The Hysteresis Phenomenon in Traffic Flow

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ABSTRACT

The application of aerial survey methods to record and study the movement of traffic on an urban freeway led to the isolation of the phenomenon of traffic flow hysteresis. This phenomenon is manifested as a generally retarded behavior displayed by a platoon of vehicles after emerging from a kinematic disturbance as compared to the behavior of the same vehicles approaching the disturbance. Although data suitable for the study of the phenomenon is still quite scarce, the appearance of the retardation effect has been confirmed for all ten platoons studied to date. This paper undertakes an analysis of the nature of the hysteresis phenomenon from both a macroscopic and a microscopic point of view. Macroscopically attention is concentrated on the relationships existing between speed and density, volume and density, kinetic energy and density and mean headway and density. Each relationship is shown to display distinctly different characteristics for disturbance approaching and disturbance leaving conditions. Microscopically consideration is given to the acceleration-deceleration asymmetry which underlies the hysteresis phenomenon and the concepts of car following theory are employed to provide further insight into the fundamental nature of the phenomenon. It is thought that the hysteresis phenomenon has substantial implications for the design of modern freeway control systems and further efforts toward its exploration are planned.

1. INTRODUCTION

The data for this investigation were collected on Interstate 71, an urban freeway in the City of Columbus, Ohio. A KA 62A aerial camera was mounted in a Bell 47 J2 helicopter and photographs were taken at a nominal time interval of 1.0 seconds flying 3000 to 4000 feet above the freeway. The accuracy of the intervalometer was closely controlled, and the mean interval at the 1.0 seconds setting was found to be 0.9971 seconds with a standard deviation of ± 0.0037 seconds. The data collection system was designed to provide the following accuracy:

error in vehicle speed	± 1.0 ft/sec
error in spacing of vehicles	± 0.5 ft.

The spacing between vehicles on a curved section of freeway was measured in straight line segments along the chord line. All photo coordinates were measured in microns using a Nistri AP/C Analytical Plotter and all data were transferred to punch cards for further reduction of the photo-coordinates to ground-coordinates by computer. Three computer programs have been developed for this purpose including a data plotting program for the IBM 1620/27 system. The resulting data points represent an accurate, visual description of vehicle positions from which vehicle trajectories were derived. The survey used for this investigation covers a time interval of 238 seconds and a distance of about 3.3 miles travelled by a platoon of about 70 vehicles. Figure 1 shows the vehicle trajectories and presents a general picture of traffic flow conditions. The data reduction and evaluation program consists of four phases providing the following printed record for each vehicle contained in a photograph as the final output:

Code number for each vehicle for identification,
Photo and ground x - y coordinates.

Accumulative distance travelled by each vehicle,
Spacing of vehicles in feet,
Time headway of succeeding vehicles in seconds,
Velocity of vehicles.

The following general information is also provided for each traffic lane and photograph:

Total number of vehicles covered,
Mean speed,
Traffic density,
Traffic volume.

The reader interested in a more complete description of the data collection and reduction process is referred to either of two references on the subject(1,2).

Analysis of the data shown in Figure 1 led to the isolation of the hysteresis phenomenon in traffic flow. Additional survey flights are presently being carried out and it is hoped that the same type of information can be obtained for different highways. The research program has recently been extended to Interstate 70 in Columbus, Ohio, and data reduction and evaluation is still progressing. It is anticipated that many data collection flights will be required as it is difficult to record a traffic condition like that one shown in Figure 1 since most kinematic disturbances either appear and dissolve very quickly or develop into a jam condition with no immediate recovery.

The traffic condition shown in Figure 1 was analyzed with regard to:

(a) Speed-density relationship,
(b) Volume-density relationship,
(c) Energy (throughput)-density relationship,
(d) Mean headway-density relationship.

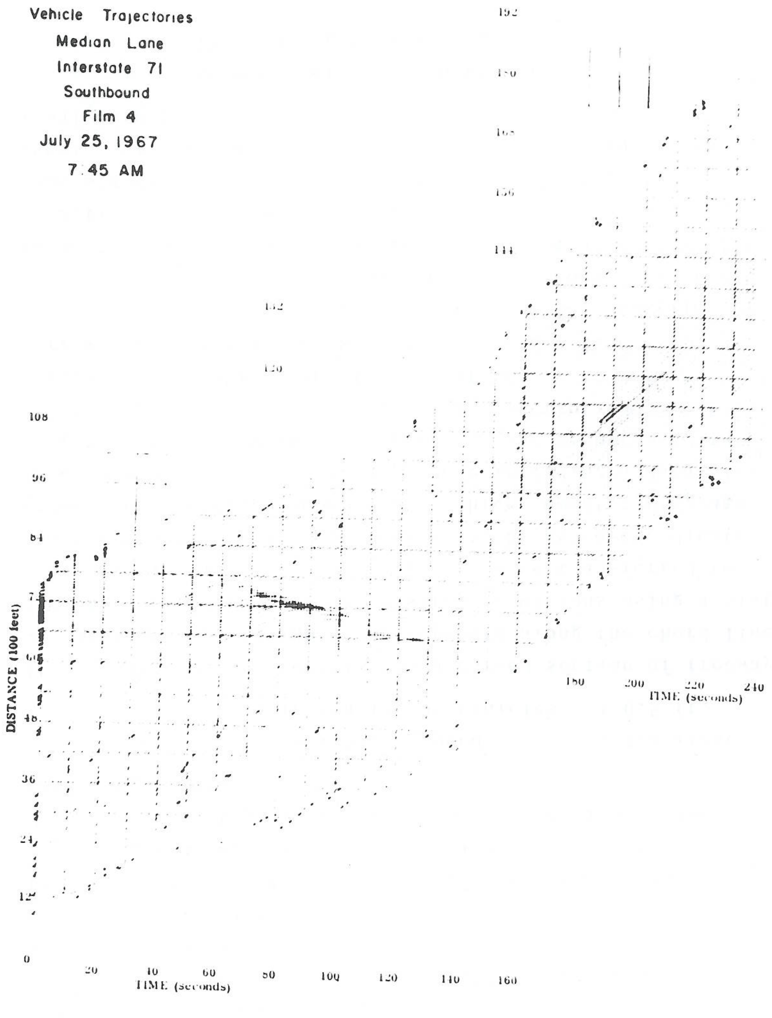

Figure 1: Vehicle Trajectories Depicting a Kinematic Disturbance

The results of this analysis are contained in the succeeding section.

2. THE HYSTERESIS PHENOMENON: A MACROSCOPIC ANALYSIS

This section of the paper is devoted to a macroscopic consideration of the hysteresis phenomenon. Specific attention is paid to the speed-density pattern, the volume-density pattern, the energy-density pattern and the headway-density pattern.

2.1 Speed-Density Relationship

Figure 2 delineates a platoon of 15 to 20 vehicles proceeding through a kinematic disturbance which forced vehicles to come to a standstill for a period of 8 to 14 seconds. No lane changing occurred during the phase leading into the kinematic disturbance, however, six vehicles joined the platoon about one minute after the original platoon emerged from the disturbance. The final size of the platoon was 16 vehicles since five vehicles left the platoon again. Figure 3 shows the speed-density relationship for the selected platoon of vehicles. Circles indicate data points for the platoon approaching the disturbance and crosses indicate data points after leaving the disturbance. The time sequence of data points is also indicated by arrows. A series of trial plots revealed that, approaching the kinematic disturbance, the speed-density relationship follows closely Underwood's function

$$u = u_f e^{-(k/k_m)}$$

though a multilinear relationship was found to be more suitable in our analysis. The recovery phase, however, displays a completely different pattern which forms two loops,

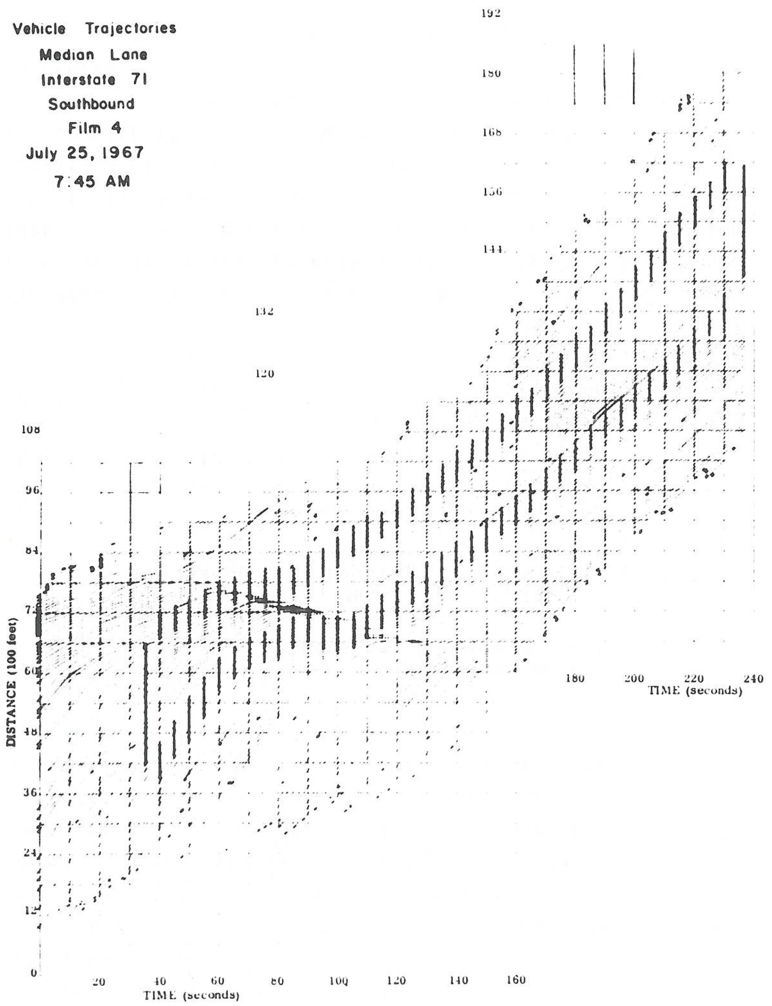

Figure 2: Vehicle Platoon Selected for Further Study (Platoon 123)

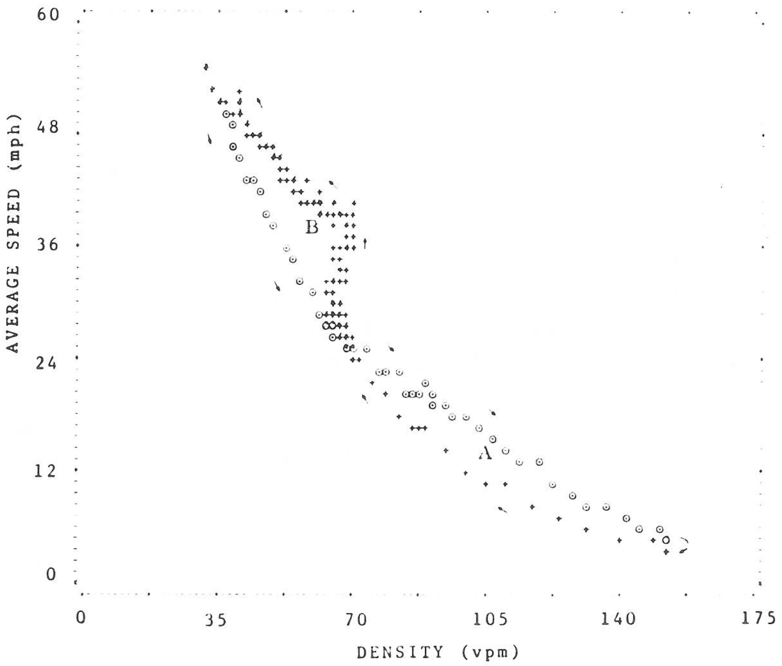

Figure 3: Speed-Density Pattern for the Selected Platoon

A and B, with the curve derived prior to the disturbance. This phenomenon has been called the hysteresis loop of traffic flow since the A-loop clearly represents a retardation in the recovery of traffic flow from a disturbance. The lag continues until traffic density has been reduced from about 150 vehicles per mile to about 66 vehicles per mile at which point the mean speed of the platoon increases from about 26 mph to about 40 mph without the usual change in traffic density. This phenomenon has been observed in all platoons emerging from a disturbance studied to date though the recovery did not occur at a density of exactly 66 vehicles per mile in all cases. Typical values for other platoons are shown in Table 1.

Table 1. Mean Density and Speed Range for Constant Density Recovery Phase

Platoon	Mean Density vpm	Approximate Speed Range mph
122	60	24 to 39
123	66	26 to 40
142	60	25 to 30
127	65	24 to 35
141	62	24 to 41
143	55	25 to 42

Finally, traffic flow returns to the original status at a lower density level, picking up more speed at a decreasing rate. The recovery phase - increase of speed at constant density first and then at decreasing density until the flow condition prior to the disturbance is restored - forms the B-loop with the density function prior to the disturbance. It appears that momentum lost in the A-loop is finally recovered in the B-loop so that the original energy level can be restored. Observations made from the helicopter by following a platoon of vehicles indicate that traffic flow will recycle around loop A if sufficient momentum is not gathered during the recovery phase. This operational mode then appears to lead to the highly inefficient stop and go operation frequently found on urban freeways during peak hours. No theoretical investigations on stop and go operations have been carried out so far since more data on this operational mode are required.

2.2 Volume-Density Relationship

The volume-density diagram (Figure 4) shows a characteristic similar to the speed-density plot. The q-k data for the phase prior to the disturbance suggest a curve similar to the form postulated by Lighthill and Whitham. The recovery phase, however, displays a completely different shape forming again the A-and B-loops.

The traffic volume (determined from $q = u \cdot k$ where q is the volume in vehicles per hour per traffic lane, u is the space mean speed and k is the density for the platoon) increases to very high values during the constant density phase of the B-loop. In this case a maximum value of about 2800 vph was theoretically reached at a density of 70 vpm. Obviously uniform acceleration of the platoon at short spacing and at increasing velocity is responsible for this high volume and differences in driver attitude or traffic composition can change conditions very much.

2.3 Energy-Density Relationship

Though it is not possible to determine the exact level of energy of a platoon of cars, an estimate was made assuming that traffic density can replace mass in the kinetic energy equation.

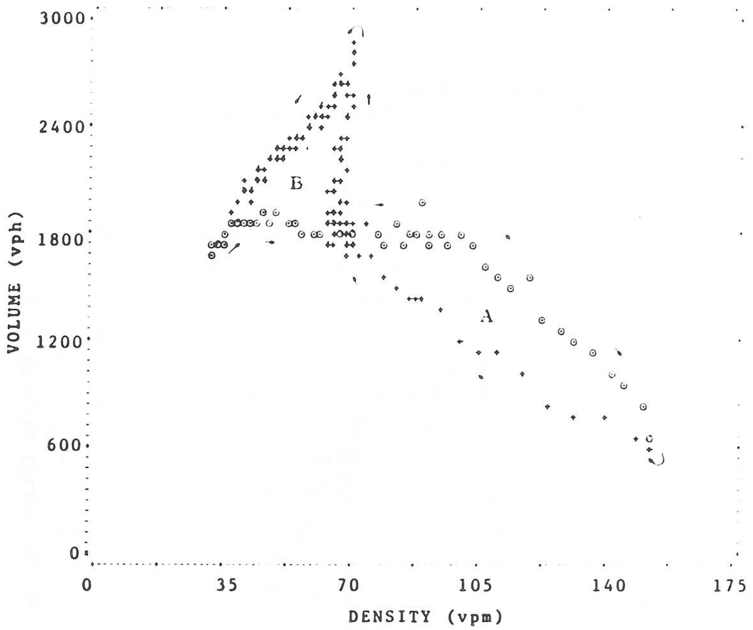

Figure 4: Volume-Density Pattern for the Selected Platoon

$$\frac{1}{2} mv^2 \approx cku^2$$

where m = mass, v = velocity, c = constant, k = traffic density, u = space mean speed of the platoon, and the expression for the level of kinetic energy for traffic flow then becomes

$$\frac{\text{vehicles}}{\text{mile}} \times \left(\frac{\text{miles}}{\text{hour}}\right)^2 = \frac{\text{vehicles}}{\text{hour}} \times \frac{\text{miles}}{\text{hour}} = qu$$

which is the throughput of the traffic system. Figure 5 shows the energy-density diagram for the selected platoon of vehicles. The plot shows a characteristic similar to Figures 3 and 4. Area A measuring approximately 88 units is about the same size as area B measuring 93 units which provides support for the hypothesis that the energy lost by the platoon in going into and through a disturbance must be regained in area B if traffic flow is to be able to return to the efficient flow condition prior to the disturbance. This level of energy gain is only made possible by attaining an energy level during the constant density recovery phase which is equal or somewhat higher than the energy level (throughput) prior to the disturbance. The attainment of such a high energy level has serious consequences with regard to safe car-following conditions. Figure 6 shows the average headway in seconds for the phases prior to and after the disturbance. These data were calculated by taking the average spacing and dividing by the average velocity. During the phase leading into the disturbance drivers adopt a headway of about 2.0 seconds over a density range of 30 vpm (mean spacing = 175 ft) to 100 vpm (mean spacing = 53 ft). As density increases further and as the average spacing decreases, the platoon acts like a unit and each vehicle in the platoon maintains approximately the same spacing. This is evidenced by small values of the standard deviation of spacing (about ± 1.75 ft) in the density domain exceeding 100 vpm. The

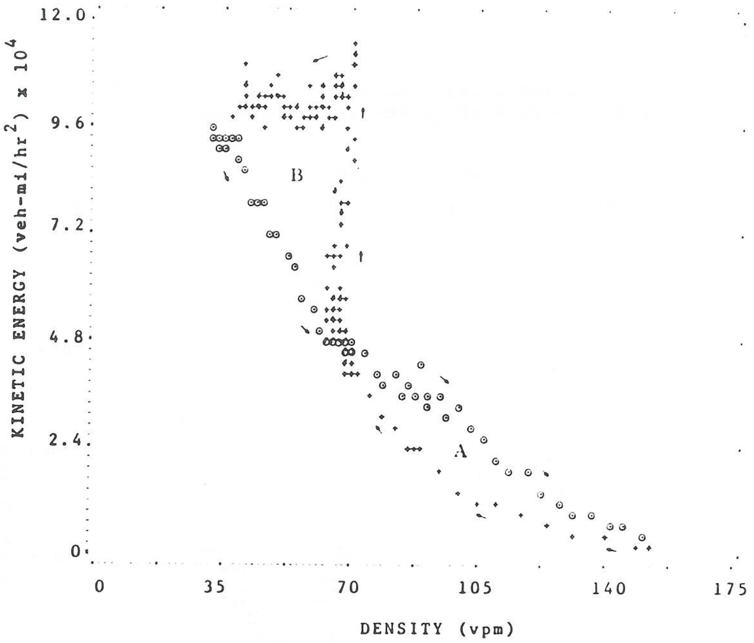

Figure 5: Energy-Density Pattern for the Selected Platoon

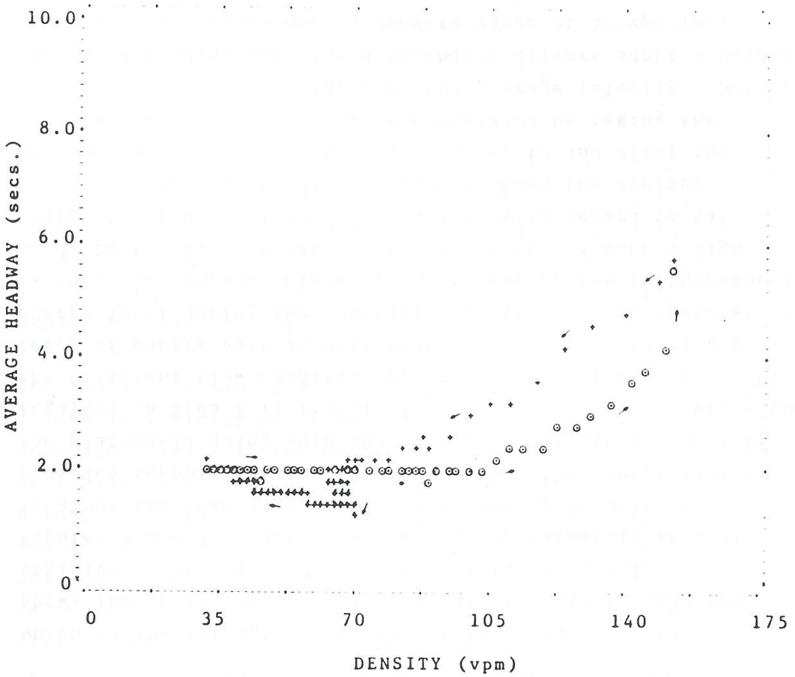

Figure 6: Mean Headway-Density Pattern for the Selected Platoon

platoon emerging from a disturbance adopts longer headways until it reaches the constant headway level at about 70 vpm. At this point speed begins to increase without substantial change in the spacing between vehicles and the average time headway is reduced to values as low as 1.2 seconds. This period of rapid energy gain appears to be the most dangerous period for the occurrence of chain reaction rear end collisions.

3. THE HYSTERESIS PHENOMENON: A MICROSCOPIC ANALYSIS

Additional insight into the characteristics of the hysteresis phenomenon in traffic flow can be obtained by analyzing the behavior of a platoon of vehicles moving through a kinematic disturbance from a microscopic point of view. Specific attention in this regard is devoted to consideration of the asymmetry between the behavior of a driver-vehicle unit engaged in a deceleration maneuver and a similar unit performing an acceleration maneuver. In addition, the change in driver attitude and response characteristics which appear to occur as a driver-vehicle unit approaches, passes through and departs from a kinematic disturbance is investigated using concepts from car-following theory.

3.1 The Acceleration-Deceleration Asymmetry

The asymmetry between the acceleration and deceleration behavior of driver-vehicle units under like stimulus conditions has been identified and discussed by several different authors. This asymmetry is a basic underlying factor in the retarded behavior of vehicles emerging from a kinematic disturbance and thus is central to an investigation of the phenomenon of traffic hysteresis.

Early evidence of the difference in driver action in an accelerating environment as compared to a decelerating environment is provided by Forbes, et al$^{(3)}$ in their study of driver reactions to differing geometric conditions within vehicular tunnels. In this study it was found that the introduction of a deceleration maneuver (followed by an accompanying acceleration maneuver) into a vehicular platoon produced an increase in the time headways existing within the platoon and a corresponding retardation of the maximum flow rate displayed by the platoon. A similar phenomenon was noted but not discussed in detail by Herman and Potts$^{(4)}$ in their study of single-lane no passing traffic flow. These authors found by fitting a reciprocal-spacing car following model to experimental data that the sensitivity of response displayed by a following vehicle was somewhat greater when the relative speed was negative (deceleration) than when the relative speed was positive (acceleration). The resulting difference was not considered consequential enough, however, to justify the introduction of a more complicated car following law.

Newell$^{(5)}$, recognizing the potential consequences of differing acceleration and deceleration behavior to the theory of traffic flow, proposed that two rather than one traffic equations of state might be required to describe the characteristics of traffic movement. One equation of state would apply during accelerating conditions while a second distinct equation would describe decelerating conditions. He then proceeded to describe how the introduction of two distinct equations of state would explain many of the previously unexplainable occurrences noted in actual traffic movement. This same approach was used by one of the present authors in a study of the applicability of the hydrodynamic approach for modeling single lane traffic flowing in a multi-lane environment$^{(6)}$. It was shown that kinematic waves carrying different flow rates along the roadway display significantly different characteristics depending upon whether the flow rate occurs during an acceleration or a deceleration maneuver.

Herman and Rothery(7) conducted a study of the propagation of disturbances through vehicular platoons in which they found a consistent and marked difference in the results for acceleration and deceleration disturbances. In this study the time of propagation of a disturbance was shown to be substantially less for deceleration than for acceleration for a platoon of given length. Edie and Baverez(8) in an investigation of the generation and propagation of stop-start traffic waves found that driver-vehicle units negotiating a given speed change assumed different average speed change rates during acceleration than during deceleration. They found in particular that average deceleration rates tend to increase with increasing amount of speed change while average acceleration rates tend to decrease over the speed change domain studied. Such a behavior would explain the retarded performance of traffic flow emerging from a kinematic disturbance as compared to the performance of the same flow approaching a disturbance.

In order to determine if a pattern similar to that found by Edie and Baverez exists in the experimental data collected on Interstate 71 and described in the preceding section, an identical analysis was carried out using acceleration and deceleration rates displayed by the vehicles shown in Figure 1. The average speed change rate used by each driver-vehicle unit was plotted against the total amount of speed change. A threshold value of 20 mph was used as the reference point for the speed change analysis. A separate plot was prepared for conditions of acceleration and deceleration. The resulting plots are shown as Figures 7 and 8, respectively. The lines on the plots are least squares fits to the data for comparison with those of Edie and Baverez.

Observation of Figures 7 and 8 reveals three interesting and important points. First, it is noted that a wide variation occurs among individual driver-vehicle units with regard to both the average acceleration and deceleration values used to negotiate a given speed change. Second, deceleration rates at a given speed change value are in general substantially greater than acceleration rates corresponding to the same amount of speed change. The difference is especially pronounced at higher speed change values. Third, although the data points are quite scattered, it is apparent that deceleration rates employed increased with increasing speed change while acceleration rates remained basically the same over the speed change domain investigated. The mean values of speed change rate calculated over the entire speed change domain are 1.6 mph/sec for acceleration and 2.6 mph/sec for deceleration. As is to be expected these values are somewhat higher than those found by Edie and Baverez (1.0 mph/sec and 1.1 mph/sec respectively) for tunnel traffic flow. The greater disparity displayed by driver-vehicle units traveling on a freeway as compared to those traveling in tunnels emphasizes the importance of a complete understanding of the mechanism of traffic hysteresis as it influences the design and operation of modern real-time freeway traffic control systems.

3.2 The Car Following Approach

The concept of analyzing the movement of a stream of traffic through the consideration of the interaction of individual vehicle pairs is an important contribution to the field of traffic science credited to Reuschel(9) and Pipes(10). Much

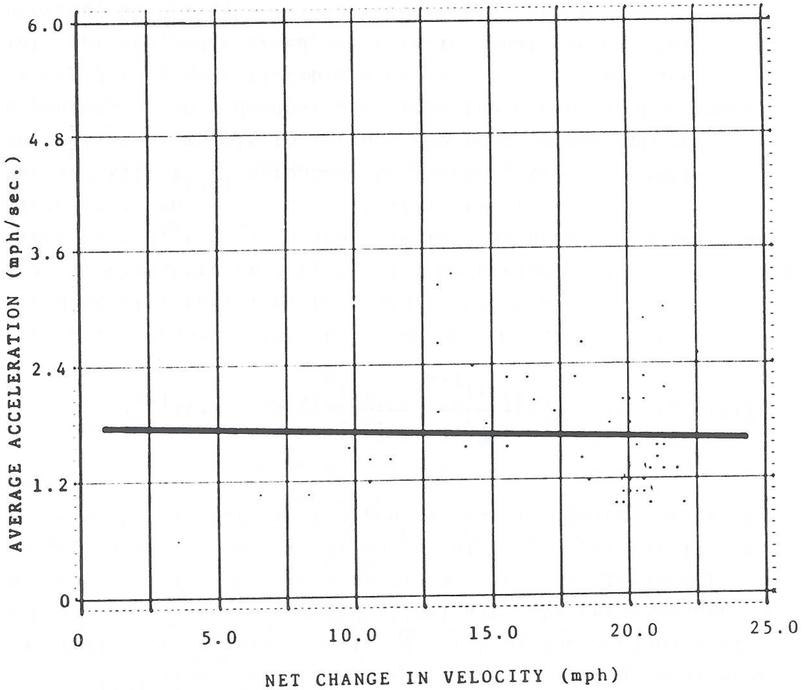

Figure 7: Plot of Average Acceleration Rate vs. Speed Change

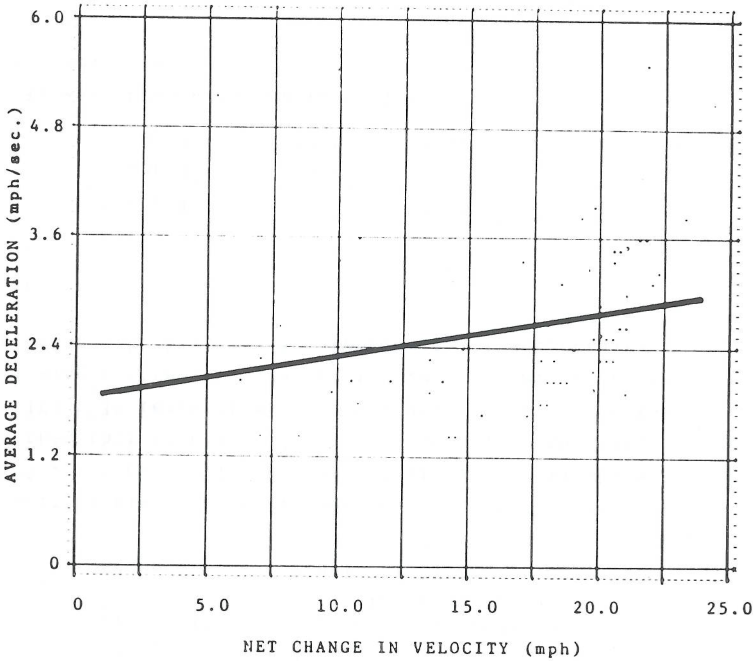

Figure 8: Plot of Average Deceleration Rate vs. Speed Change

of the significant early work using this approach both in terms of further theoretical development and experimental investigation was performed at the General Motors Research Laboratories by Herman, Chandler, Montroll, Gazis, Potts, Rothery and others and was reported in a lengthy series of publications(11 - 15).

A significant work in this regard due to Gazis, Herman and Rothery(15) discusses the applicability of various nonlinear car following formulations for describing the mechanism of vehicle pair interaction and illustrates the relationship between specific nonlinear models and several previously suggested macroscopic equations of state. Specifically it is shown by starting with a general car following law of the form

$$\ddot{x}_{n+1}(t+T) = a \frac{[\dot{x}_{n+1}(t+T)]^{m}}{[x_n(t) - x_{n+1}(t)]^{\ell}} [\dot{x}_n(t) - \dot{x}_{n+1}(t)]$$

appropriate choices for the exponents ℓ and m will yield the speed-density relations proposed by Greenshields ($m = 0$, $\ell = 2$), Greenberg ($m = 0$, $\ell = 1$), Underwood ($m = 1$, $\ell = 2$) and Pipes ($m = 0$, $\ell = 0$). Thus, in this manner, a bridge between microscopic and macroscopic traffic theory is established. May and Keller(16) extended the investigation of nonlinear car following models to include the case of noninteger exponents. They demonstrated that the use of such exponents resulted in a more flexible model for describing traffic interactions and yielded macroscopic equations of state that provided both a good fit to experimental speed-density data and satisfied a set of realistic boundary conditions. For their data a model with $m = 0.8$ and $\ell = 2.8$ was selected for use. No consideration was given, however, to the possibility of utilizing different models to describe behavior during acceleration and deceleration conditions.

A study has recently been completed by Hoefs(17) in which the acceleration-deceleration asymmetry is recognized and an attempt is made to model the two conditions separately. Hoefs, in fact, divides his data into four different groups as follows.

Group I	All Data
Group II	Acceleration Conditions
Group III	Deceleration Conditions (without braking)
Group IV	Deceleration Conditions (with braking)

As a result of his study Hoefs determined that driver sensitivity for Case I is less than that of Case II which is less than that of Case III which is much less than that of Case IV. In terms of macroscopic analysis he found that the following exponent values for the general car following model provided the best fit to experimental speed-density data.

	m	ℓ
Group I	-	-
Group II	+1.5	+0.5
Group III	+0.2	+1.9
Group IV	+0.6	+3.2

No concern was shown with regard to fulfilling reasonable boundary conditions.

In an attempt to gain further insight into the phenomenon of traffic hysteresis discovered in the traffic flow on Interstate 71, Hoefs' approach was applied to the data of Platoon 123. No attempt was made, however, to differentiate between braking and non-braking deceleration since such is impossible with the existing aerial photography data. The data was thus split into only two groups characterizing behavior during acceleration and during deceleration. Each group of data was then analyzed to determine the most appropriate choice for ℓ and m by fitting the corresponding macroscopic equation of state to the resulting speed-density data using linear regression techniques. As a result of this analysis three models were selected for each group of data as providing the best description of that data. The selected models can be characterized as 1) providing the best fit (least standard error) using integer exponents, 2) providing the best fit using noninteger exponents, and 3) providing the best fit using noninteger exponents while fulfilling reasonable boundary conditions in terms of free flow speed and jam density. The selected models are the following :

Model Category	Acceleration		Deceleration	
	m	ℓ	m	ℓ
1	0	1	1	2
2	0	0.8	0.8	1.8
3	0.2	1.6	0.7	2.5

Observation of the preceding table reveals that for all three model categories the exponent values for acceleration conditions are smaller than those corresponding to deceleration conditions. Thus it is seen (for the vehicles of Platoon 123 at least) that drivers tend to place more emphasis on both their own velocity and the spacing between themselves and the leading vehicle during a period of deceleration than while accelerating. This increased awareness during a deceleration maneuver (or laziness during acceleration as Newell(5) has characterized it) is consistent with the retarded behavior of vehicles emerging from a kinematic disturbance as described in a previous section of this paper.

4. DISCUSSION

The application of aerial survey methods to the study of

traffic flow on a multi-lane freeway has led to the isolation of the phenomenon of traffic flow hysteresis. The phenomenon is manifested as a generally retarded behavior of vehicles emerging from a kinematic disturbance as compared to the behavior of the same vehicles approaching a disturbance. Although data for analyzing the characteristics of the phenomenon are still quite scarce, an attempt has been made in this paper to describe the phenomenon from both the viewpoints of macroscopic and microscopic analysis.

Specific attention has been devoted to consideration of the speed-density pattern, the volume-density pattern, the energy-density pattern and the headway-density pattern displayed by a platoon of vehicles traveling through a kinematic disturbance. It was hypothesized that traffic flow loses energy in going through a kinematic disturbance and that the lost energy must be regained during an extended acceleration phase before stable flow can be restored. It was shown that during this energy gain process the danger of multiple vehicle rear-end collisions is especially high. It was further hypothesized that the failure of the traffic stream to regain sufficient energy results in the stop and go flow characteristics of the congested modern freeway. Analysis was also devoted to consideration of the acceleration-deceleration asymmetry and the techniques of car following theory were employed to provide further insight into the fundamental nature of the phenomenon. In each case evidence consistent with the retarded behavior of traffic emerging from a disturbance was obtained.

At present effort is being devoted to the recording of further freeway flow disturbances using aerial photography. It is hoped that this additional data will provide further insight into the mechanisms of traffic hysteresis.

5. ACKNOWLEDGEMENT

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