RECORDING AND ANALYSIS OF TRAFFIC ENGINEERING MEASURES

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This paper deals with the development of a traffic survey system that collects data on a digital tape system and provides off-line analysis by putting the tape on a general-purpose electronic digital computer. Examples of two methods that have actually been conducted in the field are presented. One example involves the use of the recorder in a moving vehicle to collect data on time, distance, and approaching vehicles passed on a freeway facility. These data are used to develop speed, flow, and density contours; delay contours; speed and delay peak-hour profiles; isochronal travel time plots; and bottleneck flow density relationships. The second example involves stationing the recorder at the side of the roadway and collecting speed, volume, and headway data through the use of road-tube detectors. These data are used to compute speeding, tailgating, and turbulence indexes. Other traffic engineering study applications are being developed.

•THE DESIGN of traffic control systems is highly dependent on traffic operations data. Many of the techniques used for collecting and analyzing these data do not fully satisfy the information requirements of today's traffic control systems, nor do they take full advantage of the automation now available for collecting and processing this information. These deficiencies have seriously retarded the development of the more advanced traffic control systems required to solve our increasingly complex traffic problems. In other words, some of the traffic congestion on our streets today could be eliminated by development of better data collection and analysis techniques.

Many studies made by manual observers or simple recording devices deal mainly with system inputs and outputs and do not provide for an assessment of the interaction between the vehicle and the control system or among several vehicles within a given system. More comprehensive studies, using aerial photography, for example, have been used successfully to provide detailed information; however, their application has been somewhat limited because of factors such as cost, complexity, and manual data reduction requirements. Another possible tool for this purpose is the digital magnetic tape recorder, which may be used to record data from several sources, e.g., detectors, odometers, signal controllers, and manual switches. These data may be analyzed directly on a digital computer without the time-consuming manual reduction steps. This technique is suited to a wide variety of traffic operations analyses.

This paper deals with two specific applications of a prototype magnetic tape recorder system developed for recording and analysis of traffic engineering measures (RATEM). In the first example, the recorder is carried within the vehicle and is used to record "floating-car" data. In the second example, the recorder is left in a stationary position and connected to temporary road-tube sensors to collect traffic flow data.

SYSTEM OPERATION

The data recorder was designed around a commercially available incremental tape unit. This unit operates on 12 Vdc, uses ½-in. computer tape, and writes 6 channels plus parity at 200 bytes per inch. It is provided with internal logic for writing the

*At the time this research was performed, the authors were with Kelly Scientific Corporation.

contents of its input register (6 bits) on the tape upon command. For analysis purposes, these 6-bit words are grouped into "records," each containing 2,048 words. The traffic inputs are required to be in switch closure form. Special interface circuitry was constructed in the prototype version to accommodate inputs such as road tubes, presence detectors, odometer pulses, traffic signal circuits (115 Vac), and manual event switches.

The prototype was designed to record 18 bits of information each time any one of the inputs was actuated. These 18 bits appear on the tape as three 6-bit words. One word was used to indicate which input switch was activated. Each traffic input circuit was assigned a unique 6-bit code, giving the system the capacity to accept 64 independent inputs. In the prototype unit, however, the necessary hardware was provided for only 16 such inputs.

The remaining 12 bits (2 words) are used to indicate the time at which the actuation took place. The time value is advanced by one unit each 2 millisec by an internal oscillator. Thus, the clock recycles approximately every 8 sec ($2^{12} \times 0.002$). The recycling of the clock is treated in the same manner as an input switch closure; i.e., an 18-bit word is recorded with the 6-bit device code identifying the clock. No record is kept of the actual time of day; however, this value may be computed by the analysis program by counting the clock recycling periods, provided that the initial time of day is known. Figure 1 shows that the 18-bit word is first entered into a memory buffer with a six-word capacity and finally recorded on the tape by the internal logic of the tape drive. The memory buffer prevents the loss of data when the input data rate temporarily exceeds the recording speed of the tape unit. This configuration promotes the most economical use of tape inasmuch as each actuation writes only three words, and no data are written except upon actuation. This permits unattended operation for several days at locations where detector impulses are being recorded.

MOVING-VEHICLE STUDIES

Detailed studies have been carried out to determine the patterns of speed, flow, density, and delay for traffic on a freeway or urban surface street through use of RATEM system hardware (1). The system was installed in a vehicle, and traffic measurements were made as the vehicle traveled through traffic. Distance measurements were recorded from "fifth-wheel" pulses directly onto the magnetic tape.

Study runs were made alternately with the system-equipped vehicle traveling "with" and "against" the direction of traffic movement being measured. When traveling with the traffic, the computer recorded each stopped vehicle that was passed (e.g., on a freeway with exit-ramp queues) as an event on the magnetic tape. When traveling in the opposite direction, the computer recorded as events all vehicles in the major traffic stream as they were passed. The data obtained in this manner for a particular roadway section of length (L) include the speed of the traffic movement of interest, V_f; the speed of traffic in the reverse direction, V_r; the number of vehicles counted within the section, N_o; and the number of stopped vehicles queued with the section, N_q.

One of the variables of interest, speed, was obtained directly from these data as V_f. The other two, flow Q and density K, may be calculated as follows:

$$K = N_q + (N_o - N_q)\,[V_r/(V_r + V_f)]/L$$

$$Q = KV_f$$

These equations may be applied only on two-way routes where the view of the oncoming traffic is not obstructed.

These calculations were performed automatically as the data tapes were read by the computer. Survey section speed, flow, and density data were then analyzed to produce the following results:

1. Speed, flow, and density contour plots;
2. Peak-hour profiles of speed and density;

3. Contour plots of delay to the freeway traffic;
4. Peak-hour travel relationships;
5. Isochronal travel time plots; and
6. Bottleneck flow-density relationships.

As an example of the moving-vehicle technique, a portion of the results of studies conducted on the Jones Falls Expressway in Baltimore, Maryland, is shown in Figures 2 through 6.

Speed, Flow, and Density Contours

Speed, flow, and density contours for the north section of the Jones Falls Expressway for southbound a. m. peak hours are shown in Figure 2. Minor congestion is evident in this figure for a short time near the downstream limit of the study. The main reason for this congestion is the introduction of two entrance ramps immediately upstream. The speeds and densities indicate that near-capacity operation is experienced at this point and that the upstream section of the freeway is quite capable of handling the traffic demand under stable flow conditions.

Speed and Density Profiles

The operation of this facility is described in the macroscopic sense by the speed, flow, and density contours derived from the data. It is somewhat difficult, however, to carry the interpretation of these contours much beyond a narrative description. Some further analyses may be performed on these data. One meaningful way of quantifying the operation is a profile plot of the average speed and density over an entire peak period. For example, Figure 3 shows speed and density profiles for the heaviest hour of the a. m. peak period (7:45 to 8:45). These profiles are useful in assessing the approximate degree of congestion throughout the length of the freeway and in identifying bottleneck characteristics. The mirror-image characteristics are particularly interesting inasmuch as the peaks of wide separation between the speed and density curves indicate the existence of bottlenecks. The most pronounced peak is observed at the southern exit ramps, where considerable congestion is known to occur. Similar, but lesser, bottlenecks are noted in the areas of the North Avenue and the 28th Street exit ramps. Another minor bottleneck occurs around mile 3.7. This may be due to the roadway curvature in this area or to the sun glare that is sometimes present during the morning peak. Some congestion is also observed close to the Cold Spring interchange where another divergence between the speed and density curves is noted.

Delay Analysis

Delay is another useful measure that may be derived from the speed, flow, and density data. There are several definitions of delay; the definition best suited for this study is as follows: "Delay, measured in vehicle-minutes, is the excess travel time expended by all vehicles on the freeway because of an operating speed lower than the desired value." Setting the desired speed at 40 mph, which is close to optimal for maximum capacity, permits the calculation of delay D for a given section of roadway as follows:

$$D = 60\ (L/V - L/40)\ \text{min/mile/vehicle}$$

where

L = length of the section, and
V = speed of traffic.

Figure 4 shows the delay contours for the morning peak period on the Jones Falls Expressway. The delay reaches a peak value of about 3 min/mile at about 8:15 a. m. and concentrates in the area of the south exit ramps.

Figure 1. Simplified data flow diagram for the RATEM system.

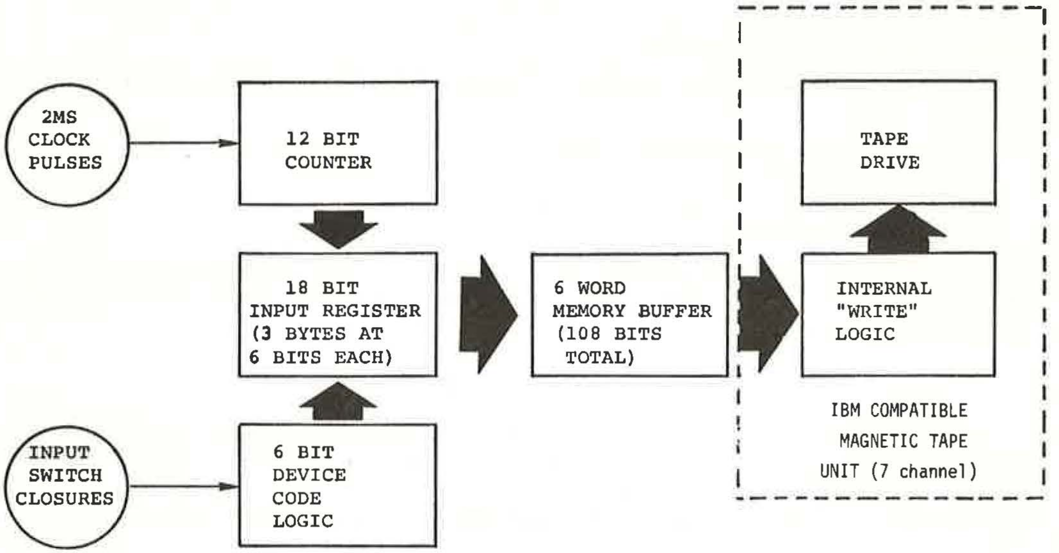
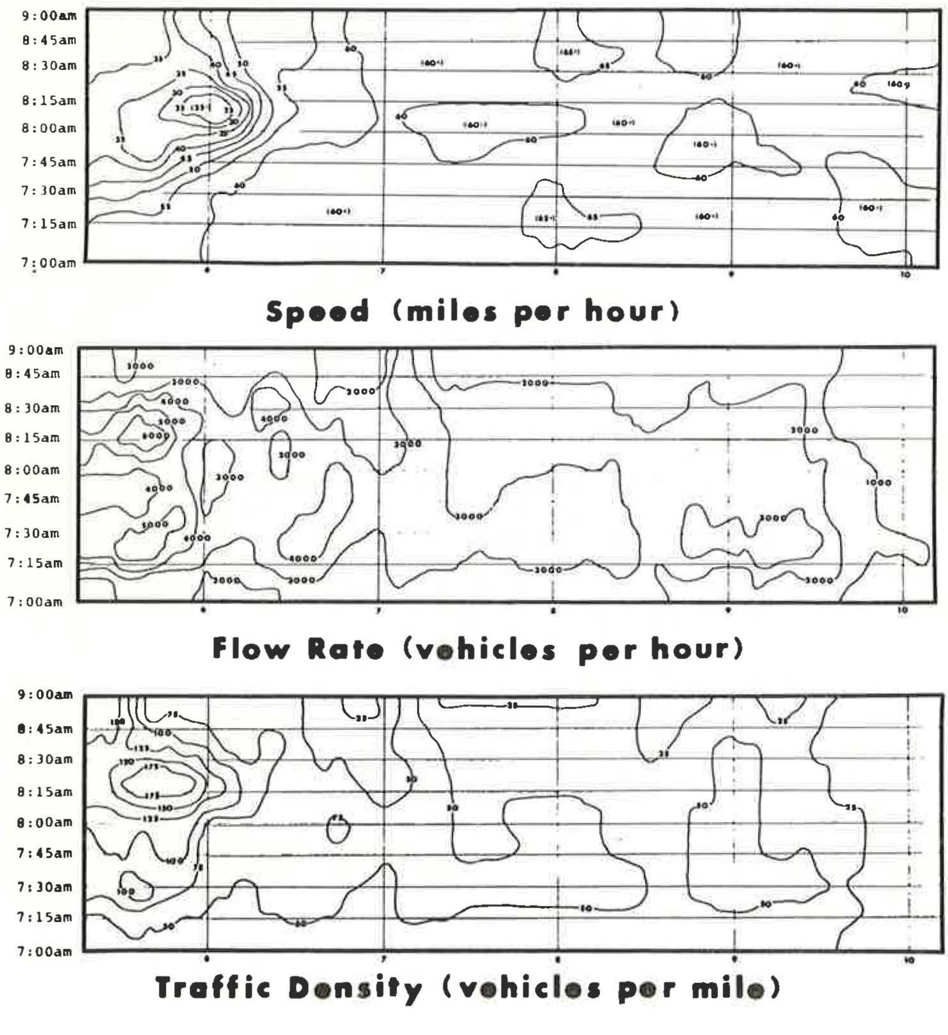


Figure 2. Speed, flow, and density contours, a.m. peak period.



Peak-Hour Travel Relationships

Four factors of interest are readily obtainable from the peak-hour travel relationships:

1. Total travel (vehicle-miles), TT;
2. Total travel time (vehicle-hours), TTT;
3. Total delay (vehicle-hours), D; and
4. Average speed (mph), V.

Total travel TT was calculated by summation of the flow measured on each section of the freeway over the 1-hour period, multiplied by the length of the section, which in this study was $\frac{1}{20}$ mile; i.e.,

$$TT = \frac{1}{20} \Sigma Q$$

Total travel time TTT was calculated by integrating the values of traffic density over both time and distance. This figure may be represented, therefore, by the total volume of space contained under the density contours.

Total delay D was calculated by the summation of the individual values

$$D = TTT - TT/40 \text{ mph}$$

obtained for each 5-min sample on each $\frac{1}{20}$-mile section within the study limits.

Average speed V was calculated by simply dividing the total travel by the total travel time; i.e.,

$$V = TT/TTT$$

The values described as determined for the southbound a. m. peak period for the Jones Falls Expressway are as follows:

Factor	Value
TT, vehicle-miles	17,764
TTT, vehicle-hours	484
D, vehicle-hours	66.6
V, mph	36.7

Isochronal Travel Time Plots

Another measure of interest in assessing roadway operations is the expected travel time for each vehicle from any point on the highway to a reference point, usually the end, as a function of the time of day as well as the distance from the reference point. These measurements are shown in Figure 5 for the a. m. peak period for the southbound Jones Falls Expressway. It is noted that the time to travel the study freeway link varies from 5 to 7 min during the a. m. peak.

Bottleneck Flow-Density Relationships

The relationship between flow and density on a section of highway is useful in determining the optimal traffic density that should be allowed on the facility as well as the capacity, or peak flow, that can be accommodated. The flow-density curve for the bottleneck area of the freeway in question is shown in Figure 6. The curve uses 5-min samples over $\frac{1}{20}$-mile sections. Points are plotted individually for each 10-vehicle/mile density increment. The maximum flow rate of 5,400 vph (3 lanes) was obtained at densities of about 170 vehicles/mile or about 57 vehicles/mile/lane. These figures fall within the range of generally accepted values.

Figure 3. Speed and density profiles, a.m. peak period.

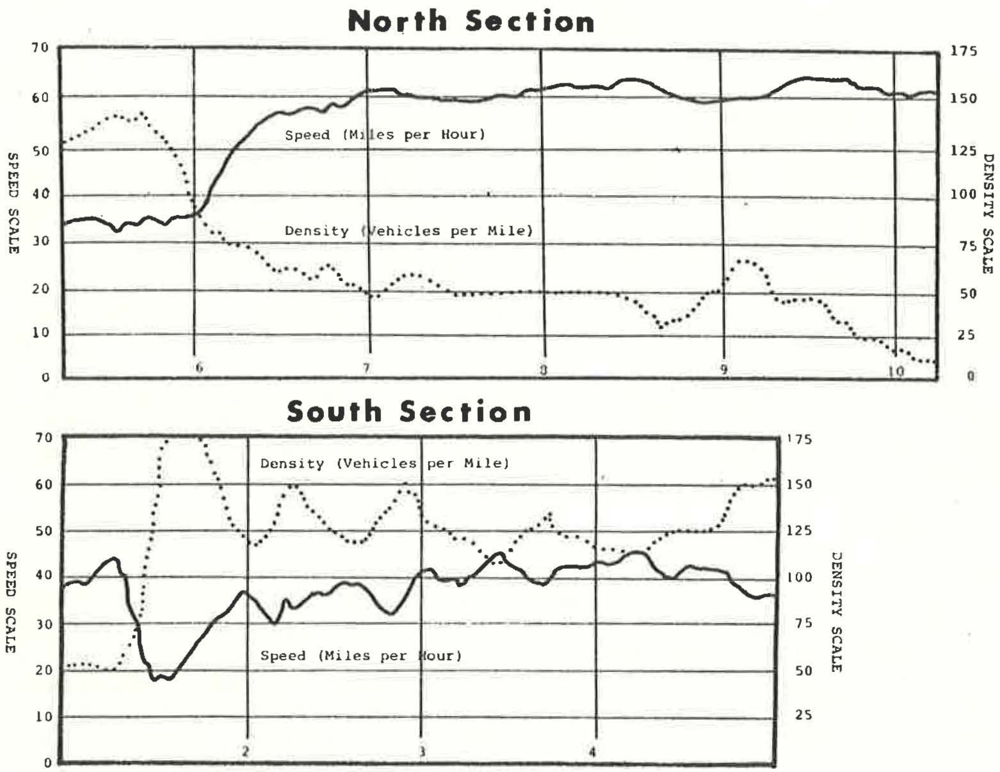


Figure 4. Delay contours, a.m. peak period.

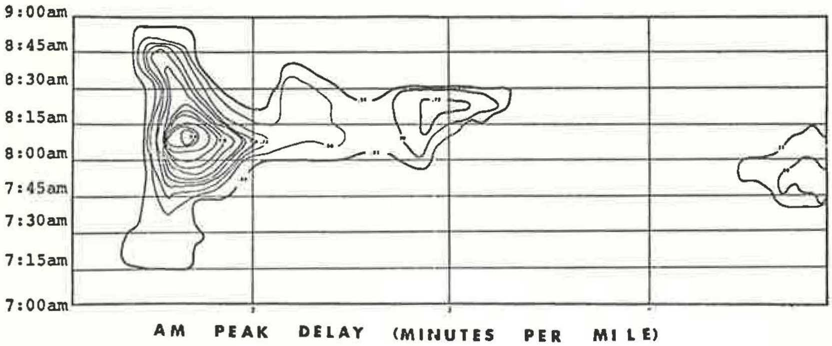
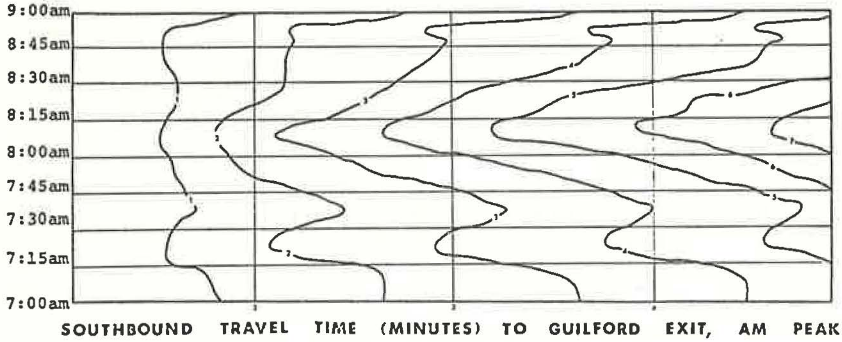


Figure 5. Travel time plots, a.m. peak period.



STATIONARY STUDIES

Data Collection

The RATEM system can be set up beside a roadway to collect a variety of traffic data by using road-tube or tapeswitch inputs. This application was initially developed for the National Highway Safety Bureau as a possible approach for sampling and recording traffic violations (2). The digital recorder was connected to temporary road-tube sensors to detect and record a variety of traffic violations and safety information. The types of data collected depended primarily on the configuration of the detectors.

The detector configurations used in the NHSB studies are shown in Figures 7 and 8 for a two-lane, two-way roadway and a four-lane, two-way roadway. The tubes were placed 4 ft apart, and the time actuations of a vehicle crossing each tube were recorded by the magnetic tape unit.

Because only actual events, axle crossings and time marks, were recorded on the magnetic tape, a single tape could record data for a complete 3-day (24 hours per day) period at a location that handled about 30,000 vehicles/day. The equipment could be left unattended; however, it was found that periodic checks were desirable.

Data Reduction

The raw data, as described earlier, were obtained in the form of axle-crossing times for all of the road-tube sensors. To convert these data into usable traffic information required that several operations be performed by the analysis program. The axles had to be identified with a particular lane on the roadway. In the case of roadways with a single lane in each direction, this was easily accomplished by reference to the location of the actuated detector. Where multiple-lane configurations were involved, it was necessary to use additional logic to determine the lane of operation. As an example, an actuation on detector B (Fig. 8) alone would indicate a vehicle in the inside lane, whereas near-simultaneous actuations on detectors A and B would indicate a vehicle in the outside lane. This concept may be extended to any number of lanes, provided that sufficient detectors are installed. Additional lanes complicate the logic considerably, however, and cause ambiguities that require data to be discarded, reducing the sample size somewhat. Where several lanes are involved it is generally preferable to use separate tapeswitches for each lane of traffic.

It is also necessary to associate individual axles with vehicles for most of the traffic measurements. An axle was considered to be associated with the preceding axle in the same lane if, and only if, spacing between the axles was less than a prescribed distance (approximately 25 ft), and the two axles were traveling at the same speed. Where more than two axles were associated with the same vehicle, additional checks were performed, based on combinations of axles, to estimate the composition of the multiaxle unit (e.g., one truck, two passenger cars, and so forth).

Traffic Measurements

The stationary study is particularly an ideal candidate for analyzing safety indexes. In the system developed and tested in the NHSB project, the computer program presented detailed analytical information that can be used directly by traffic engineers and that includes standard information such as the speed pace (the 10-mph increment that includes the largest percentage of motorists), the 85th percentile speed (the speed that is often used to set legal speed limits), and the percentage of motorists who were traveling faster than the current legal speed limit. In addition, three indexes that may be used as a measure of safety for the traffic using the roadway were developed. One of these, speeding index Sp, is calculated as

$$Sp = \left[\frac{\Sigma[(\text{speed of violators}) - (\text{speed limit})]^2}{(\text{sample size of all vehicles})} \right]^{0.5}$$

Figure 6. Flow-density relationship.

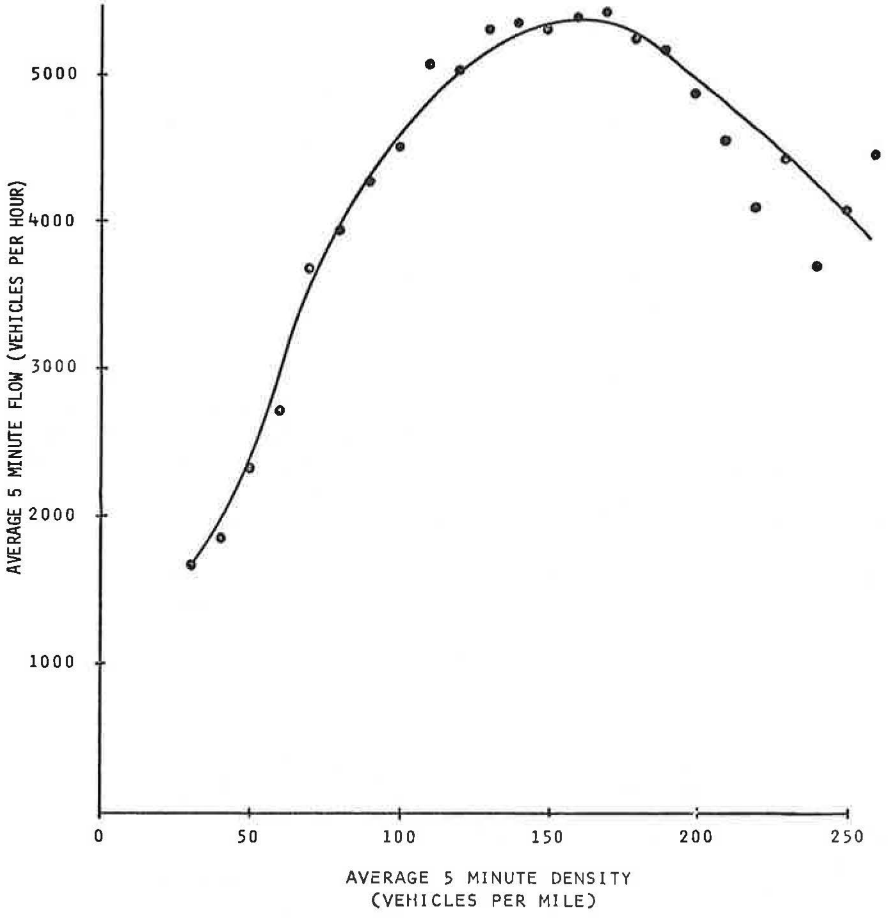


Figure 7. Multiple-tube configuration for two-lane, two-way roadway.

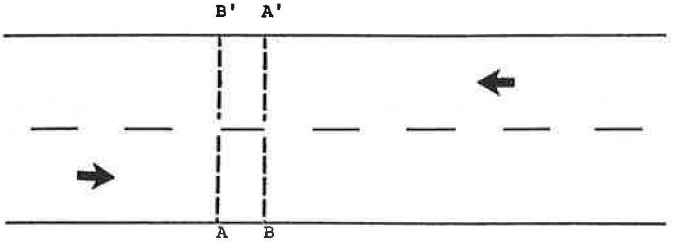
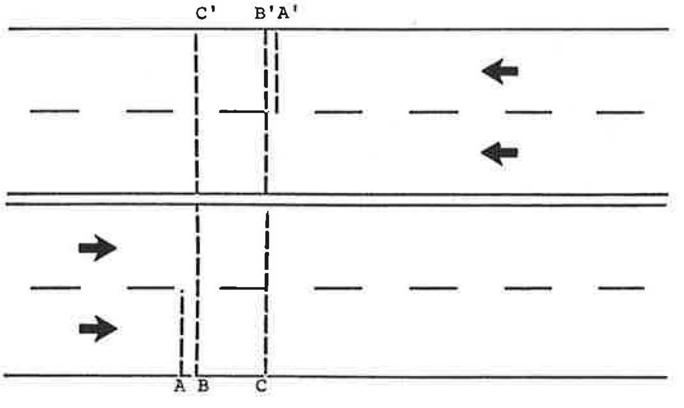


Figure 8. Multiple-tube configuration for four-lane, two-way roadway.



This index is the root mean square of the excess of speed of individual vehicles traveling faster than the speed limit. This gives greater weight to vehicles that are traveling at a speed much higher than the limit than to those who are barely speeding. The index should provide a good indicator of where speed enforcement measures should be applied. A high index figure would indicate a time and location with an extensive speed violation problem.

The tailgating index Tg is computed as

$$\mathrm{Tg} = \left[\frac{\Sigma[(\text{allowable following distance}) - (\text{actual following distance})]^2}{(\text{sample size of all vehicles})}\right]^{0.5}$$

and is the root mean square of the deficiency in following distance of the vehicles considered to be "following too close" for safety. This may have a direct safety implication because it shows the potential for rear-end collisions. The allowable following distance was considered to be 1 ft for each foot per second of speed (roughly one car length for each 10 mph). Thus, the allowable following distance is equivalent to a time gap between vehicles of 1 sec. A high index figure would indicate an area with a potential safety problem.

The third index, turbulence index Tb, is computed as

$$\mathrm{Tb} = \left[\frac{\Sigma(\alpha^2) - (\Sigma\alpha)^2/\text{sample size}}{\text{sample size}}\right]^{0.5}$$

$$\text{where } \alpha = K\left[\frac{(\text{speed of lead vehicle}) - (\text{speed of following vehicle})}{(\text{position of lead vehicle}) - (\text{position of following vehicle})}\right]$$

K is a constant, which in this study equaled unity.

The turbulence index expresses the standard deviation of acceleration α of all vehicles in the sample that passed the point. The α term was estimated by using the linear car-following model shown above. If all vehicles were traveling at or about the same speed, α would be zero or very small, and of course the index would also be small. On the other hand, if vehicles were traveling at a wide range of speeds and their respective distances were small, this would indicate that speed changes would be required to avoid collisions and the variance in acceleration would be relatively high indicating hazardous and possibly unstable flow.

The actual meaning of these values with regard to traffic safety is not yet known; however, it could be easily determined, provided that a sufficient number of studies were conducted at a variety of sites and the resulting indexes were compared to the accident records for these sites.

In the sample of the computer output, the location studied was a four-lane, two-way street. The speed limit was 50 mph. Each hourly period is analyzed, and the sample size is stated. The pace (the 10-mph speed range, which contains the majority of measured speeds) is presented with the percentage of the sample included in this speed range. The speeding violations are presented in percentage above the limit, max, and percentage below a minimum speed limit, min. Because there was no minimum at the study site the min column is 0.0. The 85th percentile speed is presented to the nearest 2-mph increment. The speeding, tailgating, and turbulence indexes were determined as described previously.

Wrong-way movements recorded if any are measured. These include the movement of a vehicle that crosses over the centerline of the roadway. Other events, such as shoulder use, can be recorded also, if needed.

SUMMARY AND CONCLUSIONS

The two examples presented in this paper illustrate the use of a digital magnetic tape system in the recording and analysis of traffic engineering measures. There are several other applications in which the same hardware configuration could be employed to collect traffic data that would be extremely useful to the traffic engineer in the planning, design, and evaluation of traffic engineering improvements. Examples of these other applications include arterial moving-vehicle studies to optimize progression, stationary studies at traffic-actuated signals to improve the efficiency of operation, and entrance-ramp merging area studies to assess the need for ramp controls.

The main purpose of the prototype system described herein was to determine the feasibility of making useful traffic operations measurements. As noted by the results presented in this paper, a large amount of valuable information can be obtained from a few moving-vehicle runs or, in the case of the stationary studies, from a relatively short field study. The time, effort, and cost for reducing the raw data are minimized by the direct use of the digital computer, which uses relatively simple analysis programs.

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