Human Factor Considerations in Traffic Flow Theory

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The many traffic flow theory formulations that have been offered have stimulated much fundamental thinking on important phases of traffic flow theory. A number of different formulations based mainly on mathematical and physical relationships have been proposed but none seems as yet to be greatly superior to another. Human factor considerations have been recognized in some but accorded a minor role in most.

The present paper proposes certain relationships based on experimental information from previous experimental studies of traffic flow by the investigator. Mathematical relationships developed from these are offered as important for traffic flow theory. Discontinuities in certain previous data may be explainable on the basis of these human factor variables.

THE MANY traffic flow theory formulations and studies published in the last few years have stimulated much fundamental thinking and interest in traffic flow from a theoretical point of view. Among the first, Greenshields (1) reported an experimental study of traffic flow, Lighthill and Whitham (2) called attention to application of fluid flow theory, and a series of other very able mathematical papers have been reviewed and additional developments reported by Newell (3) and by Gazis, Herman, and Rothery (4). The last two papers point out that none of the mathematical theories so far is entirely satisfactory and that not enough data are available for valid choice between theories.

Herman and his group introduced the concept of a driver sensitivity factor in the flow equation and various sensitivity functions have been assumed and tested not only by his group but also by Edie (5) and others. The latter also reported a discontinuity in flow data which has been difficult to explain in terms of a continuous flow theory.

Under these circumstances, it may be helpful to look at certain experimental studies of traffic flow to see whether they throw light on the driver response function and its relation to various theories of traffic flow.

EXPERIMENTAL STUDIES

Among the experimental studies of traffic flow, several are of present interest as experimental determinations of driver performance. Forbes (6) analyzed velocity and headway of high-density multilane traffic on the Pasadena freeway in 1951. Analysis was carried out by time headway, velocity, and also platoons (vehicles traveling in closely-spaced groups). These results showed that for traffic in a given lane of multilane freeway, platoon average time headways were not necessarily related to platoon average speeds. However, variability was reduced as volume increased. In peak hours, minimum platoon headway times ranged from 0.5 to 1.0 sec and average platoon time headways clustered between 1.0 and 1.5 sec. These data, therefore, would not lead to the expectation of a continuous relation between driver response and velocity beyond a limited range, even in high-density traffic.

To analyze traffic flow by platoons, a technique was developed to eliminate strag-

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glers (vehicles between the closely-grouped vehicles in each platoon). Although proceeding at about the same velocity as the others, these drivers quite evidently were not reacting immediately to the vehicles ahead. Only when the stragglers were included was there an apparent relation between headway, speed, and volume in lighter flow.

Similar results were obtained by Forbes and Wagner (7) in a study on Detroit freeways using a somewhat similar measurement and analysis technique.

These results raise the question whether it is valid to assume driver response sensitivity related to velocity or spacing in a continuous manner throughout the range of velocity, traffic volume, and traffic density.

An experimental study using a three-car "experimental platoon" by Forbes and others (8) indicated sudden changes in driver response time before and after a sudden, unexpected deceleration. Time headways of the experimental platoon were in the 1.0- to 1.5-sec. range while following at constant speed before the slowdown but about twice as large after the experimental (and unexpected) deceleration by the lead car. The design of this experiment was intended to reproduce the condition found in certain heavy traffic tunnels and arteries (and also on many freeways) where slowdowns or stoppages interfere with flow with no apparent physical cause. Thus, under a simulated dense-traffic car-following condition, a sudden change in driver response time was reflected in the time headways in and out of the slowdown:

$$t_h''' \text{ (out)} \approx 2t_h' \text{ (in)} \tag{1}$$

EFFECTS ON TRAFFIC FLOW

A change in driver response time can account for a discontinuity such as that reported by Edie. Figure 1 shows the suggested mechanism for this. On a free-flowing freeway below certain levels of density and volume, the relatively low number of vehicles scattered over the highway allows vehicles to be essentially stragglers; i.e., drivers will not be responding in a direct manner to vehicles ahead. Therefore, from the origin to some limiting time headway value, average traffic density would be simply a function of velocity and volume of vehicles available shown by the lines through the origin and representing the following equation where c results from highway speed limit and environmental factors.

$$k = q/u \tag{2}$$

$$u = c \tag{3}$$

As volume increases at a given free-flowing speed, driver response time to the vehicles ahead (t_R) becomes a factor and results in a limiting time headway and flow.

If drivers respond not only to the car immediately ahead but to several vehicles and conditions ahead with a certain minimum time for perception judgment and response, the right hand portion of Figure 1 results for minimum time headways:

$$\frac{1}{q} = t_h = t_R + \frac{L}{u} \tag{4}$$

$$u = \frac{s - L}{t_R} \tag{5}$$

$$q = uk = \frac{1 - Lk}{t_R} \tag{6}$$

Assuming average car length L = 18 ft.

Figure 2 shows several sets of data plotted over the appropriate trend lines from Figure 1. The fit seems reasonably good for free flow conditions in data (a) and (c). The data from samples (b) and (d) show earlier curvature toward the limiting driver response line.

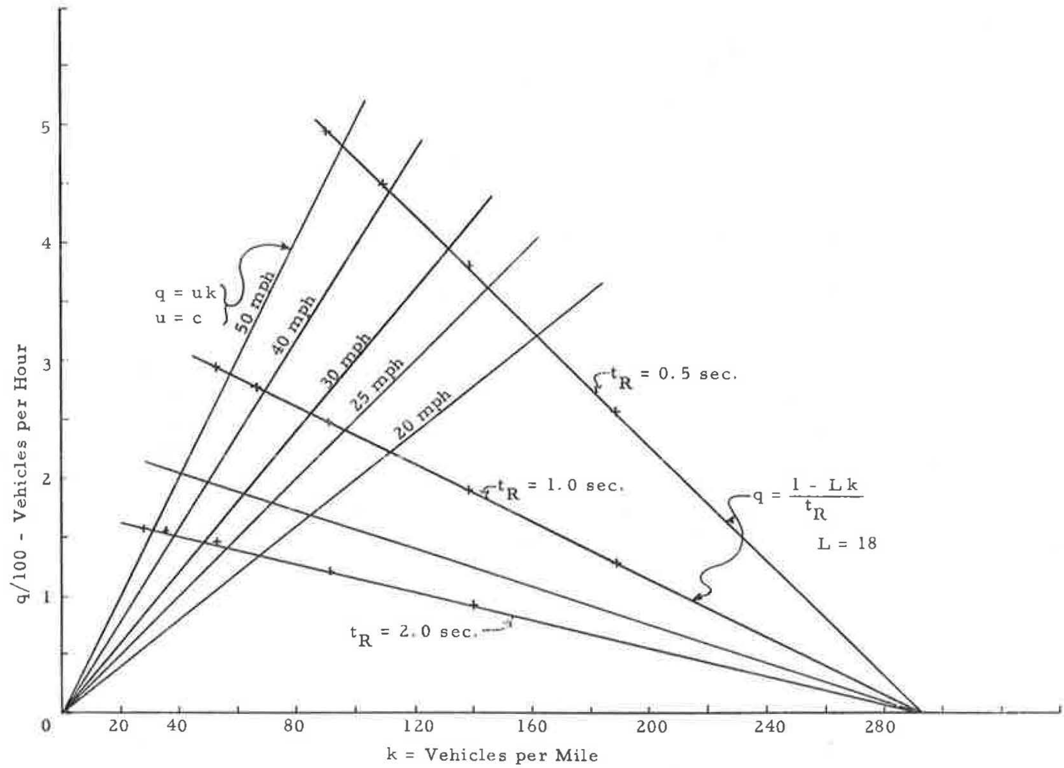

Figure 1. Relation of volume, speed, and density average values, from driver response time as a limit (right) and scattered free flow (left).

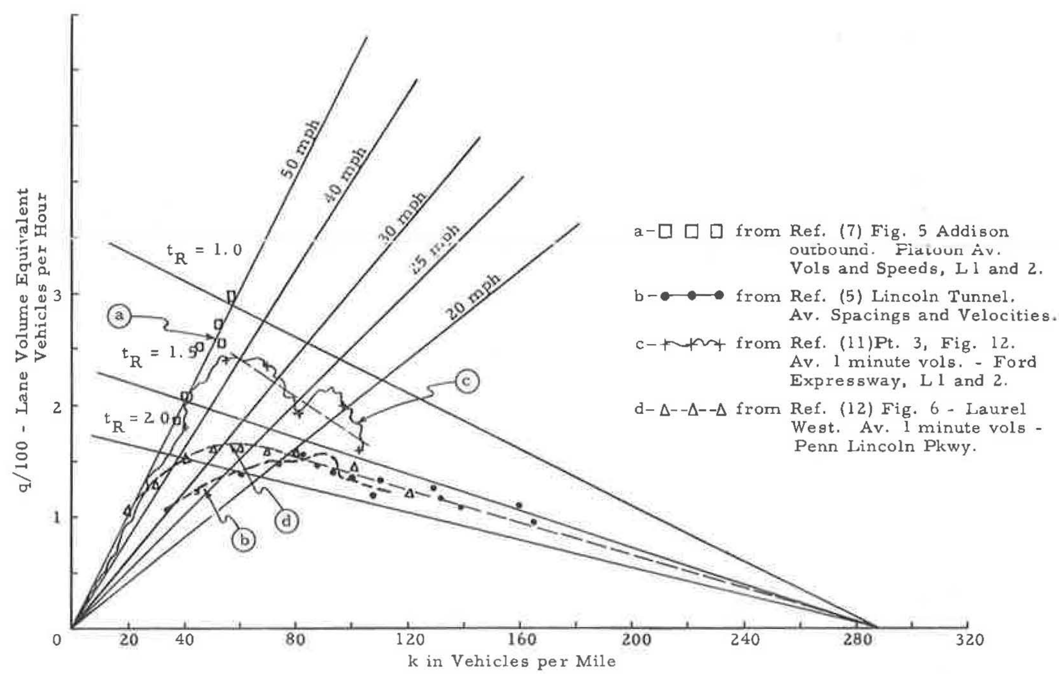

Figure 2. Four sets of empirical data plotted over theoretical trend lines of Fig. 1.

The first two data samples were from an urban expressway. Sample (a) was taken at a free-flowing outbound location on the Edsel Ford expressway in Detroit (7). Sample (c) was taken at a nearby inbound station (11). Sample (a) values consist of averages for platoons determined from time headways and speeds. Sample (c) values were average 1-min volumes and speeds.

Traffic flow at the (a) location never reached slowdown or stoppage during the observations. Actual volumes over a 15-min period flowed at the equivalent of 1,800 to 2,000 cars per lane per hour.

The data for sample (c) covered a 24-hr period. They clearly included slowdowns as well as freeflow. Data points in both of these sets of measurements approach the $t_R = 1.0$-sec line. In sample (c) there is evidence of a shift from higher volume-short response time to lower volume-longer response time.

The other two sets of data (b and d) were reported from the Lincoln Tunnel in New York (5) and the Penn-Lincoln Parkway in Pittsburgh (12). Both included congested flow and relatively freer flow. They represent averages of continuous groups of vehicles. The former exhibits a discontinuity, as pointed out by Edie.

As shown in Figure 2, this discontinuity (arrow) may represent an overshoot like that in sample (c) and return to a slower response line. Both (b) and (d) exhibit a speed reduction as maximum volume is approached as shown by the visually-fitted trend lines. They then follow fairly well a line between driver response times of 1.5 and 2.0 sec. Platoon data taken at other urban freeway locations in Detroit showed characteristics similar to sample (a) except that there was some evidence of speed reduction at higher flows approaching limiting t_R. However, the trend was more like that in (a) and (c) than in (b) and (d) (Figs. 3 and 4 in 7).

From the preceding considerations and the results showing a sudden increase in driver response time after a sudden slowdown, some relationships can be deduced regarding bottleneck behavior on otherwise free-flowing freeways and tunnels. The well-known time-space diagram is used in Figure 3 for analyzing six cases to examine possible relationships.

Various relationships are shown which could produce deceleration wave velocity AA and acceleration wave velocity BB. This velocity will be positive, zero, or negative depending on the response times, velocities, and headways.

These are limiting cases in that drivers are assumed to be alert and responding with near-minimum response times for the situation. Also it is assumed that vehicles with equal deceleration capability and equal acceleration ability are involved. Vehicle deceleration and acceleration times and distances then cancel out.

Stoppages are shown in Figures 3A and 3B. In Figure 3A, the input time headway (t_h'), equals output time headway (t_h'''). Deceleration wave velocity AA and acceleration wave velocity BB will be equal. In this case, the stoppage will just maintain itself and travel upstream at the rate shown by the slope of the lines AA and BB.

If $t_h' < t_h'''$, AA (the deceleration wave) will travel upstream faster than BB and the stoppage will more than maintain itself.

If, as in Figure 3B, $t_h' > t_h'''$, AA and BB will converge (to the right) and the stoppage will travel upstream but dissipate. The point of convergence will be the location and time at which the stoppage will dissipate. Line AA depends on a preceding driver response time (t_R) and line BB on both t_R and acceleration as shown in Figures 3B and 3D.

Figures 3C to 3F show slowdowns rather than stoppages. In Figures 3C and 3D, the slowdown will just maintain itself, advancing downstream in 3C and standing still in 3D. If the inequality conditions of 3C are reversed (not shown), the slowdown will move upstream. Assumed in Figures 3A, 3C, and 3D are output response time and time headway (t_R''' and t_h''') approximating the minimum for conditions, and $t_h' = t_h'''$.

In Figure 3E, input time headway is greater than output time headway and the slowdown will dissipate because AA will intersect BB to the right.

In Figure 3F, input time headway (t_h') is minimum and much shorter than output time headway (t_h'''), the latter approaching twice the former. Such a slowdown will move upstream and increase.

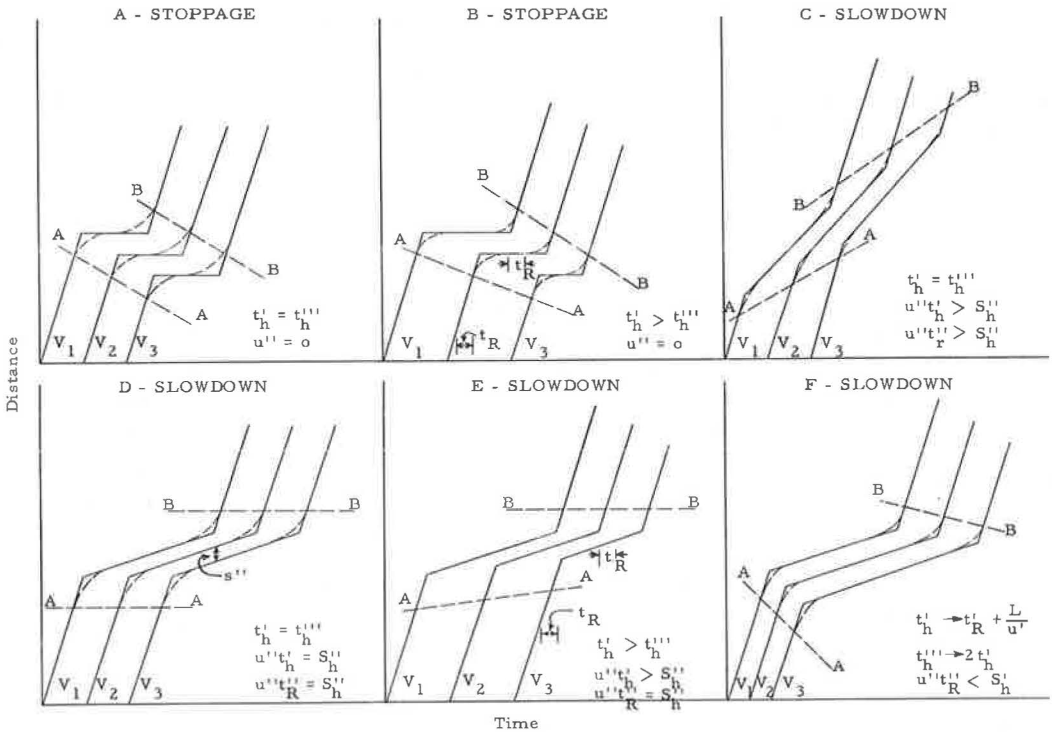

Figure 3. Acceleration and deceleration waves; time-space diagrams of six cases based on driver response considerations (AA = deceleration wave; BB = acceleration wave; V_1, V_2, V_3 = succeeding vehicles).

ANALYSIS

From these analyses it is evident that t_h''' must decrease or t_h' must increase relative to each other for a stoppage or slowdown to dissipate rather than continue or build up.

Flow at this type of bottleneck should be increased by (a) lengthening average input time headway (t_h') and (b) shortening response time in slowdown (t_R''). These effects should be possible by decreasing driver task difficulty or uncertainty. Analysis of a series of studies showed that increased psychological complexity of a task increases response time (9). Reduced visibility and lighting increased driver response or "lag" in the experimental three-car car-following study (8), so improving visibility should decrease response time that has been thus lengthened.

Use of lane control signals should have a facilitating effect on flow resulting from reducing driver uncertainty and therefore reducing t_R'. Research under way in several places will show whether this can be accomplished.

It would be expected that in any close-following traffic, there will be a distribution of time headways varying above and below average t_R values even for alert drivers. For simplicity, near-minimum times have been assumed in the time-space diagram analyses.

Proof is not offered at present that all cases of Figure 3 actually occur. However, Figures 3A, 3B, and 3F correspond to occurrences noted in the course of other studies (6, 13, and Fig. 1). Further studies are planned which may show whether the others occur.

The trend lines on the right side of Figure 1 are based on the assumption that drivers judge their following distances in terms of time to respond. From engineering psychology studies, there is theoretical reason to expect such behavior. This would correspond to Herman's driver sensitivity factor λ proportional to u/s (14).

Data falling on lines through the origin in Figure 1 indicate that drivers will approach their limiting spacing before reducing speed when they are in free-flowing traffic with a given highway speed. This seems to hold for platoon averages and 1-min samples in two studies (a and c in Fig. 2).

However, two sets of observations (b and d in Fig. 2) showed continuous speed reduction in approaching the limiting t_R trend line. These were both cases in which traffic approaches known, or at least customary, slowdown points ahead. For such conditions, Edie (5) has proposed λ proportional to u/s^2 following Herman's model and has shown a better fit to tunnel data for noncongested flow.

Newell (3) points out that although his theory includes almost everything in previous models, data are not extensive enough to determine whether drivers behave as the theory would indicate. Some of the relationships of Figure 3 would mean that they do not. Testing of these relationships by experimental observations should therefore throw light on these questions.

The work using a single-car car-following model using these driver sensitivity functions has been a great advance. The different trends shown by the noncongested flow data in (a) and (c), however, suggest that it is too simple, as most of those working in the field have recognized.

It will be recalled that the determinations in (a) and (c) using platoon averages and 1-min averages approached the t_R = 1.0-sec trend line without much slowing. A multiple-car car-following study showed evidence of anticipatory response by the third driver (8). The noncongested trend lines of (b) and (d) also suggest anticipatory driver response. In (c) there was evidence of a return to a longer t_R trend line.

The hypotheses are therefore suggested that (a) when reasonably confident of free flow from highway characteristics and conditions, drivers will maintain speed and minimum response time (t_R) within platoons. But when a slowdown or the limiting t_R is reached, return to a longer t_R will occur, and (b) when expected bottlenecks, poor visibility, or other confidence-reducing factors operate, drivers will exhibit longer response time (t_R) and platoons will slow increasingly.

Such hypotheses suppose grouping or platooning of vehicles, with complex responses of driver's partly to cars immediately ahead and partly to conditions of the highway and anticipated velocities of platoons ahead. Such a model finds support in other human engineering studies (6, 7, 8).

CONCLUSION

For many purposes, theories based on continuous functions and averaging out driver response time changes are very useful and convenient. However, to explain different slowdown relationships on two highways of similar physical characteristics, driver response differences are of basic importance.

It appears that there are two different kinds of driver response. Where open flow is anticipated, the volume-density data follow a given speed line until the limiting driver-response line is approached. But where conditions ahead lead to expectation of congestion not yet reached, the data may show a reduced speed before reaching the limiting driver-response line. In each, there may occur a sudden shift of response time in a slowdown or stoppage which is of primary importance for traffic flow.

Psychological effects on driver response times because of uncertainty from lowered illumination, or visibility and from "psychological squeezing" of lane width by an adjacent wall or object have been shown in earlier studies (8, 10). Reversing these effects should be possible. Where they are present, prediction of traffic flow effects should be possible to explain different capacities at different locations on freeways or in tunnels.

Once these analyses have been made, continuous function theories may be made more effective for simulation and other uses.

Knowledge of the limiting response times and their relationships to highway conditions for within and between platoon t_R values should lead to a much better understanding of traffic flow. From such relationships, it should be possible to predict flows on different highways more accurately than at present.

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Appendix

TABLE OF NOTATION

t_h = time headway between vehicles (center to center)

t'_h = input, t''_h = within, t'''_h = output from slowdown

Similarly:

s_h, s'_h, s''_h, s'''_h = distance headway

t_R, t'_R, t''_R, t'''_R = driver response time

u, u', u'', u''' = vehicle velocity

q = volume or flow in cars per hour

k = density (vehicles per unit of highway length)

L = average car length, assumed to be 18 ft