

Use of a Computer and Vehicle Loop Detectors To Measure Queues and Delays At Signalized Intersections

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A computer program has been developed to obtain from the pulses coming from vehicle loop detectors placed near an intersection the traffic parameters of volume, speed, space headway, density, and time headway. By finding the relations between time headway and queue length and time headway and delay, it is shown how the computer program can be used to find queue length and delay at signalized intersections. For the intersection studied, vehicle arrivals at the approaches were random; i. e., there was no platoon structure remaining after passage from the previous intersections.

Graphs are shown of plots of delay vs volume, and of queue length vs volume. A means for correcting the counts lost is also developed.

•A NECESSARY part of the installation of the computer-controlled traffic signal system in Toronto is to be able to evaluate results. Therefore, many analysis programs have been devised by the Traffic Research Corporation in order to study and improve the traffic control system. Among the most important parameters to be measured are queue length and delay at signalized intersections. This report describes one program which was devised for this purpose. The program also provides other traffic parameters, such as volume, density, speed, time headway and space headway.

PROGRAM DESCRIPTION

The program is called the VDCA (volume-density curves type A). It calculates the following traffic parameters from traffic data recorded on magnetic tape:

1. Volume—vehicles per hour per lane (veh/hr/lane);
2. Speed—mph, arithmetic average over a time period at the detector;
3. Density—vehicles per mile per lane (veh/mi/lane), over a time period at the detector;
4. Space headway—ft, over a time period at the detector; and
5. Time headway—seconds per vehicle, over a time period at the detector.

The computer flow chart for finding these parameters is shown in Appendix B. A typical printout is shown in Figure 1.

The same detectors that are used for control purposes are also used for evaluation purposes. The positioning and use of the detectors for control purposes has already been reported (3). For reasons of economy, two loops in two adjacent lanes are connected to one piece of detector electronics. It is therefore possible for two vehicles to cross the detector loops at once, and this results in a certain loss of counts. However, a formula has been derived which allows the computer to correct the counts automatically as the program is run. A derivation of this formula is given in Appendix A. Tests have shown the corrected counts generally accurate to within 5 percent.

VEHICLE DENSITY CALCULATIONS

Control Cards						
		Date	Start	End		
		Nov. 19	17.0	17.15		
Control Parameters						
A1	A2	A3	A4	A5	A6	A7
.200	1,990	1,000	11,060	.10820	.66000	.009330
Detector	Lanes	Mean Speed	Counts/ Lane/Hr	Density	Mean Space Headway	Mean Time Headway
143	2	22.70	491.	23.91	220.79	6.97
144	2	20.08	642.	61.56	85.76	3.47
145	2	18.49	623.	58.19	90.73	3.95
146	2	22.20	396.	18.96	278.48	8.78

Figure 1. Typical VDCA output.

Method of Calculating Space Headway and Density

Figure 2 shows the basic method used to calculate space headway. Pulses generated by vehicles are taken a pair at a time, and the average speed of the two vehicles is determined. Space headway S_n is then found by multiplying the average speed by the time headway H_n . Density, D , in veh/mi is found by dividing the number of feet in a mile by space headway: $D = 5280/S$ veh/mi/lane, where S is the arithmetic average of all S_n .

Meaning of Density as Calculated

The term density is generally used only to apply to homogeneous conditions, because speed, time headway and space headway are nearly uniform in space and time. These conditions do not apply near a signalized intersection. The density found under nonhomogeneous conditions depends to some extent on the method of calculation used. The calculation performed in the VDCA program is felt to be reasonable; in fact, it produces very useful results.

Volume-Density Curves

The first use that was made of the VDCA program was to plot volume-density curves (Fig. 3). The first part of the curve, near the origin, always is a straight portion whose slope is equal to the free travel speed on the road link upstream of the intersection. When queues begin to extend past the detector, indicating that approach capacity is being reached, the volume-density curve becomes parallel to the axis of density—the volume reached at this plateau is a measure of approach capacity.

Since density as calculated by the program continues to increase, as queues become longer, density can also be taken as a measure of congestion even though volume remains the same.

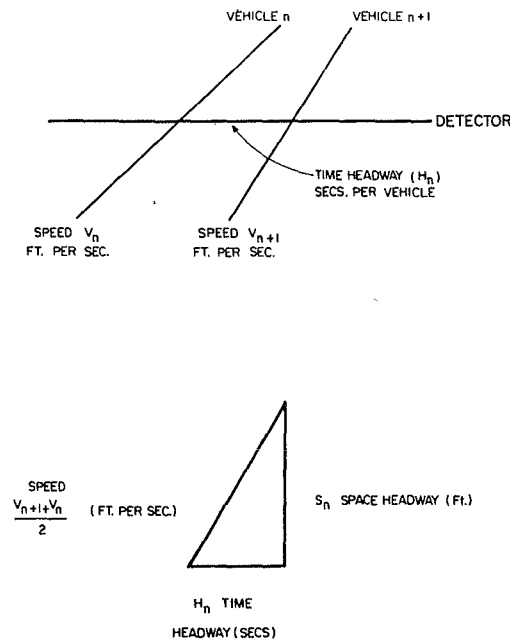


Figure 2. Method of calculating space headway.

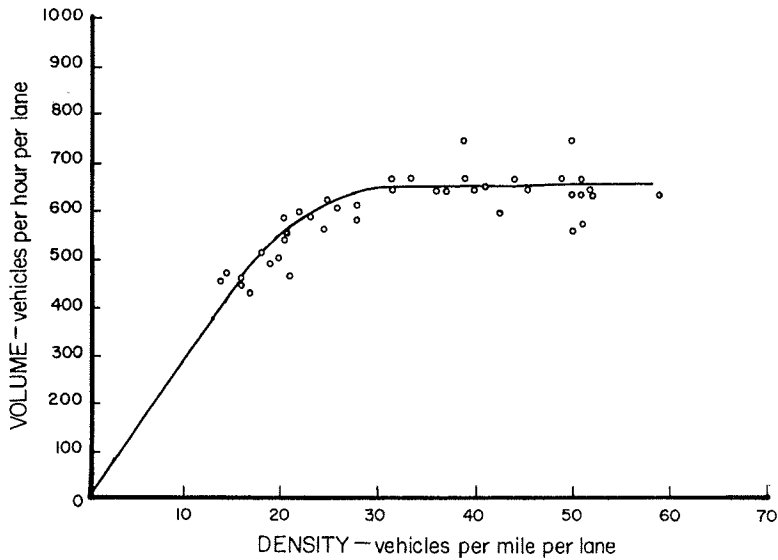


Figure 3. Volume vs density, east leg, fixed time—a.m. and p.m. (points are 15 min averages).

Calculation of Queue Length and Delay

F. V. Webster of the Road Research Laboratory has produced formulas from which queue length and delay can be found, if cycle length, split, and volume are known (1). Arrivals are random in time, meaning that there is no platoon structure in the arrivals within the cycle. His formulas have been written into a computer program by a group at MIT (2). We have prepared a modified form of the MIT program which we call QUEUE. It is theoretically possible to calculate from VDCA output the queue length and delay, provided inputs to the intersection are random in arrival. However, it has been found that in dealing with real data from detectors, difficulties present themselves when the intersection is at capacity or near it. Figure 3 shows that the throughput of an approach at capacity has considerable scatter. Thus, queue lengths and delays, as

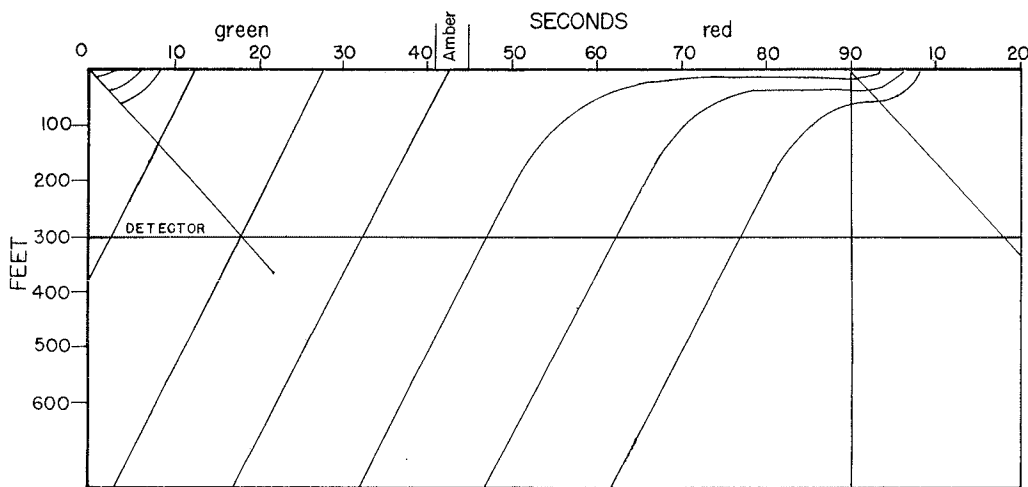


Figure 4. Trajectories in light traffic.

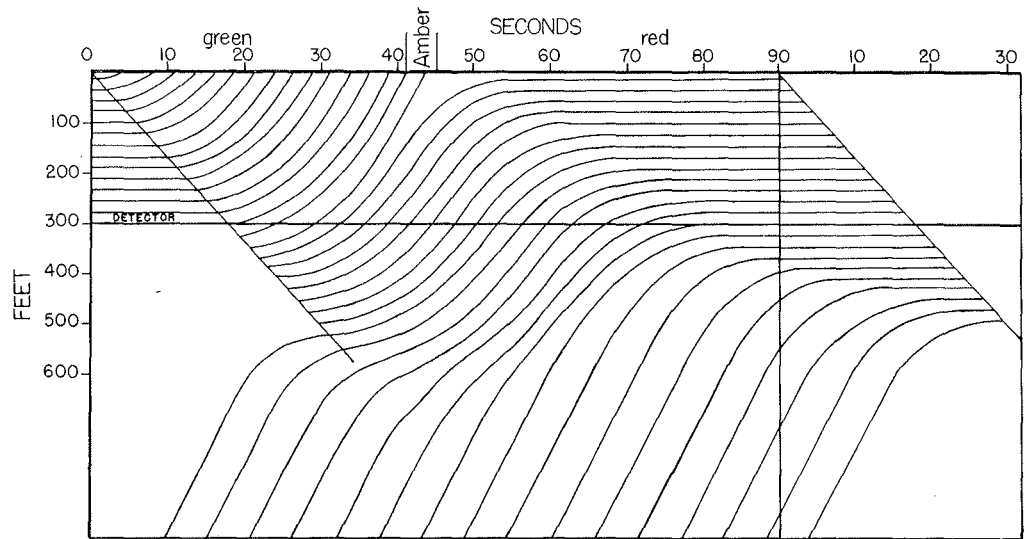


Figure 5. Trajectories in moderate congestion.

calculated, can be greatly in error near full capacity conditions when real data are used. What is needed is some quantity, measurable at the detector, which continues to increase near capacity conditions as queue lengths and delays increase, volume remaining nearly constant. This quantity could then be related to queue length and delay, resulting in more accurate results near capacity. Density, as calculated by the VDCA method, meets these requirements. However, application of this method would require a repetition of Webster's work in order to find the relationships between density, queue length, and delay. An alternative method has been devised by using average time headway at the detector. This method is described as follows.

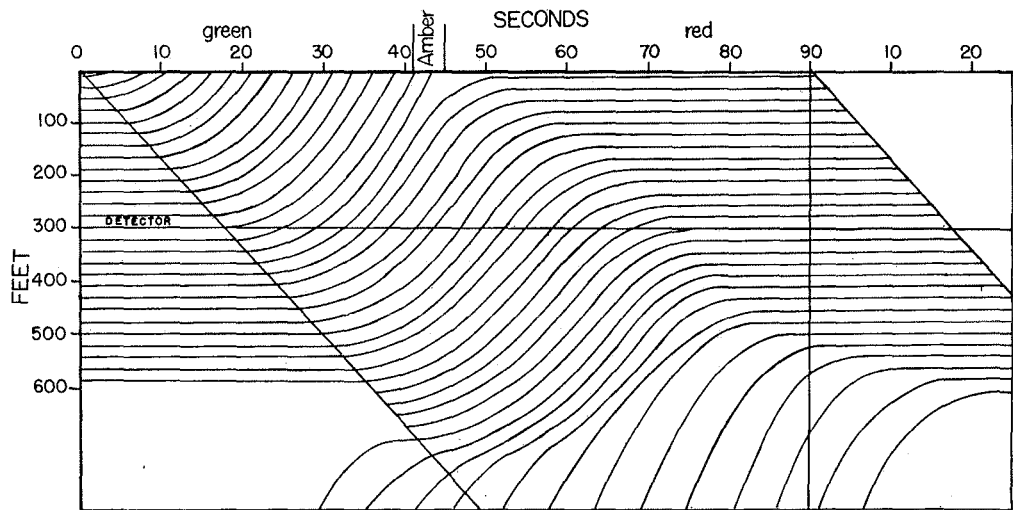


Figure 6. Trajectories in heavy congestion.

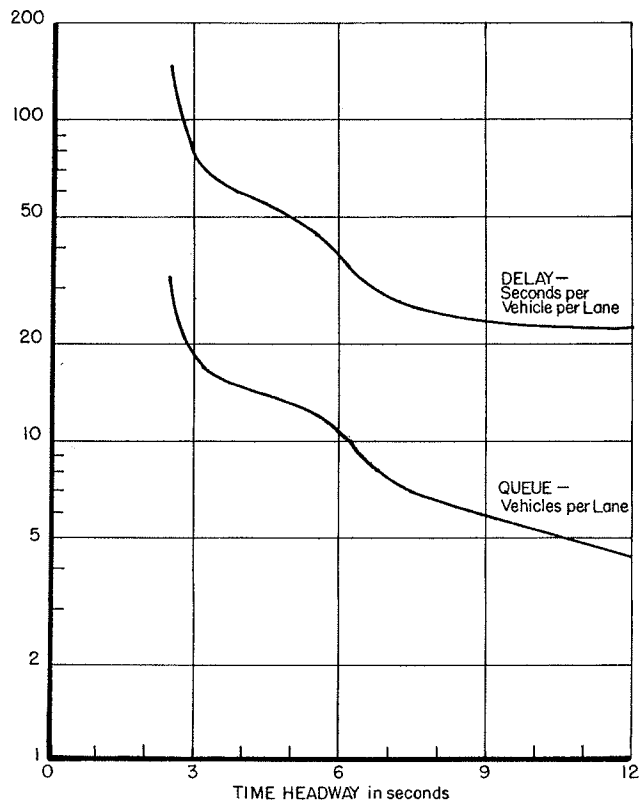


Figure 7. Calibration curve, east leg.

Figure 4 shows that when the intersection is not near capacity the average time headway at the detector is the same as that upstream of the detector, and one finds time headway simply by dividing 3600 sec by volume. As the intersection reaches capacity (Figs. 5 and 6), average time headway over the whole cycle is again found by dividing 3600 sec by volume. However, Figures 5 and 6 show that as congestion increases, vehicles move over the detector in a decreasingly smaller portion of the total cycle time. If, therefore, the average time headways can be found for only those portions of the cycle during which there is substantial flow over the detector, a quantity will have been found which, like density, continues to change rapidly while volume remains nearly constant. Two problems remain:

1. To find a means of calculating, for any split, cycle length and volume, the modified average time headway to use in producing calibration curves of time headway vs queue length, and time headway vs delay.
2. To find a means of making the VDCA program produce, not the average time headway over the cycle, but the modified time headway desired.

Appendix C explains in detail how problem 1 has been overcome. Essentially, an approximate method whereby trajectories of the vehicles can be found for different conditions has been devised. It would have been better to use a computer model of intersection behavior to obtain the necessary data. At least one such model has been constructed (5) which could be used for the purpose, but use of such a model was not considered warranted for the first trials of the method. In any case, calibration curves for the conditions prevailing at one intersection have been constructed. Figure 7 shows such a curve for the east leg of the intersection studied. As an example of how to use the calibration curves, consider the case when time headway is 3 sec (Fig. 7). Reading

TABLE 1
WEBSTER RELEASE RATES

Leg	Split	Max. Volume From Volume Density Curves (veh/hr/lane)	Webster Max. Volume (veh/hr/lane)	Webster Release Rate (sec/veh)
N	0.58	840	885	2.2
S	0.49	660	695	2.3
E	0.42	650	685	2.0
W	0.34	530	557	2.0

NOTE: The reason the splits are all different is that the north and east legs have advanced greens.

from the queue length curve, queue length (veh/lane) at the end of red is 19. Reading from the delay curve, average delay in seconds per vehicle is 75.

Problem 2 has been solved by limiting to a certain maximum level the pulse length that the VDCA program will accept. In this way, time headways are calculated only during those times during the cycle when vehicles are moving at a substantial speed over the detector, i.e., those times when only substantial flow is occurring. It should be explained that the detector has infinite presence available if desired, but

for normal use we set cutoff at 30 sec by adjustments in the hardware. For the VDCA program, no changes in the hardware are made, but the program is such that it does not use pulses greater than a certain length. This critical length has been taken as 2 sec but it is an adjustable parameter.

Results for an Intersection

For release from a queue at an approach, Webster assumes a fixed time (lost time) for each phase of a cycle during which no vehicle moves; let this time be L sec. After L sec, vehicles are released at a constant rate during green + amber time; let this constant rate be r sec per vehicle. With the help of the VDCA program, r can be found; for example, the curve in Figure 3 rises to a plateau where volume is constant. The resulting volume is the capacity of the approach. The volume in this case is 650 veh/hr. For equilibrium conditions, it is reasonable to assume that this limiting volume is 95 percent of saturation flow. Saturation flow for this particular approach is thus $650/0.95 = 685$ veh/hr. At this particular approach the cycle length was 90 sec, green time was 34 sec, and amber time was 4 sec. The number of vehicles released per cycle under saturation flow is thus:

$$\frac{\text{Green} + \text{Amber} - L}{r} = \frac{34.5}{r}$$

The hourly saturation flow rate is

$$\frac{34.5}{r} \times \frac{3600}{90}$$

Equating this to 685 and solving for r, it is seen that $r = 2.0$ sec.

The intersection studied was Bayview Avenue and Eglinton Avenue in Toronto. Performing these calculations for each approach produced the results given in Table 1.

Calibration curves were made for each approach, and the VDCA program was run for 15-min intervals from 7:30 a.m. to 9:00 a.m. and 4:30 p.m. to 6:00 p.m., for a week (Monday to Friday). The resulting delay and queue length measurements are shown in Figures 8 to 15. Not all points were plotted, since many fell on top of one another. On each plot the theoretical Webster curve is superimposed. It should be noted that since, during the times of day studied, total intersection throughput averaged over 4000 veh/hr, the results shown in the figures represent the passage of over 60,000 vehicles.

The accuracy of the results is dependent upon inputs to the approaches being random. In other words, no platoon structure remains after the vehicles have traversed the distance from the previous signalized intersection. Randomness was tested by means of the LINKS program, the features of which have already been reported by Wormleighton (4). In every case, except the east leg in the a.m., inputs were random to a high degree, and even on the east leg a.m., there was only a moderate departure from randomness.

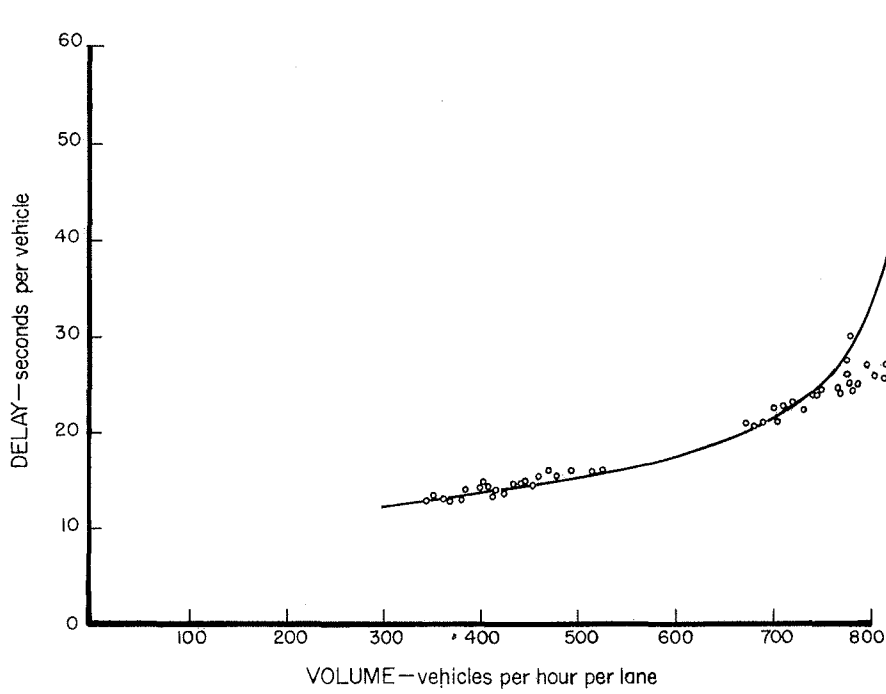


Figure 8. Delay vs volume, north leg (90 sec cycle, 0.58 split).

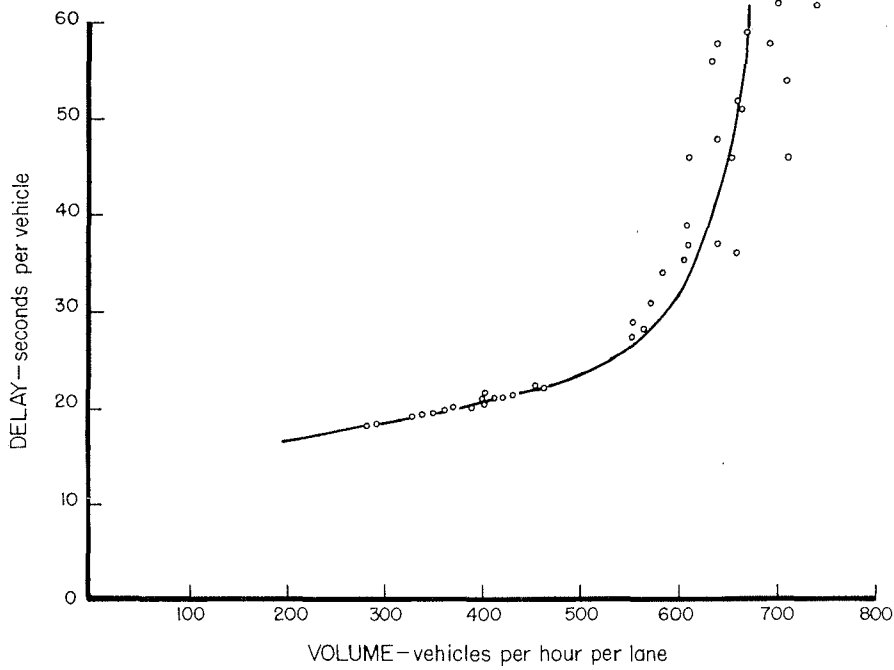


Figure 9. Delay vs volume, south leg (90 sec cycle, 0.49 split).

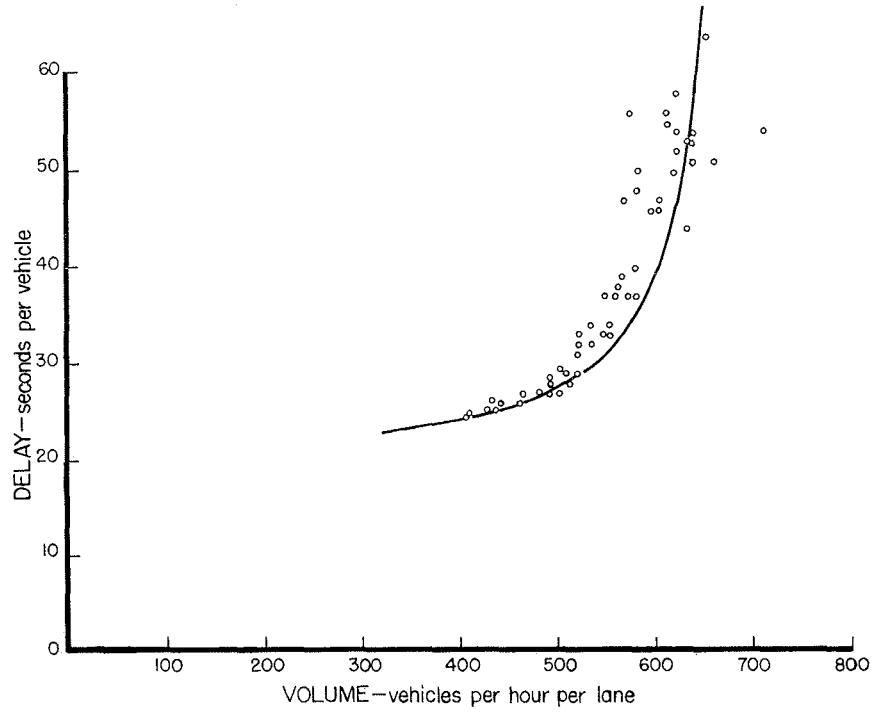


Figure 10. Delay vs volume, east leg (90 sec cycle, 0.42 split).

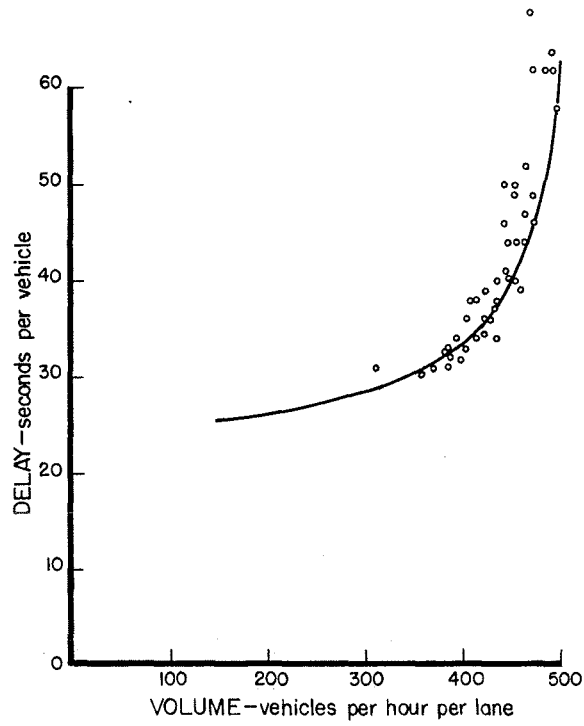


Figure 11. Delay vs volume, west leg (90 sec cycle, 0.34 split).

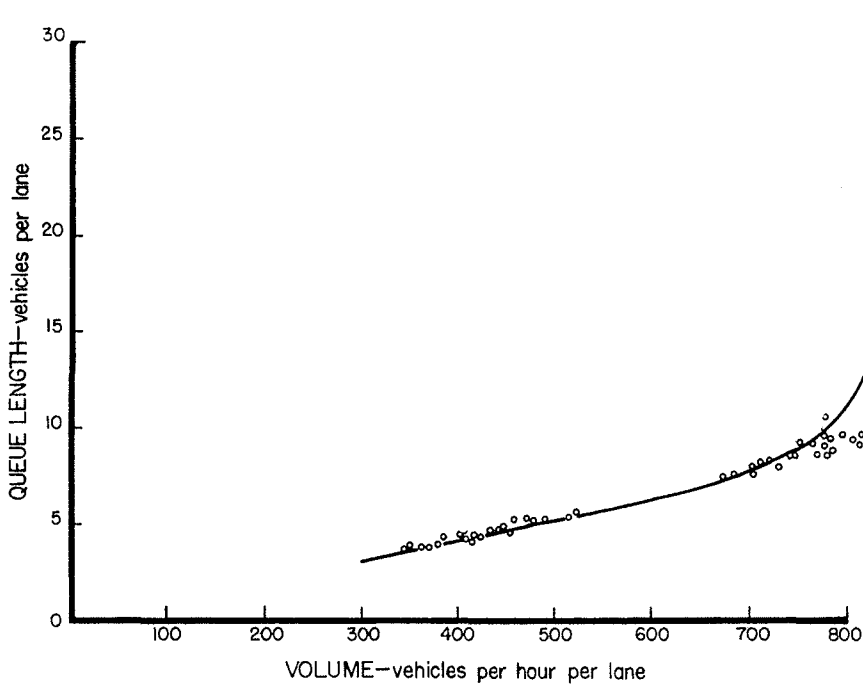


Figure 12. Queue length vs volume, north leg (90 sec cycle, 0.58 split).

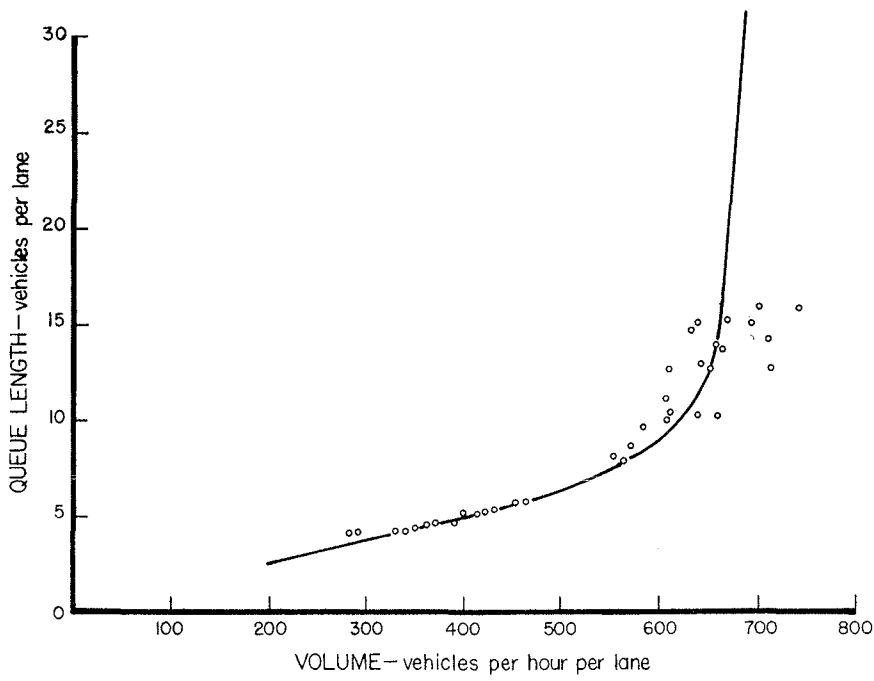


Figure 13. Queue length vs volume, south leg (90 sec cycle, 0.49 split).

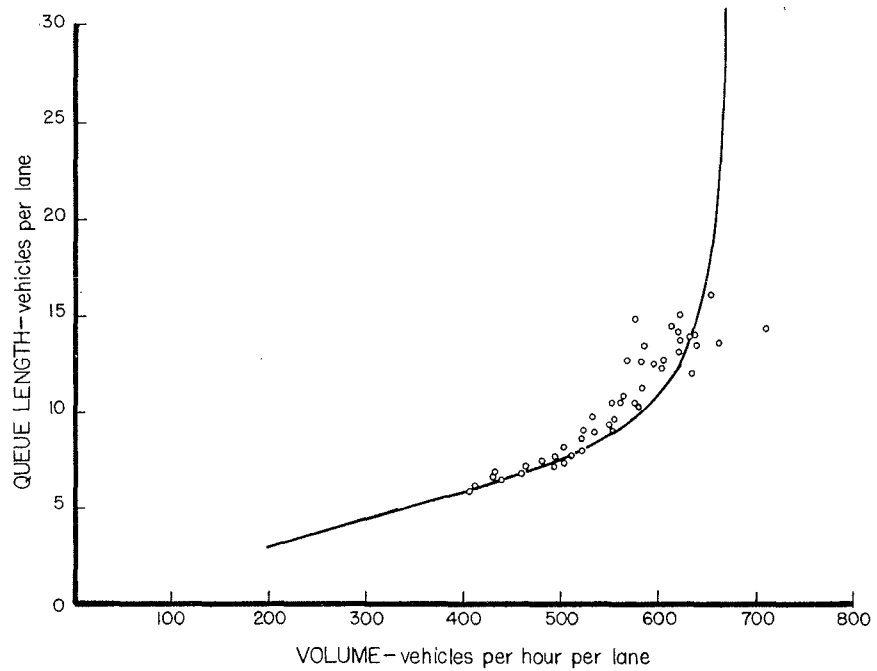


Figure 14. Queue length vs volume, east leg (90 sec cycle, 0.42 split).

Test of the Method

Trials have been held to test the accuracy of the method. Observers counted vehicles in the queue at the end of red for many cycles. The queue lengths were averaged over 15-min periods and compared with queue lengths as predicted by the VDCA method. The results of one such trial are given in Table 2. However, the results shown in Figures 12 to 15 were not checked against observation.

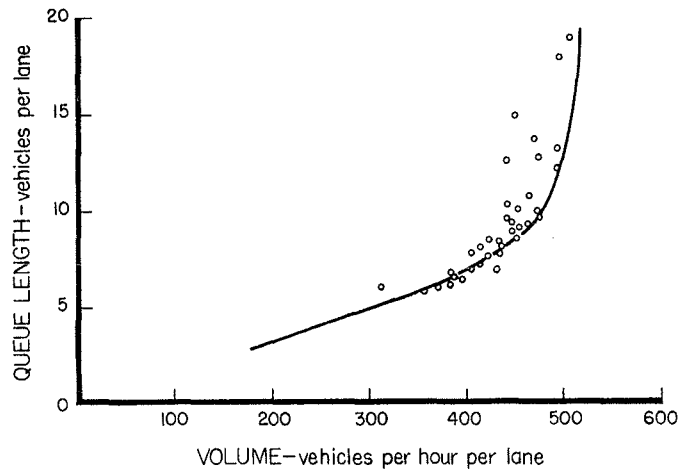


Figure 15. Queue length vs volume, west leg (90 sec cycle, 0.34 split).

TABLE 2
OBSERVED VS CALCULATED QUEUE LENGTHS

Time	Average Observed Queue at End of Red	Calculated Queue at End of Red
1609-1624	9.3	9.2
1624-1639	8.0	9.5
1639-1654	15.2	14.0
1654-1709	21.2	20.0

Use Under Other Conditions

By constructing enough trajectory diagrams, it is possible to use the VDCA method when arrivals have a definite platoon structure; this procedure has been used at Traffic Research Corporation.

It is also theoretically possible to extend the method to testing non-fixed-time intersections, but the work required would be prohibitive. Also, accuracy would be doubtful, since the method depends to a

large extent on averaging over many minutes. For general use in evaluating intersection performance, we have still another program called DELAY, details of which we hope to publish soon. The DELAY program is an off-line simulation which uses as input the actual detections that have been received and recorded on magnetic tape. For the intersection studied, results from the VDCA method agree substantially with results from the DELAY program method.

CONCLUSION

A method has been found whereby the output from vehicle loop detectors situated near an intersection can be used to find traffic parameters, such as volume, density, space headway, and time headway. It has also been shown how the time headway, as calculated, can be used to produce queue lengths and delays at signalized intersections.

ACKNOWLEDGMENTS

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4. Wormleighton, R. Queues at a Fixed-Time Traffic Signal with Periodic Random Inputs. Jour. Canadian Operational Res. Soc., Vol. 3, No. 3, 1965.
5. Gerlough, D. L., and Wagner, F. A. Improved Criteria for Traffic Signals at Individual Intersections—Interim Report. NCHRP Report 3, 1964.

Appendix A

CORRECTION FOR COUNTS LOST DUE TO OPERATION OF ONE DETECTOR OVER TWO LANES

The design of the detector used is such that when a certain rate of increase of inductance occurs, the detector is turned on. Thus, a vehicle entering activates the detector. The opposite occurs when a vehicle leaves.

When two vehicles are passing at once, one in the first lane and one in the second lane, the following occurs. Suppose that vehicle A, in lane 1, is slightly ahead of vehicle

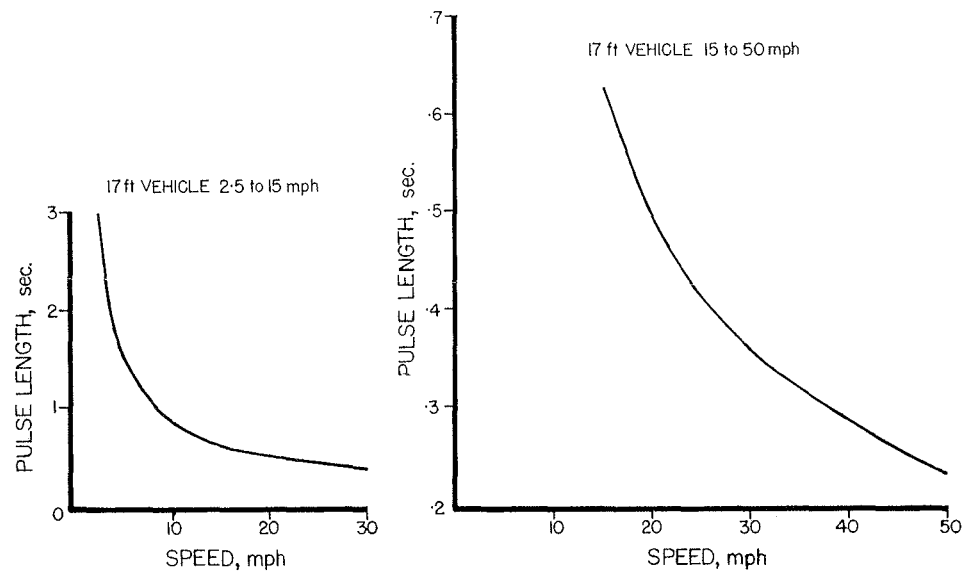


Figure A-1. Detector calibration.

B, in lane 2. Then, when the front of vehicle A passes over the loop, the detector is turned on. When the front of vehicle B crosses the loop, nothing happens, since the detector is already on. When the back of vehicle A leaves the loop, the detector is turned off. When the back of vehicle B leaves the loop, nothing further happens. It is thus evident that, if vehicles are of the same length, passage of two vehicles at once has no effect on the generated pulse length, but one count is lost.

Derivation of Correction Formula

The following shows the derivation of a formula which corrects the loss of counts due to double-lane operation. These assumptions are made: (a) in two-lane operation, traffic divides equally; (b) speeds are the same in both lanes; (c) all vehicles are 17 ft long; (d) vehicles are uniformly spaced; and (e) the pulse length vs speed calibration curve for all detectors is as shown in Figure A-1. Symbols used are as follows:

- C' Measured vehicle counts per hour, both lanes together, as received by the detector, assuming all vehicles pass over the loop, and assuming no vehicle makes more than one count;
- C Corrected vehicle counts per hour, both lanes together, after correction for loss of counts due to one detector covering two lanes;
- k Correction factor for loss of counts due to one detector covering two lanes

$$\left(k = \frac{C'}{C}\right);$$
- t' Measured average pulse length, sec;
- D' Measured vehicle density, veh/mi/lane, before correction factor k is applied;
- D Corrected vehicle density, veh/mi/lane $\left(k = \frac{D'}{D}\right);$
- V Measured vehicle speed, mph;
- v Measured vehicle speed, ft/sec;
- L Measured vehicle length, ft, as seen by the detector ($L = t'v$);
- S' Measured vehicle spacing, ft, per lane; and
- S Corrected vehicle spacing, ft ($S = kS'$), per lane.

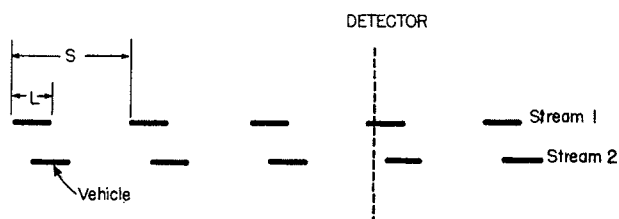


Figure A-2. Diagram of two lanes of vehicles.

Figure A-2 shows vehicle positions—if two parallel streams of traffic are crossing the detector—for one particular offset of stream one with respect to stream two. Since it is assumed that there is no correlation between the offset of streams one and two, on the average all possible offsets will be obtained. Therefore, for a fraction $2L/S$ of the time, two vehicles will be crossing the detector at the same time, and only one count will be obtained for two vehicles. During the remaining time $(S - 2L)/S$, there will be one count for each vehicle. For the time period needed to travel S , the average number of counts is

$$C' = \left(\frac{S - 2L}{S} \right) \times 2 + \frac{2L}{S} \times 1 = \frac{2S - 2L}{S} = 2 \left(1 - \frac{L}{S} \right)$$

Since corrected counts C is 2, the correction factor k is

$$\frac{2 \left(1 - \frac{L}{S} \right)}{2} = 1 - \frac{L}{S}$$

Since $S = kS'$

$$k = 1 - \frac{L}{kS'}$$

Solving for k ,

$$k = \frac{1}{2} + \frac{1}{2} \sqrt{1 - \frac{4L}{S'}}$$

ignoring negative square root. It has been found in practice that more accurate results are obtained by replacing the 4 by 5.72. Therefore:

$$k = \frac{1}{2} + \frac{1}{2} \sqrt{1 - \frac{5.72}{S'}}$$

Correction in Terms of Density

Since density is $5280/S$, and since L may be taken to be 17 ft, the following is an alternative formula for k :

$$k = 1 - \frac{17D}{5280} = 1 - \frac{D}{311}$$

Thus, counts lost are directly proportional to true density.

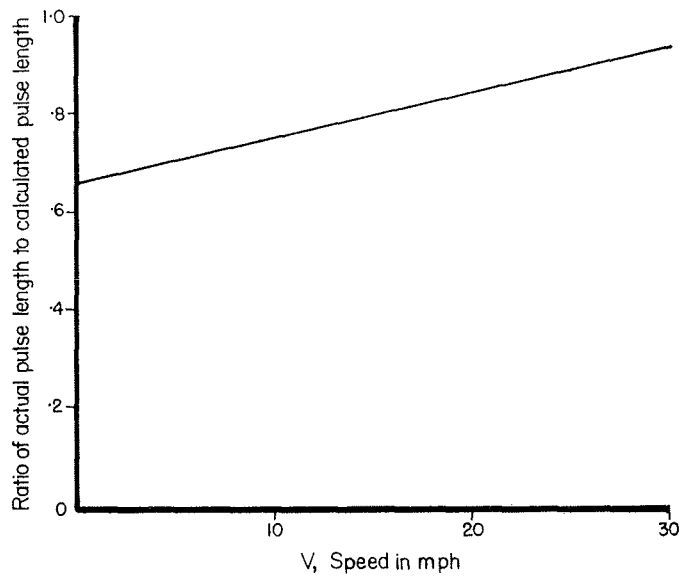


Figure A-3. Alternative detector calibration.

Formulas for Speed

Figure A-3 shows one form of the detector calibration curve. It is really a comparison of the detector used with a perfect detector. A perfect detector would simply give a straight line at unity. From Figure A-3:

$$L = 17 (0.66 + 0.00933V)$$

Since $t'v = L$ and $v = \frac{44}{30} V$, it is possible to solve for v and V' and get

$$v = \frac{11.2}{t' - 0.1083} \text{ fps}$$

$$V = \frac{7.65}{t' - 0.1083} \text{ mph}$$

Appendix B

VDCA PROGRAM DESCRIPTION

Figure B-1 shows the flow chart for the VDCA program. In step one, choice of a_1 determines the shortest acceptable pulse, a_2 the longest, and a_3 sets the minimum acceptable spacing between pulses. In step two, the pulse lengths are converted to speeds for each two successive pulses, and an average speed for the two is obtained. In step three, the time between the pulses is found. In step four, the space headway is found by multiplying speed and time headway. From here the program branches to single lane or double lane.

Single Lane

Step five finds the arithmetic mean of all headways from step four. Step six finds the arithmetic mean speed of all speeds from step two. Step seven calculates the

FIGURE B-1. VDCA PROGRAM FLOW CHART

Pulse p_n occurs at time T_n seconds, and is t_n seconds long.

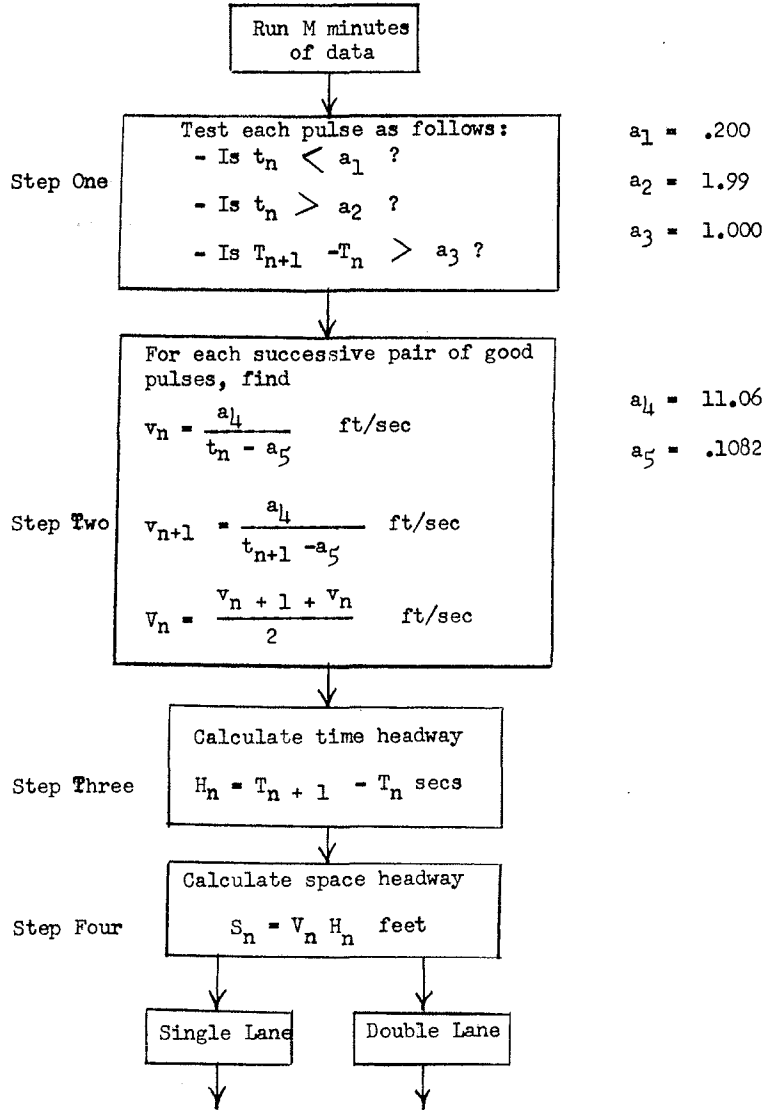
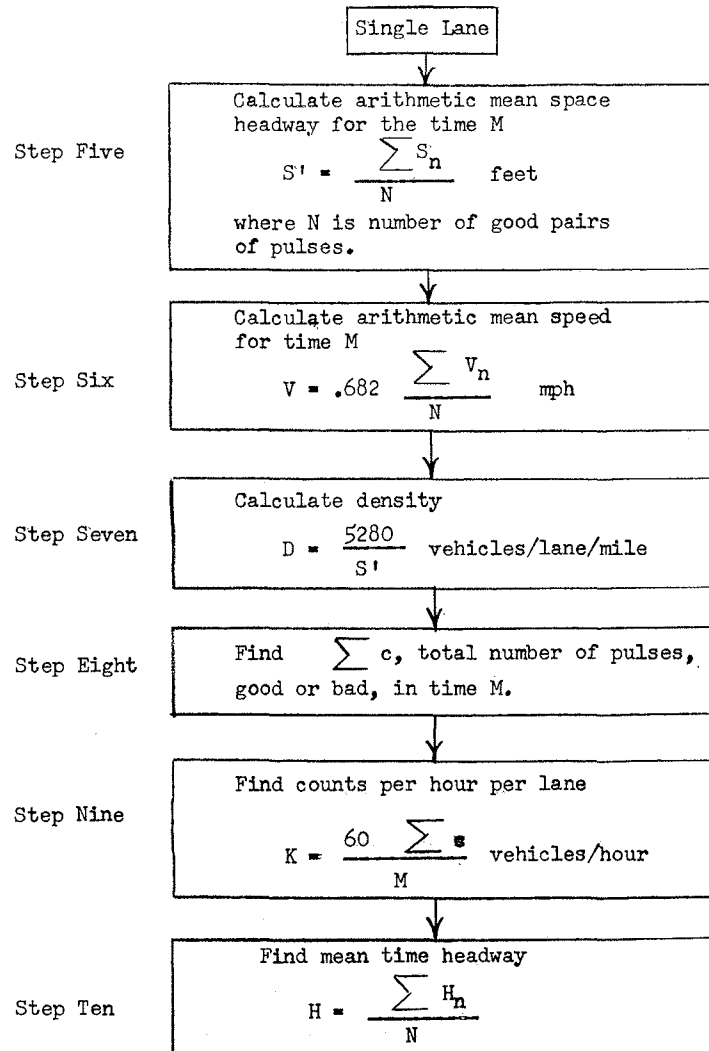


FIGURE B-1 (continued).



Print:

Detector number, lanes, uncorrected counts per hour
(= K for single lane),

V, correction factor (= 1 for single lane), D, S', H.

FIGURE B-1 (continued).

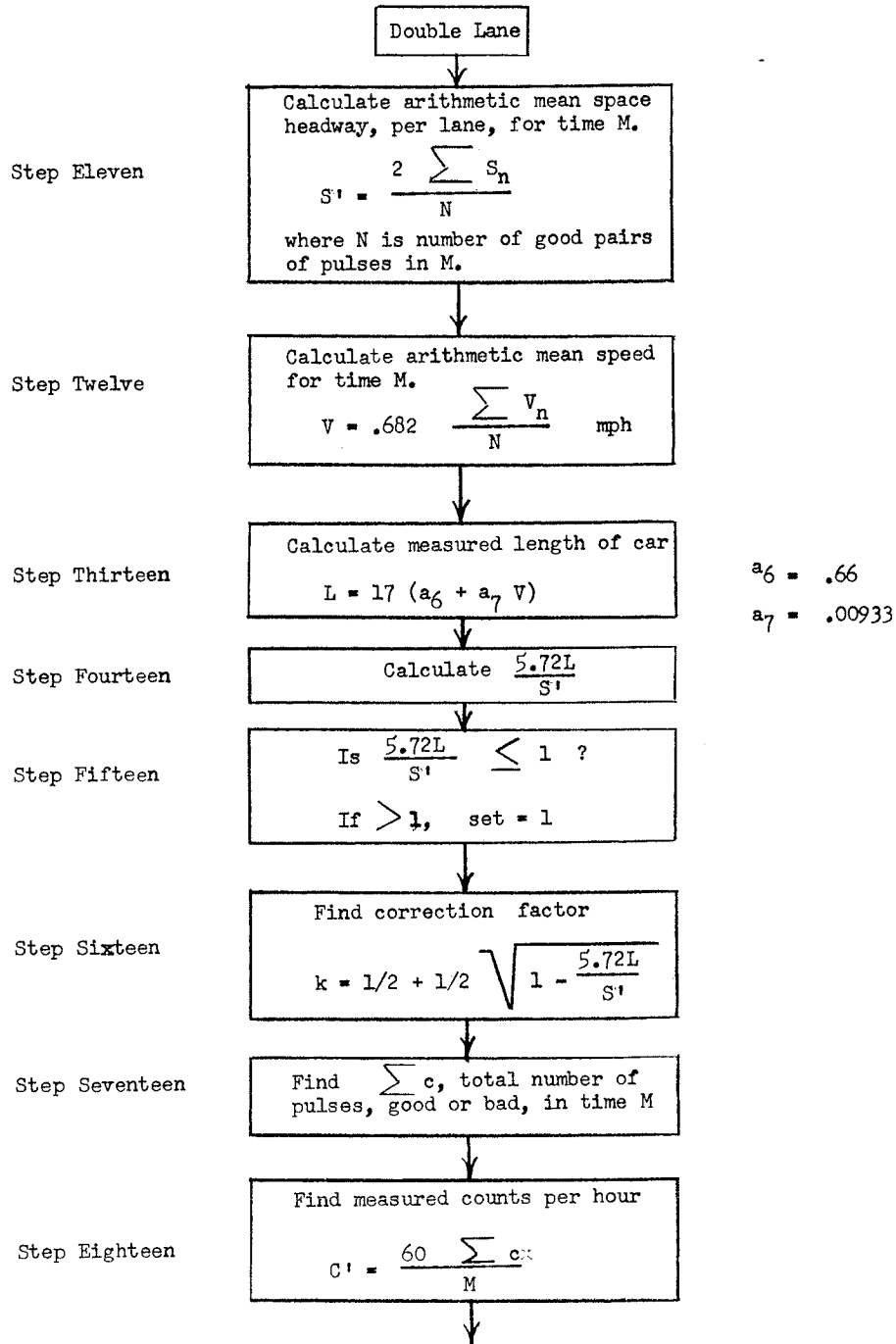
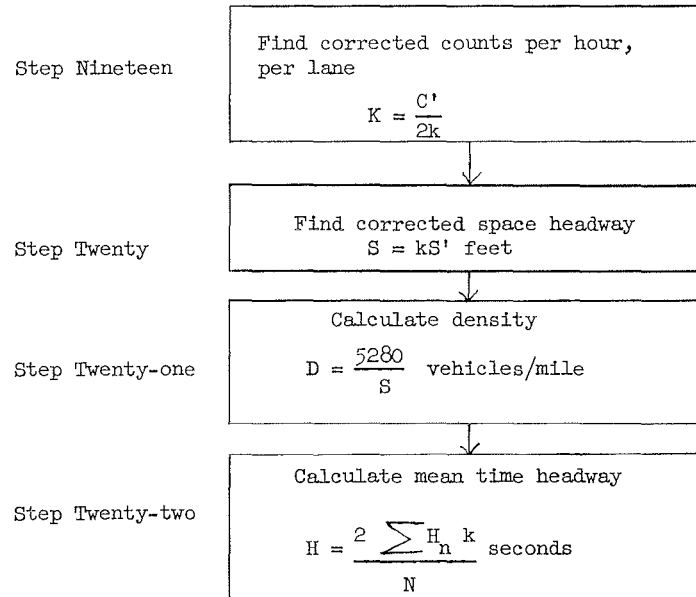


FIGURE B-1 (continued).



Print:

Detector number, lanes, C', V, k, K, D, S, H

density. Step eight finds the total number of pulses, good or bad. Step nine converts the total number of pulses found in step eight to vol/hr/lane. Step ten finds the arithmetic mean of all headways found in step three.

Double Lane

Step eleven calculates measured space headway per lane. Step twelve calculates arithmetic mean speed in mph for use in step thirteen. Step thirteen uses the calibration curve to find measured vehicle length. Steps fourteen, fifteen and sixteen calculate the correction factor. Step seventeen finds the total number of pulses, good or bad. Step eighteen converts measured counts to hourly volume, per approach. Step nineteen finds corrected volume, veh/hr/lane. Step twenty finds corrected space headway. Step twenty-one finds density. Step twenty-two finds corrected mean time headway.

Speed of the Program

The program is written in FORTRAN IV. The limit to the speed is set by the time it takes to find the data on the tape. In the worst case, when four detectors (one intersection) are being done, ratio of real time to computer time is 6 to 1. The number of detectors which can be processed at one time is 100. This takes little more time than doing four detectors.

Appendix C

PREPARATION OF CALIBRATION CURVES

As explained in the body of the report, time headways are calculated only for the vehicles which are in motion over the detector. Any vehicle which stops on the detector is not counted. Table C-1 shows figures for the conditions prevailing on the east leg of Bayview-Eglinton. All but the starred figures have been calculated using Webster's formulas. It is found that up to a volume of 600 veh/hr, no vehicles stop on the detector. Therefore, time headways are simply 3600 sec divided by the volume. However, above

TABLE C-1
VALUES FOR 0.42 SPLIT, 90 SEC CYCLE,
RELEASE RATE 2.0 SEC PER VEHICLE

Volume (veh/hr/lane)	Delay (sec/veh/lane)	Queue (veh/lane)	Time Headway (sec/veh/lane)
250	21.2	3.6	14.4
300	22.1	4.4	12.0
350	23.1	5.1	10.3
400	24.3	5.8	9.0
450	25.7	6.5	8.0
500	27.8	7.5	7.2
550	31.1	8.7	6.5
600	38.5	10.8	6.0
650	67.0	16.8	3.2 ^a
672	147.8	32.5	2.5 ^a

^aCalculated from trajectory drawings.

600 veh/hr, a certain number of vehicles form a queue past the detector, and it is necessary to find the time during which vehicles are in motion. This is done by drawing trajectory diagrams.

The trajectories for a volume of 650 veh/hr are shown in Figure C-1. A volume of 650 is about 16 veh/cycle. The Webster formula states that the queue at the end of red is 16.8 vehicles, say 17. It is therefore necessary to produce trajectories such that 16 vehicles enter per cycle, and the queue at the end of red is 17 vehicles. The first step is to produce a line representing the motion wave as vehicles start from the queue. It has been found in our studies that for Toronto this has a speed of 100 ft every 6 sec.

Thus, draw from the origin (start of cycle)

lines of this slope. Next, mark out along this line the position of each vehicle in the queue. We chose a spacing of 22 ft, representing a jam density¹ of 240 veh/mi/lane.

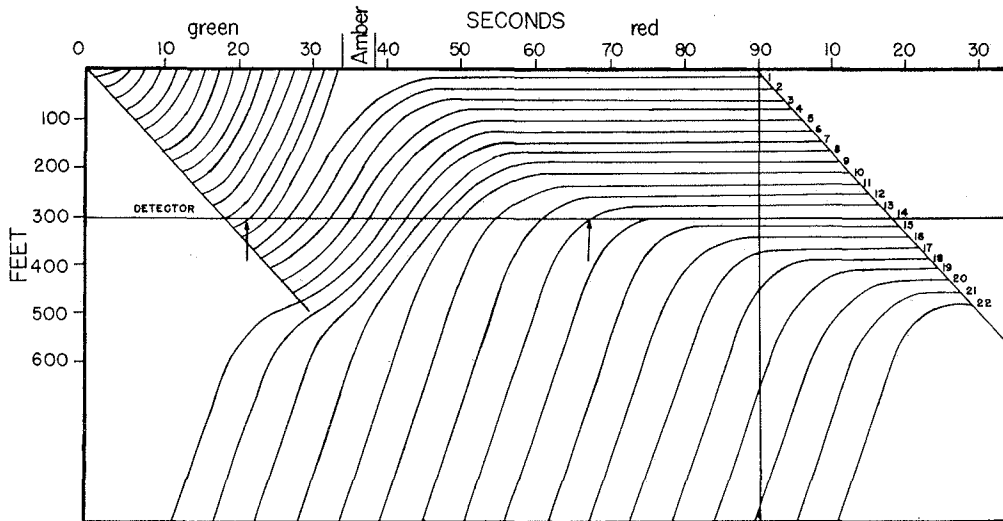


Figure C-1. Drawing of trajectories.

¹Jam density is that density in traffic flow which occurs when all vehicles have been forced to stop.

The release points along the time axis occur every 2 sec, starting at 3.5 sec. Once these points are marked, trajectories can be drawn in for those vehicles released every cycle. For the remainder of the vehicles, a deceleration rate of about 4 ft/sec/sec has been chosen. The time of arrival of each incoming vehicle can be found by using the fact that the 17th vehicle is the last in the queue at the end of red, and the fact that deceleration is 4 ft/sec/sec. Once the 17th vehicle is found, the remaining vehicles are spaced out to cover the cycle. A speed of 30 mph has been chosen for the speed of incoming vehicles. Uniform spacing is allowed as an approximation to random arrival, since the VDCA method averages over many cycles. The remaining parts of the trajectories can now be drawn in. They need only be approximate, since their form does not alter critically the calculation of headway.

It will be seen from Figure C-1 that the 14th vehicle is stopped over the detector. Therefore, the time during which vehicles are in motion over the detector is that time between the arrows. In this case it represents 45 sec. Since there are 14 vehicle intervals, the average time headway is $\frac{45}{14}$ or 3.2 sec.

For the remaining volume in Table C-1, it may be assumed that the queue is so long that release over the detector is practically the same as that at the stop bar. Assume therefore that the time over which vehicles are in motion is about 35 sec. There are again 14 vehicle intervals, and headway is therefore $\frac{35}{14} = 2.5$ sec. The values given in Table C-1 are those shown in Figure 7 of the main body of the report.