

concern. Such a capability needs to be developed and sensitivities analyzed. Other headway distributions such as the Erlang, Lognormal, Pearson, and Composite models should be investigated. Only when there is a thorough understanding of the significant variables and their impact on fuel consumption can any reliable conclusions be drawn concerning signal timing for the purpose of minimizing fuel consumption. It is felt that, of the available computer programs, NETSIM offers the greatest potential for determining these requirements.

REFERENCES

1. C.S. Bauer. Some Energy Considerations in Traffic Signal Timing. *Traffic Engineering*, Feb. 1975.
2. K.G. Courage and S.M. Parapar. Delay and Fuel Consumption of Traffic Signals. *Traffic Engineering*, Nov. 1975.
3. S.L. Cohen and G. Euler. Signal Cycle Length and Fuel Consumption and Emissions. *TRB, Transportation Research Record 667*, 1978, pp. 41-48.
4. J.W. Hurley and R.P. Ball. Energy Savings for Fixed Time Traffic Control. *Modeling and Simulation*, Vol. 9, Proc., 9th Annual Pittsburgh Conference, 1978.
5. J.W. Hurley and R.P. Ball. Evaluation of Energy-Based Signal Settings for Traffic-Actuated Control. *Modeling and Simulation*, Vol. 10, Proc., 10th Annual Pittsburgh Conference, 1979.
6. Network Flow Simulation for Urban Traffic Control Systems: Phase II. Federal Highway Administration, U.S. Department of Transportation, Vols. 1-5, 1977.
7. E.B. Lieberman and S.L. Cohen. New Technique for Evaluating Urban Traffic Energy Consumption and Emissions. *TRB, Transportation Research Record 599*, 1976, pp. 41-45.
8. P.J. Claffey. Running Costs of Motor Vehicles as Affected by Road Design and Traffic. *NCHRP, Rept. 111*, 1971.
9. J.W. Hurley. Feasibility of Transportation Projects: An Energy-Based Methodology. Univ. of Florida, Gainesville, Doctoral dissertation, March 1975.
10. G.E. Gonet. A Preliminary Investigation of the Fuel Consumption Characteristics of Freeway Ramp Metering. Virginia Polytechnic Institute and State Univ., Blacksburg, M.Sc. thesis, March 1979.
11. R. Conley. Effect of Grade on Starting Headway Time. *Traffic Engineering*, Vol. 22, No. 4, Jan. 1952.
12. A. Dick. Effect of Gradients on Saturation Flow at Traffic Signals. *Traffic Engineering and Control*, Vol. 5, No. 5, Sept. 1963.
13. The TRANSYT Signal Timing Reference Book. Federal Highway Administration, U.S. Department of Transportation, 1978.

Abridgment

Traffic Data Acquisition from Small-Format Photography

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A simple and economical method for collecting traffic data at complex urban intersections is described. The technique, developed at the University of Leeds, involves the collection of data in digital form by use of small-format photography taken from a hovering helicopter. The data are obtained in this form by means of a coordinate reader and processed by means of a computer that, using a two-dimensional coordinate transformation system, transforms the data to ground data and outputs information on a range of traffic-flow parameters. These parameters include approach volumes, the origins and destinations of all vehicles followed through the intersection, and the mean journey time and speed for each route. The potential of 16- and 35-mm photography to provide suitable photographic coverage is evaluated. The accuracy of the coordinate transformation systems is determined, and a computer-based coordinate-matching technique is developed. Finally, the accuracy and costs of obtaining traffic data by using the technique are compared with those associated with more conventional ground-survey methods. It was found that, where comprehensive traffic data are required, the technique can provide a simple, accurate, and economical method of traffic data collection and could be a workable alternative to conventional ground-survey methods.

While conventional ground-survey methods seem incapable of keeping abreast of the expanding data needs of today's traffic engineers, photographic techniques appear to have the potential to do so, particularly when combined with modern coordinate reader and computer technologies (1). The major problem associated with photographic techniques has, in the past, always been the difficulties associated with extracting and analyzing the vast quantities of information available from photographs (2), a prob-

lem that is particularly acute at intersections because of the complex nature of traffic movements at such locations. The basic objective of the research described in this paper was to find a solution to this problem.

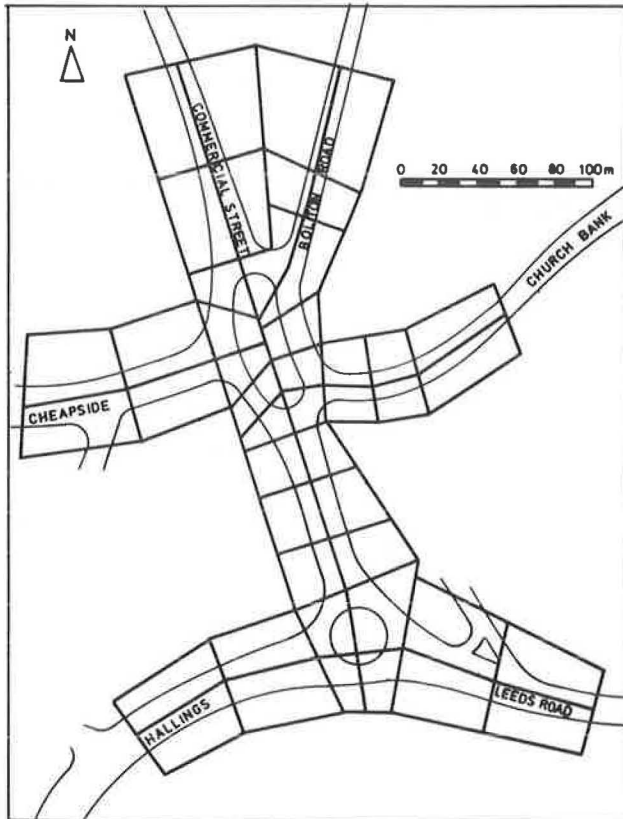
STUDY AREA

The site selected for study in this project was a complex double roundabout system near the center of Bradford in northern England. One portion of the system has five legs and the other has three, which gives a total of 36 possible routes through the study area. In order to include any queues on the approaches, it was decided that it would be necessary to include a minimum distance of 50 m on each approach to the roundabouts. Thus, the minimum area of coverage necessary was approximately 0.15x0.31 km.

DATA COLLECTION

To obtain comprehensive traffic data at such a location, it is essential that the photography used should be capable of providing continuous coverage of the entire intersection for a period of at least 1 h. Time-lapse photography is immediately suggested, but using any type of ground camera position would have restricted the field of view too much. A better vantage point could be obtained from the air,

Figure 1. System of zones used for vehicle tracking: Forster Square, Petergate, Bradford.



but there is then a problem in keeping the study area continuously in the field of view (3,4).

On balance, it was concluded that a time-lapse camera mounted in a hovering helicopter offered the best possibilities for providing the required photographic coverage. It was found that problems caused by helicopter vibration could be, if not totally eliminated, reduced to an acceptable level simply by the use of a fast shutter speed. Two cameras were used: the 16-mm Vinten Mark III and the 35-mm Robot Motor Recorder 24C. Color-reversal films were chosen for use in both cameras because small-format color photography is relatively inexpensive and the aid to vehicle tracking afforded by color justifies the additional costs over black-and-white emulsions (5).

In this study, filming was done at a rate of 1 frame/s. Analysis could then be carried out both by using every frame and by missing some frames so that a variety of time-lapse intervals could be simulated and compared.

DATA EXTRACTION

In the past, the reduction of traffic data has been done by various means that span the full range from manual to fully automatic (2). Although automatic methods will probably offer the ultimate solution to the problems encountered in data extraction, the need for further research and development of both hardware and software, together with a considerable reduction in the costs involved, renders semiautomatic methods the most feasible solution for the immediate future (6,7).

Semiautomatic methods are based on the identification of vehicle positions in terms of photographic

coordinates, expressed relative to any arbitrary pair of rectangular axes. This is achieved by means of machines known as coordinate readers. These machines are semiautomatic in that a human operator is required to identify the points of interest and activate the machines, which then automatically output the rectangular coordinates of the points of interest on recording media such as paper tape. Semiautomatic techniques are simple to apply and less tedious than manual methods, and the equipment required is readily available and inexpensive in comparison with that required for fully automatic data reduction.

COORDINATE TRANSFORMATION

Photographic coordinates obtained by using a coordinate reader do not make any allowance for the distortions inherent in single photographs, and the axes and origin will not necessarily be the same from frame to frame. It is thus necessary to convert photographic coordinates to a common system of coordinates, the most convenient of which in Britain is the National Grid.

Conversion can be accomplished by using mathematical transformation techniques. There are two such techniques available: linear transformation (8) and projective transformation (9). Both techniques were thoroughly investigated. It was found that the photographic coordinates could be converted to National Grid coordinates quickly and conveniently by using either linear or projective transformation techniques and at a level of accuracy adequate for the majority of traffic engineering purposes. Although it was found that both methods were capable of similar levels of accuracy in the case of the study area used, projective transformation was preferred for its greater flexibility (10).

VEHICLE TRACKING

Having obtained suitable photographic coverage of the study area and having found a method of relating vehicle positions on the photographs to their actual positions on the ground, the next, and perhaps most important, stage in the project was to devise a technique that would enable the coordinates of individual vehicles to be matched from frame to frame. In order to do this, each set of coordinates had initially to be given an identifying code to relate the coordinates to the appropriate vehicle. The best way to do this is to base these codes on the observable characteristics of the vehicles. The photography obtained in this study provided sufficient detail to determine the color, type, and lane of travel of each vehicle. Numerical identification codes were devised based on these characteristics.

Vehicle identification codes obtained in this way are, of course, by no means unique, and it is necessary to devise a method by which the mismatching of the coordinates of apparently identical vehicles can be avoided. Attempts have been made to solve this problem in the past (8,11), but the techniques devised have in all cases been applicable to links on which the direction of vehicle travel is constant. A rather different approach is needed for the study of intersections where not only a vehicle's direction can change but also each vehicle has a choice among a number of alternative directions.

The approach adopted in this study was to use a system of zones. The Bradford study area was divided into zones (see Figure 1) so that a vehicle in any particular zone in one frame could only be in one, or perhaps two, other zones in the next frame. In order to follow vehicles, a computer program was

written so that, for a vehicle in a particular zone, a search was made for an identical vehicle in the next frame in the most likely zone first, then in the next most likely zone, and so on until a match was found.

In this way, the coordinates of each vehicle at discrete intervals of time were determined. A number of traffic-flow parameters were then determined, including the flow on each leg of the roundabout classified according to direction, the origins and destinations of all vehicles followed through the roundabout system, and the journey time and speed for each route.

RELATIVE ACCURACY OF THE DATA OBTAINED

One essential requirement of any useful new technique for traffic data collection is that it should be capable of providing levels of accuracy similar to those currently achieved by using conventional methods, at similar or reduced costs. In addition to comparing the accuracy of the extracted data and the costs associated with obtaining these data, by using both 16- and 35-mm photography, the efficiency of using 1-, 2-, 3-, and 4-s time-lapse intervals was also investigated.

The levels of accuracy attainable by using the photographic technique are given below:

Parameter	Error Limit for 95	
	Percent of Data (%)	
Link volumes	±11.6	
Origin-destination volumes	±17.0	
Journey times	±10.9	

The levels of accuracy were not found to vary significantly with the type of photography or the time-lapse interval used.

Although these levels of accuracy are lower than those that might be achieved by using conventional methods, they were within limits acceptable for the majority of engineering and planning purposes. The slightly reduced accuracy levels are, in fact, offset to some extent by the additional data that can be readily obtained from the photography. These include traffic density, vehicle paths, and gap acceptance, all of which could not be easily obtained by using conventional methods.

RELATIVE COSTS OF THE PHOTOGRAPHIC TECHNIQUE

The cost of a traffic survey can be evaluated in terms of two basic units, time and money, and it is desirable that the costs in terms of both should be minimized. Relative costs in terms of these two basic units are summarized below [1 £ = U.S. \$2.32 (1980 average)]:

Method	Cost	
	Time (man-hours)	Money (£)
Photographic		
1-s time-lapse interval	1100	2700
4-s time-lapse interval	300	1000
Conventional	550	1700

Investigations showed that an overall reduction in the number of man-hours required for data collection and analysis could be achieved by using the photographic technique with a 2-, 3-, or 4-s time-lapse interval. The photographic technique, however, requires that the majority of man-hours be worked consecutively and thus, although the photographic technique requires considerably fewer personnel, the overall time period required to produce data in a useful form tends to be rather longer than

that required for conventional surveys. If a 3- or 4-s time-lapse interval is used, however, an overall time period of less than two months should generally be adequate to obtain comprehensive peak-hour traffic-flow data at an intersection similar to the one studied in this project (assuming that it is not necessary to wait very long for suitable flying conditions). Although the overall time period is about twice as long as the overall time required to obtain similar data from a ground count, the time scale is not excessive and should be acceptable in the majority of cases.

Monetary costs do not vary significantly with either the 16- or 35-mm formats, and from this point of view either could be used equally well. The time-lapse interval used is, however, one of the major determinants of costs. If it were necessary for the user to pay full agency rates for computer processor time, the photographic technique would be rendered uneconomical irrespective of the time-lapse interval used. If it is necessary to pay only overhead costs for computing time, then the use of a 3- or 4-s time-lapse interval can render the photographic technique economical irrespective of the traffic density. The use of a 1-s time-lapse interval, on the other hand, would make the technique both too lengthy and too expensive.

CONCLUSIONS

Small-format, time-lapse photography taken from a hovering helicopter provides a relatively simple and economical technique for collecting comprehensive traffic data at complex intersections. Extraction of the data from the photography by using a coordinate reader to obtain the data in digital form, combined with computer analysis of the data, can form the basis for a simple and relatively rapid data-extraction technique. The technique can be used at any location to provide comprehensive traffic data, if suitable photographic coverage is available, and can provide data with a reasonable level of accuracy at costs similar to or lower than those encountered in using conventional ground-survey methods.

REFERENCES

1. D. Bayliss. Traffic Data for Transport Policies and Programmes. Proc., Conference on Traffic Data Collection, Univ. of Leeds, Leeds, England, Jan. 1979, pp. 1-25.
2. The Practicality of Aerial Traffic Data Collection. Institute of Traffic Engineers, Washington, DC, Informational Rept., 1975, pp. 5-24.
3. J.B. Garner and L.J. Mountain. The Potential of 16mm and 35mm Time Lapse Photography Taken from a Helicopter for Traffic Studies at Complex Intersections. Photogrammetric Record, Vol. 9, No. 52, 1978, pp. 523-535.
4. J.B. Garner and L.J. Mountain. Traffic Data Collection: An Alternative Method? Traffic Engineering and Control, Vol. 19, No. 10, 1978, pp. 451-454.
5. D. Berry, G. Ross, and R. Pfefer. A Study of Left-Hand Exit Ramps on Freeways. HRB, Highway Research Record 21, 1963, pp. 1-16.
6. L.J. Mountain. Traffic Data Collection. Traffic Engineering and Control, Vol. 29, No. 3, 1979, pp. 129-131.
7. C.M.G. Francis. The Microdensitometer as an Aid to the Interpretation of Multispectral Photographs for Mineral Exploration Purposes. Photogrammetric Record, Vol. 8, No. 45, 1975, pp. 309-316.
8. J. Uren and J.B. Garner. Integrated System for Urban Traffic Data Collection. TRB, Transport-

- tation Research Record 699, 1979, pp. 41-49.
9. J. Taylor and R. Carter. Photogrammetric Data Acquisition for a Freeway Ramp Operations Study. HRB, Highway Research Record 319, 1970, pp. 78-87.
 10. L.J. Mountain. The Potential of Small-Format Photography for Traffic Data Collection. Univ. of Leeds, Leeds, England, Ph.D. thesis, 1979.
 11. J. Uren. Urban Traffic Data Collection from Conventional Aerial Photography. Proc., Conference on Traffic Data Collection, Univ. of Leeds, Leeds, England, Jan. 1979, pp. 143-166.

Decentralized Control of Congested Street Networks

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A mathematical model for traffic flow in city streets and its control is presented. The model is thought to be appropriate to the kind of control systems anticipated over the next 10-20 years. These systems are expected to rely to a considerable extent on communications that are less binding on driver behavior than the traffic signals that are now virtually the sole communication-control devices. The model is accordingly probabilistic. It is not limited to the problem of optimal signalization. On the contrary, optimal as well as satisfactory traffic control can be based on it. In either case, the problem develops into one of a special kind of nonlinear programming and of very large scale. A scheme is described for its decomposition into decentralized control, and several algorithms for its computational execution are outlined.

The most important technological development during the past decade may have been that of the very-large-scale-integration (VLSI) circuit chip. By all present indications, its impact will be widespread and profound. The control of traffic in city streets is likely to be affected. One can perhaps anticipate that current control systems will be supplemented and perhaps even supplanted by others that use the new technology. The new generation of such systems might seek to induce desirable traffic patterns by greater flexibility in its adjustment of red-green splits and in its use of turn signals at intersections. It might also combine the conventional signals with traffic advisories broadcast over general, citizens band, and perhaps even dedicated radio transmission channels, all in an effort to create a more satisfactory traffic-flow pattern.

The common characteristic of most of these strategies is that they are not binding on the driver in the way that conventional traffic signals now are. One can accordingly expect drivers' reactions to them to be of an even less deterministic nature than their reactions to the present ones. A model of the traffic system under these conditions seems most appropriate if formulated stochastically, and this is what has in fact been done in this study. The control variables of the system are, roughly speaking, the probabilities with which vehicles can be induced to make right turns, left turns, or no turns at the intersections of the street network in response to the various signals to which their drivers are exposed. The traffic signals, of course, remain as a set of control variables as well.

The problem of designing a traffic control system can then be viewed as that of making the best, or at least a satisfactory, choice of those probabilities. Formulated in this way, it develops into a constrained mathematical programming problem whose solution is made difficult partly by its non-linearity and partly by its large scale. The non-linearity is admittedly of a very special kind. The constraints, as well as the objective functions, are typically multilinear in the control variables.

This is a feature that should be exploited in the solution procedure, and the several solutions that have been considered do so.

The large scale of the problem, on the other hand, suggests decentralized control schemes. Such schemes are at least intuitively most appropriate when the controlled system is made up of many subsystems geographically distributed over a wide area. It is then an appealing idea to exercise control over each subsystem separately, perhaps based mainly on inputs obtained locally, and to perform the necessary coordination through a hierarchy of supervisory controllers. Decentralized control schemes have the potential of reducing the cost of data communications, providing a high level of fail-safe capability, and allowing greater flexibility in the design and implementation of control strategies.

Surprisingly, however, little work has been reported on the application of decentralized control concepts to optimize the operations of large-scale urban transportation systems and even less work that treats these systems stochastically (1). The currently accepted versions of these concepts are explained in a recent article by Barry (2). Chu (3) explored the optimal decentralized control of a string of high-speed, densely packed vehicles using on-board controllers. Looze and others (4) and Kumar and others (5) proposed decentralized control schemes for regulating traffic on urban freeway corridors. Saridis and Lee (6) discussed the general problem of hierarchical control and management of traffic systems, while Chu (7), Sarachik (8), Singh and Titli (9), and Gershwin and others (10), among others, suggested decentralized control algorithms for large street networks, in nonstochastic formulations. A comprehensive survey of decentralized control methods and their applications to large-scale systems has recently appeared (11).

In this paper, a traffic network model based on probabilistic concepts is developed, and the problem of traffic control in such a network is formulated. The reasoning that leads to decentralization as a technique for the solution of that problem is outlined, and, finally, solution algorithms are briefly discussed, those that are already available as well as those that have been developed in this study.

TRAFFIC NETWORK MODEL

A traffic network is treated in this study as a stochastic system that is controlled by influencing the probability that a vehicle arriving at an intersection will make a right or left turn or no turn at all. The discussion presented here is based on a rather simple network of streets. Its extensions to