each level of service for a two-lane by two-lane uncontrolled intersection:

Level of Service	Percentage of Vehicles Required to Stop	Intersection Service Volume (vehicles/h)
A	40	1200
B	60	1400
C	70	1500
D	75	1600
E	75	1600

Similar graphs and tables can be constructed for other traffic controls and lane arrangements.

Case 4

To design the intersection so that 1600 vehicles/h can be accommodated while a level of service A is maintained, different lane arrangements and traffic control schemes were tried. The TEXAS model was run with these geometrics and controls with a volume of 1600 vehicles/h until the desired level of service was attained. An efficient and economical way would be to try the most likely arrangement. For a first trial, a two-lane by two-lane stop-sign-controlled intersection was tried. A level of service D was provided, so a four-lane by four-lane, two-way, stop-sign-controlled intersection was tried. The level of service that was now provided was A. Other combinations were tried, but no other lane arrangement and traffic control scheme gave a level of service A.

Table 3 gives a matrix of lane arrangements and control schemes that were run and shows the level of service that would be provided under each scheme. The table can be used in two ways: to determine the level of service of an existing or proposed intersection or to design an intersection to provide any desired level of service. The table is to be used when total intersection volume is 1600 vehicles/h, distributed according to the assumed traffic data given earlier. Similar tables can be constructed for different intersection volumes once the proper distribution is determined.

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The contents of this paper reflect our views, and we are responsible for the facts and the accuracy of the data presented. The contents do not necessarily reflect the official views or policies of FHWA. This report does not constitute a standard, specification, or regulation.

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Integrated System for Urban Traffic Data Collection

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A technique developed at the University of Leeds that combines the collection, analysis, and presentation of data on urban traffic flow in one integrated system is described. Black-and-white aerial photographs of the central area of the city of Leeds were used. The analysis technique involves the use of a coordinate reader and a computer. Data on vehicles in motion and temporarily halted vehicles are collected on a street-by-street basis and fed into the computer on high-speed paper tape. These data are then used to calculate several major

traffic parameters, including directional vehicle spot speed, volume, lane concentration, and headway distribution. The advantages and disadvantages of the technique are presented and discussed. It is concluded that the technique compares favorably with more traditional techniques of urban traffic data collection.

Data analysis has always been the main stumbling block in obtaining traffic data from photography. The very nature of a traffic survey involves the collection of large amounts of data, and this invariably means many hours of tedious work to extract the required information.

Although many photographic surveys have been undertaken in the past, they have dealt mainly with either analysis or data presentation and have not combined the two into a complete technique. Skilled technicians are often required to undertake such surveys, and the information obtained may be rather limited and may not justify the expense involved in its collection.

This paper discusses in detail a technique developed at the University of Leeds that combines the collection, analysis, and presentation of data on urban traffic flow in one integrated system.

AIMS OF THE STUDY

The aims of the work were

1. To use the computing facilities now generally available to reduce analysis time;
2. To develop a complete technique of traffic data analysis that presents the information in an immediately useful form;
3. To obtain results that are sufficiently accurate for traffic engineering purposes, usually ± 10 percent (1);
4. To develop a system that can be operated by unskilled or semiskilled personnel; and
5. To obtain information on a wide range of traffic parameters.

It should be noted at this stage that the only vehicles considered were those in motion or at a temporary halt. Information on parked vehicles was not collected.

STUDY AREA

The city center of Leeds was selected as the most convenient site for study. The photography had to be such that it completely covered this area; it was found that only one strip of photographs was necessary for this purpose. The final study area measured approximately 2000 m in an east-west direction and 900 m in a north-south direction. Fifty-eight streets were selected for study.

PHOTOGRAPHIC TECHNIQUE

The size of the area limited the possible techniques to those that involve moving aircraft, and 23×23-cm aerial photographs were used. To accommodate as many photographs as possible of each street that was analyzed in each run of the aircraft, an extended longitudinal overlap was used that was usually in the region of 80 percent. This ensured that each street appeared in at least four consecutive photographs in each flight.

Black-and-white photography was used in preference to color. Preliminary investigations with black-and-white photography showed that individual and particular vehicles could be identified with little difficulty and, of course, black-and-white photography was considerably cheaper.

The flight was carried out during the evening peak period between the hours of 4:00 and 6:00 p.m. on a typical weekday. The area was flown over in an east-west direction and the flights were repeated at approximately 15-min intervals during this evening peak period.

Because of adverse weather conditions, it was not possible to anticipate the actual day on which the photographs were to be taken, and thus it was not possible to arrange a ground survey by which the results could be directly compared with those obtained from the photographic survey.

The specifications for the photography were (a) black-and-white panchromatic paper prints, double weight; (b) a scale of approximately 1:4000; (c) a flying height of 640 m; (d) 152.78-mm focal length of camera; (e) a shutter speed of 0.003 s; and (f) a 4-s time interval between successive photographs. The 4-s time interval was used because it was the shortest possible interval that could be guaranteed by the air survey firm to give the maximum possible overlap when the aircraft was flying as slow as was practicable. The minimum cycling time of the camera prevented shorter intervals of time from being achieved accurately.

ANALYSIS TECHNIQUE

The main objective was to reduce as far as possible the tedious work involved in data extraction while retaining a satisfactory level of accuracy in the results. A D-Mac coordinate reader and the University of Leeds ICL 1906A computer were used in the analysis. The coordinate reader consisted of a table that was capable of reading coordinates to ± 0.05 mm; this was interfaced with a high-speed paper tape punch. In addition, a 6X magnifying eyepiece, fitted with crosshairs and attached to the coordinate reader, effectively increased the 1:4000 contact scale to approximately 1:700, which was found to be ideal for identification of vehicles.

Since the intention of the study was to obtain information on several traffic parameters, it was necessary to convert the D-Mac machine coordinates to coordinates of the National Grid Coordinate System so that, although only one section of the total area could be studied at any one time, the results from all the sections could be related to the same coordinate system to give a comprehensive picture of the study area. A linear transformation technique (2) was used in which the photographic coordinates were effectively converted to National Grid coordinates by means of the following equations:

$$X_N = Ax_p + By_p + C \tag{1}$$

$$Y_N = Ay_p - Bx_p + D \tag{2}$$

where

X_N, Y_N = National Grid coordinates,
x_p, y_p = photographic coordinates, and
A, B, C, D = transformation coefficients.

If the National grid coordinates and photographic coordinates of two control points are known, four equations can be formed that enable the transformation coefficients to be evaluated and subsequently used to convert other photographic coordinates to the National Grid. The equations make no allowance for variations in height over the photograph or between control points, and they do not correct for any tilt that may be inherent in the photograph. It was also found that the transformation gave satisfactory results only when the points to be transformed were either on or near the line that joined the two control points.

However, since the study area was the town center of Leeds, where there were only small variations in height, and the photographic tilt was guaranteed to be less than 2°, it was found that, if the distance between control points was not excessive (say, 50 to 100 m), the transformation equations were suitable. The problem of points lying on or near the line that joined the control points was easily solved in this case: The streets that were analyzed were long and narrow and, when the control points were placed on or near the roads, the vehicles were invariably situated on or somewhere near the lines that joined the successive control points.

CHOICE OF CONTROL POINTS

The distance between the control points was an important factor. Previous studies had shown that control points at 50-m intervals gave greater accuracy in speed measurements than control points at 100-m intervals. Control points were therefore set up at approximately 50-m intervals wherever possible (because of the problem of locating suitable control points along the study streets, this value was flexible). The interval was always kept below 100 m. A comprehensive check later showed that, if the distance between control points was less than 100 m, accuracy depended not so much on the distance between points as on the distance each vehicle strayed from the line that joined the two points.

Wherever possible, points were chosen along the side of the study road or, ideally, along the center of the road on traffic islands. Corners or buildings were used, but care had to be taken because buildings tended to mask the control points when they occurred near the edge of the photographs. Corners of curbs were often used because they were easily identified and were at ground level. All the control points chosen were at ground level, and only points that were readily identifiable in the photographs were used.

It is important to note that the control points were marked only on the photographs and on Ordnance Survey plans, not on the ground; their National Grid coordinates were measured from the 1:1250 Ordnance Survey plans, and no fieldwork was required.

A total of about 655 control points were set up. In streets that contained tall buildings on both sides, the control points were set up in pairs—on opposite sides of the road wherever possible—to overcome the masking problem caused by the buildings.

DATA COLLECTION

A street-by-street method of analysis was adopted. All photographs of a street from one strip of photographs were attached to the coordinate reader table, and the coordinates of the control points for that street in the first photograph were taken. The coordinates of the vehicles in that street in the first photograph were then taken lane by lane. Starting with the inside lane of one direction, each vehicle was coordinated in turn by moving the magnifying lens down the lane of vehicles in a direction opposite to the direction of travel. The point on the vehicle that was actually coordinated was the front offside corner. This procedure was repeated for subsequent photographs of the selected street. Each street usually appeared in at least four consecutive photographs.

At the end of the analysis, the paper tape was fed into the computer, and the required information was obtained. The program calculated the National Grid coordinates of each vehicle and used them to calculate several traffic parameters. A special booking form was designed to help monitor the movement of vehicles from one photograph to the next.

PROBLEMS IN THE ANALYSIS

If the same vehicles appeared in each photograph and no vehicles entered or left during the photographic coverage, then the analysis would be straightforward. This situation was, however, uncommon; it was much more usual for vehicles to leave or enter the study street from one photograph to the next. In addition, vehicles do not always enter at one end of the street or leave at the other end. Additions to or subtractions from the flow can occur throughout the length of the street—for example, when a vehicle parks on the street or on streets that are fed by or feed several side roads. Thus, a vehicle that appears in the first photograph of a particular street may not be present in the second but, to avoid confusion, must be retained in the second photograph despite the fact that it is no longer present in the street. Similarly, the first two vehicles in the first photograph may be split by a third vehicle that enters in the second photograph. Here again, to avoid confusion, the presence of the third vehicle must be recorded in the first photograph despite the fact that it has not yet arrived in the street.

To allow for this, the vehicles in each photograph were recorded on a booking form and, at the end of the analysis, the paper tape was input into the computer and a printout was obtained. Editing techniques were then used to insert identifiers at the points in each photograph at which vehicles had entered or left. These identifiers caused the computer program to bypass various sections and move to the next vehicle. This editing ensured that, for example, the seventh vehicle in the second photograph was the same as the seventh vehicle in the fourth photograph.

Editing the files so as to insert vehicles is, unfortunately, necessary. Several attempts were made to introduce a system that would overcome this problem automatically, but none was successful. To obtain traffic information on such parameters as speed, headways, volumes, and densities, it is necessary to keep vehicles in a strict order so that direct comparisons can be made.

At times, particularly in the case of the "rounder" type of vehicle (such as the Volkswagen), the front offside corner of each vehicle was not easily identified. In addition, buses caused problems because of their height, and vehicles were occasionally masked as they passed under bridges. It was not always possible to see the required corner of the vehicle at ground level because of the effect of parallax. In such cases, which were rare, the crosshairs were placed over the point where the corner was estimated to be.

In the photographs taken toward the end of the study period, daylight was beginning to fail and a control point or a dark vehicle was occasionally difficult to identify against a very dark background. This also occurred in areas of heavy shadow, but rarely.

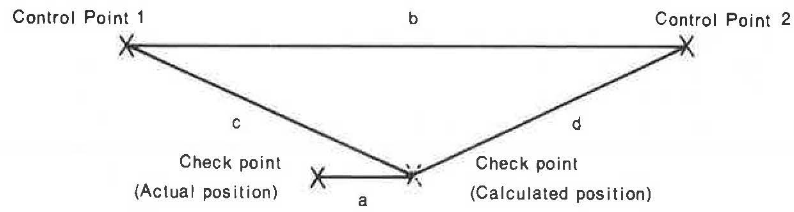


Figure 1. Parameters involved in error analysis.

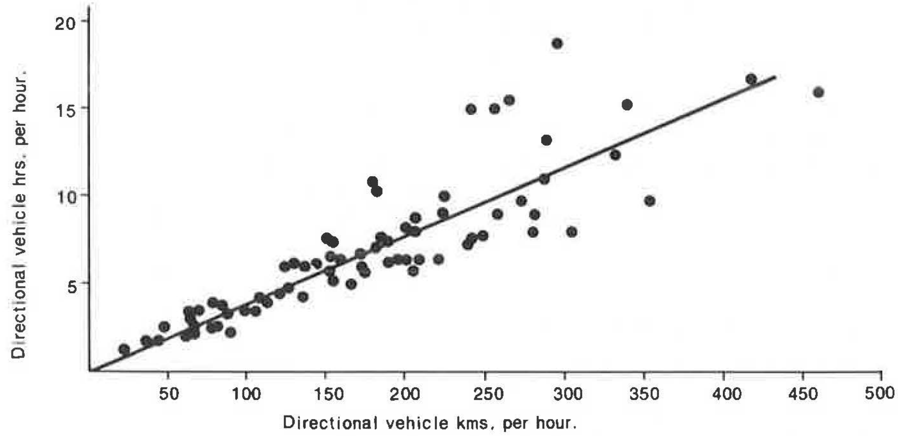


Figure 2. Directional vehicle hours per hour versus directional vehicle kilometers per hour.

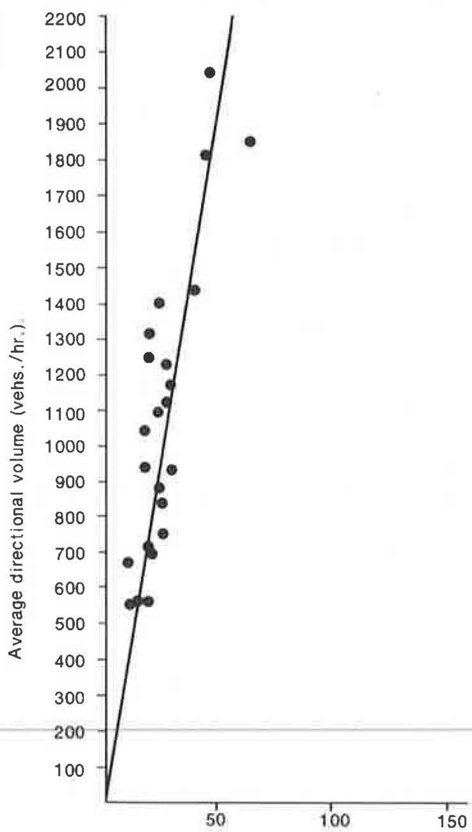


Figure 3. Average directional volume versus directional concentration.

Occasionally, a vehicle from one lane would overtake a vehicle from the same lane. In the strict order of analysis of vehicles, an overtaken vehicle must be analyzed before the vehicle that has overtaken it. Following the principle of lane-by-lane analysis reduced this problem since it was found that the vast majority of drivers remained in the same lane.

The method of analysis used in the program involved the selection of the two control points nearest each individual vehicle. In certain instances, such a method resulted in a vehicle having two control points that were not appropriate. Careful positioning of control points reduces this problem.

Eyestrain became a problem after 3 or 4 h, and the grinding noise emitted by the high-speed paper tape punch also became an annoyance.

A simple three-tier classification that divided traffic into automobiles and light commercial, heavy commercial, and public service vehicles was used on the booking forms. This was found to be useful in later automobile studies and also because the presence of a large, heavy commercial vehicle or public service vehicle greatly helped in the analysis by breaking up the smaller vehicles into manageable groups.

ACCURACY OF THE TRANSFORMATION TECHNIQUE

To test the accuracy of the initial results, a comprehensive check was undertaken on four selected streets. In each of the four streets, several ground-level checkpoints were selected from Ordnance Survey plans. The National Grid coordinates of the points were then measured from these plans by using a 1:1250 metric scale rule. Corners of buildings, walls, and steps were used as well as any distinct features in the road or foothpath surface. Several points that blended in with the background were chosen to represent vehicles that were more difficult to identify because of shadow and lighting problems. These checkpoints were treated as vehicles, and their photographic coordinates were transformed to National Grid coordinates by using the control points on that street. The difference, of course, was that the National Grid coordinates were actually known, and thus the computed values could be compared with the actual values.

Each street was analyzed several times by using different intervals between control points. More than 3200

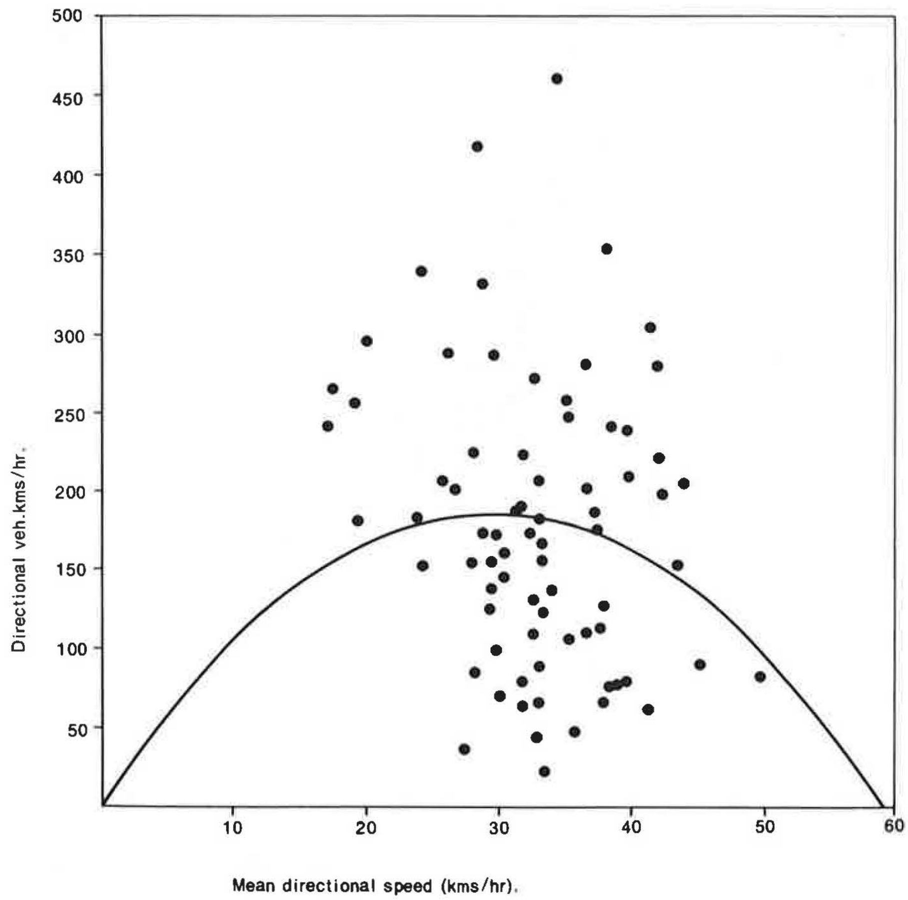


Figure 4. Directional vehicle kilometers per hour versus mean directional speed (free-flow speed = 59 km/h).

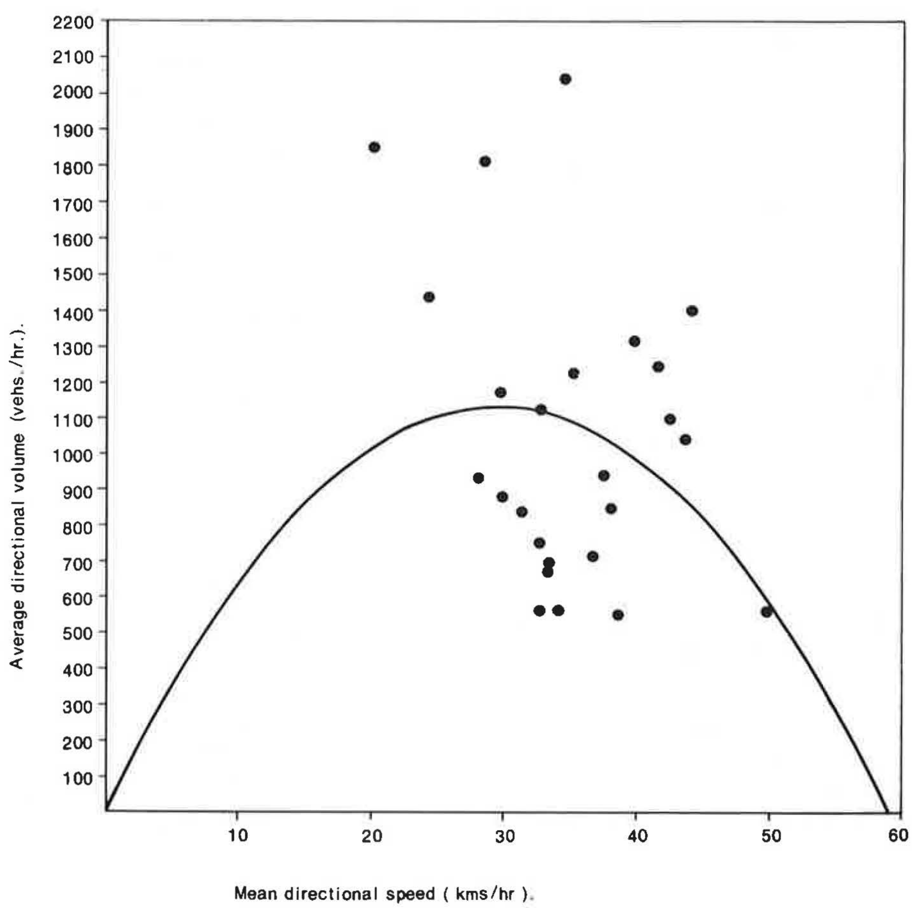


Figure 5. Average directional volume versus mean directional speed (free-flow speed = 59 km/h).

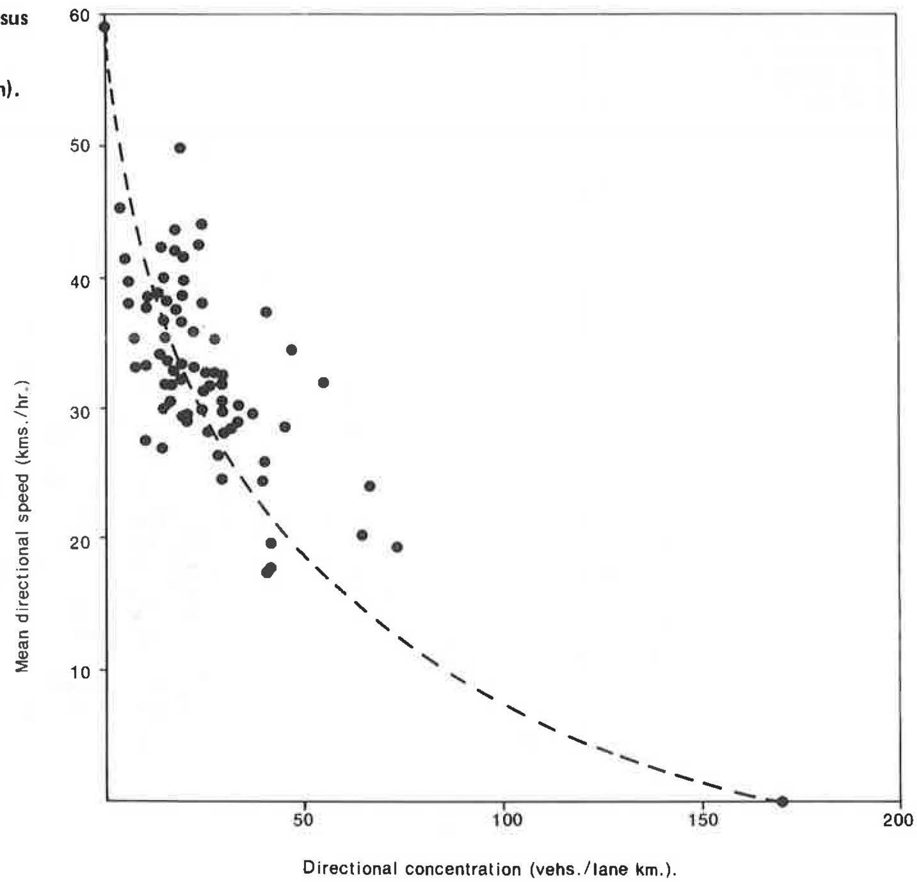


Figure 6. Mean directional speed versus directional concentration (free-flow speed = 59 km/h and saturation concentration = 170 vehicles/lane-km).

Figure 7. Postulated relation for mean directional spot speed versus directional lane concentration.

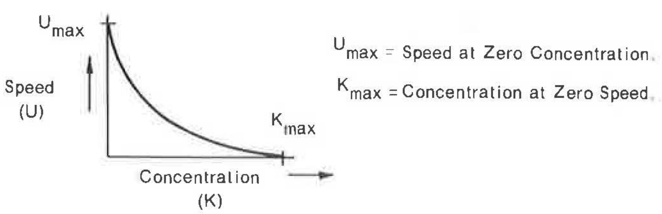
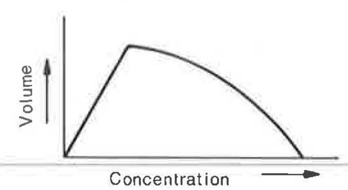


Figure 8. Curve for volume versus concentration.



points were coordinated in this way and analyzed.

Figure 1 shows the parameters involved in the analysis. In the figure,

a = error in the placing of the checkpoint,
b = distance between control points,
c = distance from control point 1 to the checkpoint,
d = distance from control point 2 to the checkpoint, and
e = (c + d) - b.

Values of a, b, c, d, and e were obtained for each checkpoint.

A study of the results showed that the e-values of Figure 1 were the critical factors in the resulting error values. The e-value is the difference between the distance between control points and the sum of the distances from the control points to the checkpoint. Three ranges of e-values were considered: less than 15 m, between 15 and 30 m, and greater than 30 m.

The effect of the e-values and the positioning errors of the checkpoints (distance a in Figure 1) were considered with respect to determination of vehicle spot speed. Spot speed was calculated from the distance traveled from one photograph to the next in the 4-s time interval.

The table below gives the standard errors in vehicle position and spot speed that occurred at different values of e (1 m = 3.3 ft; 1 km = 0.62 mile):

e (m)	Standard Error in Position (m)	Standard Error in Spot Speed (km/h)
<15	±0.96	±1.22
15-30	±1.26	±1.60
>30	±2.09	±2.66

In practice, any one error will have a 68 percent chance of being less than the figures given in the table. These figures apply to distances of no more than 100 m between control points.

The speed values give the best indication of the accuracy of the technique. If the e-values can be kept below 30 m or, better still, below 15 m, the errors that occur in the speed values will be less than those that normally occur on the speedometers of vehicles. The e-value and the limitation it sets provide a very useful guide in setting up control for future surveys; in this study, it provided the basis for deciding on the positions of the control points.

TRAFFIC PARAMETERS

The computer program used during the study produced the following traffic parameters from the data:

1. The National Grid coordinates of each vehicle,
2. The distance traveled by each vehicle from one photograph to the next,
3. The cumulative directional distances traveled by all the vehicles in each street for each photographic flight (this was expressed as directional vehicle kilometers per hour),
4. The spot speed of each vehicle from one photograph to the next,
5. Mean directional spot speeds of all vehicles in each street for each flight,
6. Vehicle trajectory curves,
7. The directional lane headways of the vehicles in each street for each flight,
8. The mean directional volume of vehicles in each street for each flight,
9. The directional lane concentration of vehicles in each street for each flight,
10. The cumulative directional time spent by all vehicles in each street for each flight (expressed as directional vehicle hours per hour), and
11. Traffic-density contours for the whole study area for each flight.

DISCUSSION OF RESULTS

Figures 2-6 show the graphs that were drawn from the traffic parameters obtained. Only the free-flowing cases were considered—that is, those cases in which traffic was moving easily and without restriction or interference from other road users. The three road types considered were dual carriageways, normal two-way streets, and one-way

Figure 9. Density contour map for Leeds central area.

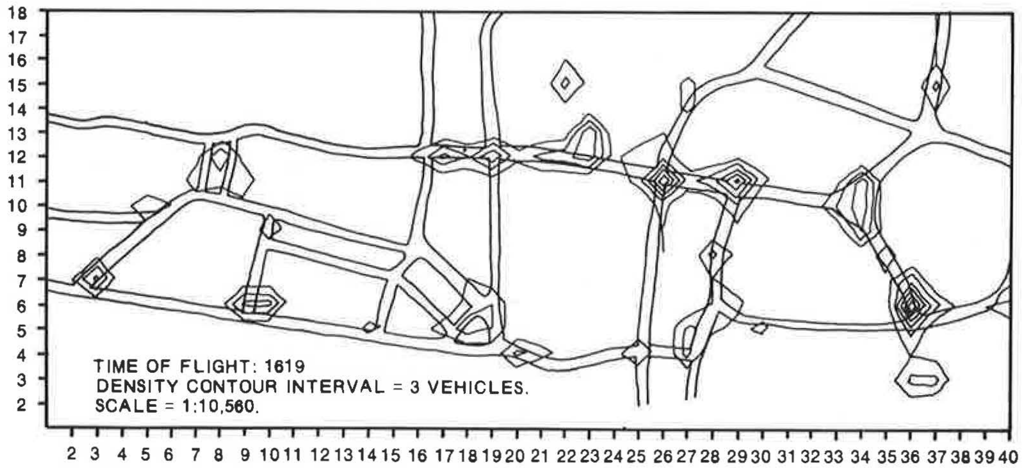
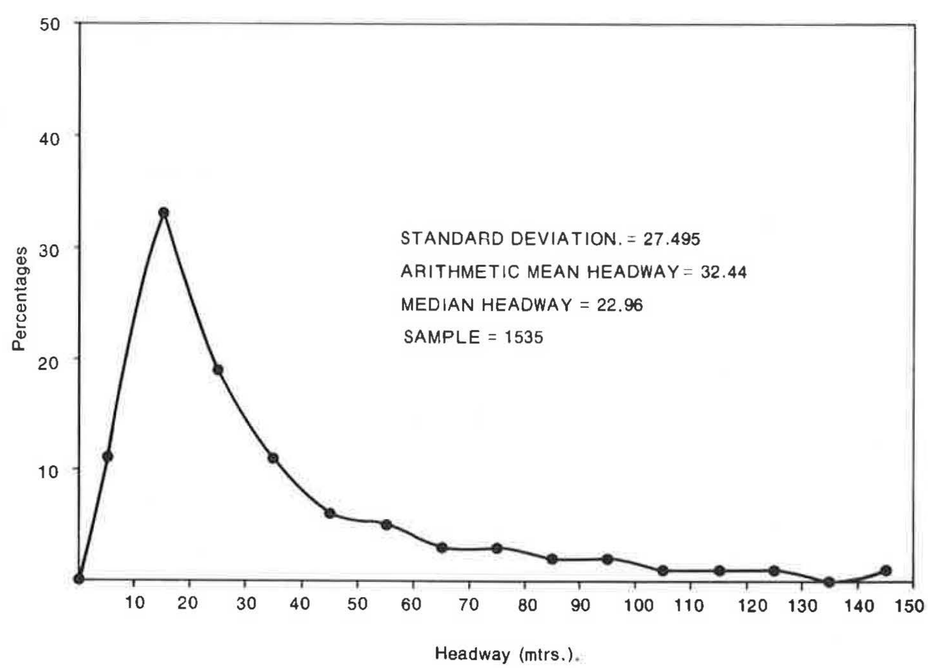


Figure 10. Typical headway distribution.



streets. Figures 2-6 present data for dual carriageways.

Good linear relations were obtained when directional vehicle hours per hour was plotted versus directional vehicle kilometers per hour (Figure 2) and when average directional volume was plotted versus directional lane concentration (Figure 3). Parabolic curves were fitted to the results obtained by plotting directional vehicle kilometers per hour versus mean directional spot speed (Figure 4) and average directional volume versus mean directional spot speed (Figure 5), but large scatters were obtained.

Figure 6 shows the nonlinear relation obtained when mean directional spot speed was plotted versus directional lane concentration (the broken curve is only a trend line and not the true curve fitting the points). This relation was found to be similar to one postulated by Drake and others (3) and May and Keller (4), which is shown in Figure 7. This gave a possible reason for the scatter obtained for the parabolic curves since, for such speed-concentration curves, the volume-concentration curves are of the form shown in Figure 8—that is, a straight-line section running into a parabolic curve as the concentration increases.

The volume-concentration results obtained in this study were linear in form, and this would suggest that they represent part of the straight-line section shown in Figure 8. This is substantiated when it is remembered that this linear relation was obtained for free-flow conditions (conditions that have low concentration values). In addition, the speed-volume curve associated with the curve shown in Figure 7 tends to differ from the traditional parabolic form and consists of a combination of a straight line and a parabola. The curves obtained for speed versus volume and speed versus vehicle kilometers per hour in this study did show a large scatter when a parabolic curve was fitted, which may result from the straight line-parabola effect.

In addition to the graphs, good results were obtained for the traffic and automobile-unit density contour maps. Figure 9 shows one of the density contour maps based on numbers of vehicles only, but similar graphs can be produced that allow for any specified system of automobile units. Headways were easily calculated from the data; Figure 10 shows a typical headway distribution for dual carriageways. Successful vehicle trajectory curves were also produced.

Despite the fact that no ground survey was undertaken as a check, information on many traffic parameters was obtained that shows good correlation with some established theories of traffic flow.

DISADVANTAGES OF THE TECHNIQUE

The problem of data analysis still remains to some extent even though computers and coordinate readers greatly reduce the time involved in performing calculations on the data. The data cannot be fed directly from the coordinate reader output into the computer, however, and certain amendments are necessary if a strict vehicle order is to be maintained.

The maintenance of this vehicle order is very important because, to compare individual vehicles from one photograph to the next, it is vital that the whereabouts of each vehicle in relation to all the other vehicles is known. Of course, this requires an operator who is skilled in computer-program editing methods. This part of the process is comparable to the data-checking process undertaken in manual traffic surveys. The time involved is not excessive and, once the data are corrected, they are ready for computer analysis.

The small time coverage of traffic movement on individual streets hampered studies of traffic volume. It is difficult, however, to reduce the time interval by using conventional aerial survey cameras. Thus, despite the correlation of the volumetric curves to theoretical hypotheses, the photographic technique is not easily adaptable to the measurement of volume. It seems unreasonable to calculate values from such small samples unless the time coverage can be increased.

It is unfortunate that no ground survey could be undertaken to act as a check on the photographic technique. Such a survey would have been very useful and might have thrown some light on the problems encountered during the determination of volumes.

Specialized equipment is required in the analysis. Coordinate readers and computing time are expensive, and the ideal situation would be to have a direct link to the main computer from which the editing of the data could be undertaken.

ADVANTAGES OF THE TECHNIQUE

The accuracy of the method has been shown to be more than adequate for traffic studies. More careful positioning of the control points could increase the accuracy even further if it were necessary. A very important aspect of the study was that all the control points were established from the aerial photographs used in conjunction with the 1:1250 Ordnance Survey plans without fieldwork. The National Grid coordinates of the control points were read directly from the plans, and the accuracy with which these coordinates could be read was clearly inferior to the accuracy that could be obtained by performing an accurate field survey to establish the control. Despite this, sufficient accuracy was obtained.

For a smaller area—one that involves perhaps 30 vehicle-carrying streets—it is probable that the whole study could be completed by one person less than one month after the photographs were received. This must be compared with the number of people and the time required to complete alternative ground surveys.

One great advantage of a photographic study is the amount of supplementary information that can be gleaned from the photographs. This study has been confined to moving traffic; no observations have been made of parked vehicles, which make an ideal subject for study by means of this type of photography. The photography also contains a wealth of other information that may be useful to those outside the field of traffic engineering.

Many other problems associated with moving vehicles could be investigated by using the same blocks of photography, and other highway problems—such as road widths, road markings, location of possible new roads, use of derelict land for parking, surveys of street furniture, and areas of heavy congestion shown by the traffic density contour maps—can be studied from the photography.

The short sampling time can be an advantage. Although, during free-flow conditions, a sampling time of less than 1 min could yield so few vehicles as to be statistically unreliable (as, for example, in the volume calculations undertaken in this study), the use of such a short increment of time ensures that an almost instantaneous picture of flow conditions is provided. Vehicles in the sample can only be a few seconds apart in time, and this results in a limitation on the possible changes in flow characteristics that might take place during longer sampling periods.

SUMMARY

This study has shown the technique used to compare favorably in many ways with more traditional techniques. Problems of data extraction have been eased if not totally eliminated.

A comprehensive check has shown the level of accuracy to be suitable for traffic studies, and an analysis of the results has shown that in many cases they agree with established theories. Deviations from these theories have occurred only where the particular theory itself is in doubt.

Several types of surveys—e.g., origin-destination studies—would, however, be difficult to undertake, and volume studies present problems. The photographs provide a permanent record of traffic conditions at that time and can be referred to later as and if required. The technique can be undertaken by unskilled or semiskilled personnel, and an accurate analysis is quickly obtained.

If some method could be found to eliminate the necessity of maintaining a strict vehicle order and thereby allow the data obtained from a coordinate reader to be read directly into the computer without any need for editing, the method could have many applications and could effectively replace some traditional ground-survey techniques. Even if one allows for this drawback, however, the photographic technique is a feasible one and represents a definite alternative to conventional ground methods.

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Measurement of the Performance of Signalized Intersections

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A survey technique for the measurement of the performance of signalized intersections is described. The technique is simple to perform in the field and produces the following types of information: (a) vehicle delay and its variability, (b) pedestrian delay and its variability, (c) vehicle flow rate, (d) total number of effective vehicle stops, and (e) a complete record of signal phasing and timing. Details are given for implementation of the technique as a conventional field survey, an "instant analysis" field survey, or a simulation model subprogram. The use of the survey technique in the evaluation of schemes for bus priority signalization is also discussed.

Although there has long been an interest in the performance level of intersections, especially signalized intersections, this interest has been heightened in recent years by the necessity to ensure that the existing transportation system operates at peak efficiency. This concentration on the performance of existing systems has been labeled transportation system management (TSM) and covers a wide variety of techniques. One of the major TSM techniques is managment of the system so as to give priority to high-occupancy vehicles. Examples of such priority techniques are priority lanes and bus priority signal systems. Such priority systems give preferential treatment to high-occupancy buses, usually at the expense of low-occupancy automobiles. However, before such a scheme is implemented or continued beyond a demonstration period, an assessment should be made of the relative impacts on various types of vehicles. In the case of bus priority signals, this assessment involves a survey of intersection operating conditions and performance levels.

The measurement of the level of performance of an intersection has been an area of concern in traffic planning almost since the birth of the profession. One can trace the attempts of traffic engineers to grapple with this problem through the works of several authors (1-6). In this evolution of techniques of performance measurement there have been two major variables: (a) the definition of criteria for level of performance and (b) the physical technique for obtaining such a measurement.

Indirect measurements of performance level that have been used include load factor (7), intersection flow ratio (8), and degree of saturation (9). Direct measurements of performance level include vehicle delay (however defined) and proportion of vehicles stopped. Reilly and others (6) describe the various definitions of delay and conclude that the most appropriate definition to use is that of approach delay, which includes not only the delay incurred by a vehicle while actually stopped but also the delay incurred while the vehicle is decelerating and accelerating as a result of the intersection operation. Their definition of the proportion of vehicles stopped is, as the name implies, the number of vehicles that come to a complete halt (no matter how many times) divided by the total number of vehicles crossing the stopline. They also classify the survey techniques into four types: point sample, path tracing, input-output, and modeling. They conclude that the point-sample method is the most desirable.