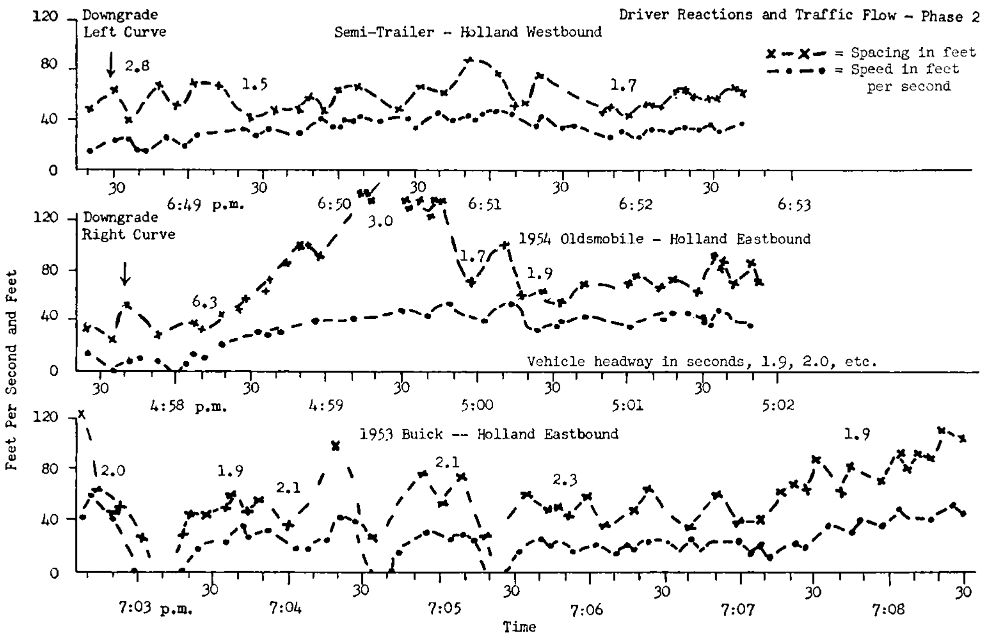

Figure 8. Floating runs, Holland Tunnel.

arated only by a 6-in. marking. A steel railing and panel on the right separated the right lane from a pedestrian walk also creating an impression of narrowed lanes and being "hemmed in."

In the New York tunnels, the protecting police patrol to the rear, familiarity with the locations, and some familiarity with the problem, may have reduced effects of the factors investigated. However, there was some indication of increased time headway on down-grade when combined with low illumination and the over-all averages for the tunnels showed differences.

In the tunnel floating runs during and just preceding peak hour conditions, deceleration maneuvers and traffic flow limitations started first on the down-grade and later occurred farther on as the traffic load built up. This would bear out the experimental results.

The plots showed experimentally that drivers learned to respond to the second car ahead, thus shortening driver response in the third car to almost that of the second. This result bears out interpretation of time-headways in a previous report (*2*).

Practical Implications

Practical implications of these studies include the following points:

1. Traffic flow can be increased by any change which improves driver visibility of several cars ahead. This might be accomplished by improved lighting, use of left curves instead of right curves on down-grades, and even possibly use of mirrors under some conditions.
2. Limitation of flow apparently occurred first on the down-grade due to drivers' tendency to hang back and, therefore, the effects of visibility factors should be greater on the down-grade.
3. Of advantage in increasing flow efficiency will be reduction of factors tending to impress the driver (a) with his speed and (b) with apparent constriction. Such factors may be railing posts tending to increase the impression of speed, and railings, high curbs or visual effects tending to give the impression of narrow lanes.
4. Learning "to drive two or three cars ahead" was of importance for shorter time headways with safety when decelerations occurred. This driver habit or skill is, therefore, of great importance in the high lane volumes reported in a number of studies. This learning factor probably explains the more efficient flow in commuter traffic as compared to weekend traffic on many facilities.

Any method of teaching weekend drivers to attend to two cars ahead (rather than only one) should, therefore, increase maximum flow while maintaining safe operation.

Theoretical Implications

Theoretical implications of these findings are of great importance also. A number of studies have been made of traffic flow relationships from a mathematical and physical point of view. Several papers have been published on mathematical models of traffic flow applying formulas from hydraulic and other analogies laying a basis for mathematical simulation of traffic. This approach and all data which contribute the necessary variables and constants for such mathematical models are of importance for developing new approaches.

In most of the studies to date, little or no account has been taken of driver behavior factors except to assume that they will average out. One recent and comprehensive study notes that the mathematical functions developed check fairly well with measurements of traffic, except that for different traffic samples, different constants representing maximum flow are necessary. The explanation of these variations was not given.

The effects on driver behavior reported in this study from different physical and psychological driving conditions furnish an explanation of the different maximum flow constants. Further investigation on a large enough scale to obtain a greater range of conditions and more stable determinations should make it possible to develop functions relating the constants to factors affecting driver behavior in decelerations. Such functions added to present mathematical model approaches will make possible accurate mathematical simulation of free flow conditions. This represents the simplest condition upon which simulation for other more complex cases of traffic flow can be built. The end result will be to furnish an important research tool for highway and safety research.

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