THE DEVELOPMENT OF TECHNIQUES FOR
THE ANALYSIS OF OPERATION OF MAJOR INTERCHANGES

By

Dr. Joseph A. Wattleworth
Head, Traffic Systems Department
Texas Transportation Institute
and Principal Investigator, NCHRP Project 20-3

Claude Archambault
Research Assistant, Texas Transportation Institute

Charles E. Wallace
Research Assistant, Texas Transportation Institute

and

James D. Carvell
Engineering Research Associate
Texas Transportation Institute

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I. INTRODUCTION

Traffic engineers, economists, planners, and motorists recognize that congestion on roadways is very costly in time, money, social costs and personal stress. However, these same people do not agree except on the fundamental principle that travel-time is a measure of congestion: otherwise, opinions are quite confused, not to say divergent, as to what should be a good measure of effectiveness, even as to what system should be defined to provide meaningful results.

It is suggested that a systems approach would greatly benefit all those concerned, by taking into consideration all relevant aspects of the problem. Of the many definitions proposed for systems design, this one, by Charles Hitch (1), by being very general, is undisputable: "A system approach is the systematic examination of broad alternatives".

Accordingly, there is a need for traffic engineers to use traffic parameters that would reflect the operations of roadways, and freeways in particular, and be capable of measuring the different levels of operation, or levels of service, in a systematic fashion. Different types of studies have been proposed and are being used today with various degrees of success to measure the effectiveness of highways in carrying traffic. This paper will be concerned with one type of study which holds considerable promise toward fulfilling the objectives of a systems approach: the input-output study.

Data have been collected at two different interchanges (Figures 1 and 2) on the John C. Lodge Freeway in Detroit as a part of NCHRP Project 20-3: "Optimizing Freeway Corridor Operation Through Traffic Surveillance, Communication, and Control".

In this report the input-output analysis is applied to major interchanges, although the technique could be applied, with certain modifications, to other traffic situations. The input-output analysis may be used to evaluate traffic operation on isolated portions, e.g.: the inbound portion of an interchange or an on-ramp with poor geometric design. The analysis could also be applied to evaluation of all elements of an interchange, although this becomes quite involved, both in the analysis of data and the amount of personnel and in the equipment required for data collection.
Figure 1. Lodge-Ford Interchange

Figure 2. Lodge-Davison Interchange
II. OBJECTIVES OF THE INVESTIGATION

Need for System Measurement

While interchanges are major components of freeway system little attention has been devoted to a systematic evaluation of traffic flow on the interchange itself with the possible exception of the diamond interchange. Because diamond interchanges are more frequent on urban freeways than other interchanges (cloverleaf, parclos, semi-directional or directional), their operational characteristics have been described in detail (2,3). Interchanges other than diamond have been described mostly in qualitative fashion (4,5).

Each of the characteristic problems generally associated with major interchanges are well documented individually in the literature: merging capacity (6,7) downstream bottleneck (8), diverging capacity (9), weaving capacity (10), and special ramp configurations such as left-hand entrance ramps (11) and successive entrance and/or exit ramps (17). However, little attention has been given an analysis of the entire interchange as a system or combination of subsystems.

There is a need to define an interchange in terms of its fundamental movements: merging, diverging or weaving. For instance, the four-legged, directional interchange shown on Figure 1 may be divided into 8 basic components (Figure 3). Each of these components includes one or several inputs, a conflict area (merging, diverging or weaving) and one or several outputs. In system analysis, the inputs and the outputs can be described in terms of actual performance, mathematical relations or statistical distributions. It is important to define the boundaries of the system so that a change in the system would not affect the inputs. In other words, the variation in the output due to a variation in the system must not be attributable to a variation in the input.

Measures of Effectiveness

Various figures of merit have been proposed to evaluate traffic operations on a section of roadway. Basically, these may be classified in one of three different categories: minimization of individual costs and fulfillment of individual desires, maximization of total output while maintaining the highest quality of traffic service, and optimization of the total transportation system (12).

The first criterion is evidently restricted to a study of individual drivers and their vehicles in the traffic stream. Several different variables can be measured which are representative of the quality of service to the driver individual travel-time, individual speed, galvanic-test tension response, and fuel consumption (which is directly related to acceleration noise (13).

However attractive these measures may be to the individual driver, they are not very useful in a systems approach to traffic operation.
Figure 3. Basic Components of Interchanges
because they violate an important principle of systems engineering: the principle of optimization (14). This principle implies that optimizing a component of a system does not necessarily improve the system performance, nor does optimizing all elements ensure attainment of an overall optimum.

The second criterion, loosely described as maximizing total output while maintaining the highest quality of traffic service, involves the measure of several traffic variables: average volume, average density, average speed for all vehicles in the stream, total travel in the system, total travel-time in the system, kinetic energy of the system and interchange ratio. These variables indicate the performance of a system, although the importance of each measure is somewhat subjective when attempting to describe the quality of traffic flow.

A system-like approach to evaluate traffic flow has been used by economists to measure possible benefits from roadway and traffic improvements (15,16), but all these evaluations are essentially based on one parameter: travel-time in the system, although Wohl discusses total output as a figure of merit to be used in conjunction with travel-time (17).

The third criterion, optimization of the total transportation system, is the ultimate goal of all traffic planners and engineers, but this objective is beyond the scope of this paper.

Review of Some Study Procedures

Four main procedures are currently used to study traffic flow: ground counts, photographs, moving vehicles, and license-plate surveys:

a. Ground vehicle counts obtained manually or by automatic recording detectors, can describe traffic flow at different points over a system. When defining a closed system, they are most useful to describe traffic flow over any subsystem, or over the total system, for any interval of time.

b. Photographs provide an instantaneous picture of a length of roadway, but are limited as to the area covered (ground photographs) or the time the area is pictured (aerial photographs).

A helicopter or a balloon may provide continuous pictures both in time and in space (18), and would seem to be an ideal procedure, but severe limitations as to altitude, lens resolution, and data reduction and processing, defeat the initial purpose of this type of study.

The information usually provided by aerial photographs falls into two categories:

(1) Quantitative description of traffic flow by density, speed, time headways, acceleration, etc.
(2) Qualitative description of traffic flow by provided visual
description of traffic variations due to accidents, construc-
tion, congestion or any other type of obstruction on or off
the roadway.

An evident advantage of photographs is that they provide permanent
records of traffic which may be studied at any convenient time using
special equipment to measure coordinates, punch cards, and transfer
data to computer tape.

c. Moving vehicle techniques have been advantageously used to eval-
uate various traffic parameters: traffic flow (19,20), average speeds,
amount of travel, and more recently acceleration noise (21). Limita-
tions are obvious, and statistical inference may be hazardous, as
pointed out by Mortimer (20), due to the very small number of samples.

d. License-plate studies have been used to evaluate travel-time
and delay (22), but their use is cumbersome, and the data difficult to
process. Matson et al. (23) give a brief description of the method
and its shortcomings.
III. INPUT-OUTPUT STUDY

Earlier Applications

The application of systems analysis to traffic engineering was sug­gested in the early 50's (24), and one of the first attempts to evaluate the performance of a freeway network was done about a decade later when Brenner et al. (22) applied what is essentially an input-output study technique on a section of the Hollywood Freeway in Los Angeles. The chosen measure of effectiveness was travel time in the system. Al­though many different factors suspected of varying the traffic flow were analyzed, the complexity of the procedure used at that time (license­plate study) precludes its use on almost any system.

Matson et al. (23) briefly described an input-output study used to evaluate parking accumulation in a closed network, where all the inputs are taken into account.

Wattleworth (8) discussed the application of continuous input and output counts to evaluate the effects of controls on maximizing the output rate. It is noted that, at any instant, the rate at which vehicles are entering a closed system, $i(t)$, equals the rate at which they are leaving the system $o(t)$, plus the rate at which they are being accumulated within the system, $s(t)$:

$$i(t) = o(t) + s(t)$$  \hspace{1cm} (1)

It is also shown that this analysis permits a close look at con­gestion formation and duration on any system of interest. In particular, the demand may exceed the system "capacity" output rate for a certain interval of time (from $t_0$ to $t_1$) but congestion will last for a longer interval of time (from $t_0$ to $t_2$), the excess time being necessary for the accumulated difference between the input and the output to dissipate.

Wattleworth and McCasland (25) further discussed the possibility of applying input-outputs counts to capacity studies, and, in addition, described the mechanics of this type of study. This is a very exacting procedure, although it simply involves continuous counts of vehicles for predefined time intervals.

Haynes (26), in defining density as the most accurate means of de­scribing congestion, is rather critical of the input-output study, which he calls "Density Trap Study Method", because of the limitations that will be discussed later in this paper. However, Haynes used the method with some success, or so it seems, for he concluded his article by stating that: "The density-trap method of study offers advantages in studying the continuously variable nature of density and the relation­ship between density and speed and volume", the first relationship being of interest to the individual motorist, the second to the traffic engineer.
Development of the Parameters

The input-output analyses described above will be extended to evaluate travel, travel-time, average density and average speed in the system, kinetic energy, and delay, by selecting suitable boundaries and time intervals. The notation used throughout this paper is given in Appendix A.

Number in the System - Figure 4 shows a time-space diagram for a length of one-way roadway AB, say one mile for convenience. Two observers, A and B, stationed respectively at section a-a and section b-b and using the same time basis, will record the number of vehicles crossing their sections in predefined intervals of time, say 5 minutes. A begins his count when the "signal car" crosses a-a, and notes the time \( t_A \). Similarly, B begins his count when the signal car crosses b-b, and notes the time \( t_B \). If the signal car overtakes any vehicle, or if it is overtaken, between A and B, the net number is recorded and added to, or subtracted from, the counts. The signal car is thus a boundary to the system in time.

At \( t_B \), 7 vehicles have entered the system at point A, and one vehicle (the signal car) is leaving the system.

\[
N(t_B) = 7 \text{ veh.}
\]

Note that \( N(t_B) \) is measured on both axes distance and time.

At \( t_o \), A and B record the cumulative counts at their respective locations. The cumulative input at A is 15 vehicles, while the cumulative output at B is 9 vehicles. Accordingly,

\[
Vin(t_o) = CUM(t_o) - N(t_B) \quad (2)
\]

\[
= 15 - 7 = 8 \text{ veh.}
\]

\[
Vout(t_o) = CUMout(t_o) \quad (3)
\]

\[
= 9 \text{ veh.}
\]

The number of vehicles in the system at \( t_o \) will be

\[
N(t_o) = N(t_B) + Vin(t_o) - Vout(t_o) \quad (4)
\]

\[
= 7 + 8 - 9 = 6 \text{ veh.}
\]

and in general

\[
N(t) = N(t-5) + Vin(t) - Vout(t) \quad (5)
\]

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Figure 4. Space-Time Diagram
Figure 5. Travel
Average Density - For any time interval, the average density can be defined as the average number in the system divided by the length of the system:

$$k_L = \frac{N(t-\Delta t) + N(t)}{2} \cdot \frac{1}{L_L}$$  \hspace{1cm} (6)

Travel - The travel in the system (Figure 5) may be defined, for a given time interval, as the product of the flow through the system by the length of the system. Edie (27) calls it the "aggregate vehicular transport", a very descriptive definition.

On any small section $dx$, the travel will be

$$TT^t_{dx} = n \cdot dx$$  \hspace{1cm} (7)

where $n$ is the number of vehicles that pass through $dx$ in time period ending at $t$

The travel over the entire section $A-B$ will be obtained by integrating the above equation over the distance $AB$:

$$TT^t_{AB} = \int_A^B n \cdot dx = n \cdot L_L$$  \hspace{1cm} (8)

Since $n$ is a variable in $x$, the integral cannot be evaluated unless the function $n = f(x)$ is known. Rather than multiplying the number of observation points between $A$ and $B$, it can be assumed that the flow of traffic is constant over a small interval of time at $A$ and at $B$, even if it is different at each location (due to the storage or accumulation in the system). This may be written:

$$TT^t_{AB} = \frac{Vin(t) + Vout(t)}{2} \cdot L_L$$  \hspace{1cm} (9)

On Figure 5, the travel between $t_i$ and $t_{i+5}$ is

$$TT^c_{i+5} = \frac{11 + 10}{2} \times 1$$

$$= 10.5 \text{ veh. miles for a 5 minute interval}$$

It is interesting to note the additive properties of travel when adjacent subsystems are so chosen as to be mutually exclusive and to possess a common limit. In this manner, the interior limits between the subsystems
become observation points on the variable n. Quantities of travel can thus be added both in time and in space, to yield total travel in a system.

\[ \text{TT}_{\text{sys}} \text{time} = \sum_{i=1}^{\text{Sys}} \sum_{t=0}^{\text{time}} \text{TT}_{i} \]  

**Hourly Rate of Travel** - The hourly rate of travel HRT is defined as the total travel that would be obtained in one hour on any subsystem of system if the five minute travel during time interval \( i \) were constant throughout the hour:

\[ \text{HRT}_{\text{AB}}^{t_i} = 12 \cdot \text{TT}_{\text{AB}}^{t_i} \]  

From Figure 5,

\[ \text{HRT}_{\text{AB}}^{t_{i+5}} = 12 \times 10.5 \]

\[ = 126.0 \text{ vehicle miles for a 1-hour interval} \]

**Travel Time** - From Figure 6, the travel time in the system is defined as the summation of all the time intervals spent in the system by the vehicles that have been in the system at any time, or the time of occupancy which is used by Rothrock and Keefer (28) in their definition of the Congestion Index Number. The overall travel time includes stops and delays incurred on the roadway due to congestion, accident, maintenance, etc.

The travel-time accruing to the vehicles on a unit length of roadway during a small interval of time \( dt \) is:

\[ \text{TT}_{\text{AB}} dt = m \cdot dt \]  

where \( m \) is the number of vehicles on AB in time interval \( dt \)

The travel time over a time interval \( T_{5 \text{ min.}} \) will be obtained by integrating this equation over time.

\[ \text{TT}_{\text{AB}}^{t_{i-5}} = \int_{t_{i-5}}^{t_{i}} m \cdot dt \]  

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Figure 6. Travel-Time
Following the procedure outlined above in the case of travel, assume that the storage in the system at any time is approximated by the average of the storages at time $t_{i-5}$ and time $t_i$:

$$TTT_{AB}^i = \frac{N(t-5) + N(t)}{2} T_{5 \text{ min.}}$$  \hspace{1cm} (14)$$

From Figure 6, the travel-time on the link $A-B$ between $t_{i-5}$ and $t_i$ is

$$TTT_{AB} = \frac{6 + 5}{2} \text{ - 5 minute period}$$

$$= 5.5 \text{ vehicles - 5 minute period}$$

Total travel-time is most often expressed in vehicle-hours:

$$TTT_{AB}^T = \frac{1}{12} TT_{5\text{-min. period}}$$

$$= 0.46 \text{ veh.-hour}$$  \hspace{1cm} (15)$$

For mutually exclusive but adjacent subsystems, travel-time has the additive properties, both spatial and temporal, described in the case of travel.

Note that travel is measured over a unit time interval and that travel-time is measured over a unit length of roadway, and that these unit quantities are implicit in the expressions for $TT$ and $TTT$.

**Average Speed** - Dimensional analysis suggests that travel and travel-time be related to define an average speed in the system.

$$U_{\text{mph}} = \frac{\text{Travel in veh.-miles}}{\text{Travel-time in veh.-hours}} = \frac{TT}{TTT}$$  \hspace{1cm} (16)$$

This hypothesis can be verified from the basic definitions of travel and travel-time, assuming that both parameters have been measured on the same subsystem and during the same interval of time.

This average speed is, of course, the space-mean speed defined by Wardrop (29) since, in terms of time, it is the length of the route divided by the mean journey time, or travel-time.

$$U = \frac{\sum_{i=1}^{n} \Delta X_i}{n} = \frac{\sum_{i=1}^{n} \Delta X_i}{n} = \frac{TT}{TTT}$$  \hspace{1cm} (17)$$
The quantity in the numerator is the total travel, accruing to the n vehicles stored or accumulated on the slice \( \Delta X \) during the period of observation.

The quantity in the denominator represents the total travel time on a unit length of roadway, since it is the sum of the times spent by the n vehicles on the unit slice.

It is evident that the average speed, being a ratio, does not possess the additive properties of its components, but rather has to be evaluated separately for any subsystem, and for any interval of time.

**Kinetic Energy** - It has been shown (30) that the energy of motion of a traffic stream is analogous to the kinetic energy \( KE \) as defined in classical mechanics:

\[
K.E. = \frac{1}{2} m v^2
\]  
(18)

where \( m = \text{Mass Density} \)

\( v = \text{Velocity} \)

Mass density being analogous to the concentrations of vehicles in a traffic stream, and substituting the average stream speed for the velocity of the mass, the relation becomes

\[
KE = \alpha k.u^2 = \alpha q.u \]  
(19)

where

\[
q = \frac{n}{T} = k.u \]  
(20)

In equation 19, substituting the expression for \( u \) given by equation 17 and the expression for \( q \) given by equation 20, the kinetic energy becomes

\[
KE = \alpha \frac{n}{T} \frac{\Delta x}{\Delta t} = \alpha \frac{n}{T} \cdot \frac{TT}{TTT} \]

From equation 8, define \( n \) in terms of \( TT \):

\[
KE = \alpha \frac{TT}{T.L_x} \cdot \frac{TT}{TTT} = \alpha \frac{(TT)^2}{TTT} \cdot \frac{1}{T.L_x} \]  
(21)

Kinetic energy is expressed as \((\text{veh-mile})/\text{hour}\)^2, as easily verified from equations 19 and 21, and the units are seen to be the same as for acceleration.
Assuming the total energy in a system constant from a given input, the total energy being the sum of the kinetic energy and the internal energy, it follows that any increase in the kinetic energy, other things being equal, will be accompanied by a decrease in the internal energy, or acceleration noise, due to a lower internal friction between the vehicles in the traffic stream (31).

Kinetic energy cannot be added over different subsystems on different time intervals, but must be evaluated separately over given conditions for TT and TTT. A basic assumption (equation 19), is that KE is a point measurement, the flow rate q being measured at a point.

Assuming q constant over a length of roadway, one can say that the kinetic energy at any point over that roadway has the particular value defined at the principal point.

Kinetic energy has been used to describe the level of service on a system (30), and a normalized variable was used to get a measure, between zero and one, of the level of service:

\[ KE_{\text{norm}} = \frac{KE_{\text{meas}}}{q' u' m} \]  \hspace{1cm} (22)

where the subscripts m refer to optimum values of q and u.

Interchange Ratio - The ratio of ramp volume to total volume (ramp volume plus freeway volumes) is evidently related to the operation of interchanges. Ideally this ratio should be determined at the design stage, and the interchange designed accordingly, i.e., a ramp with a high interchange ratio should have better geometrics than a ramp with a small ratio. Actually, this ratio could be used to determine the level of ramp volumes at which controls become necessary, since the merging process may be dependent not only on the total volume, but also on this ratio.

Delay and Delay Rate - These parameters are of great interest both to the individual drivers and to the traffic engineers, since they define a meaningful quantity that can be easily measured or evaluated. There exist two principal methods of evaluating the delay accruing to a number of vehicles on a roadway or the average delay to a vehicle. The first makes use of the principal relations derived in queueing theory, and has been used mainly in England to define the average delay at signalized intersections (33) and in the U.S.A. to define the average delay at toll booths and tunnels (34). It appears, however, that these principles cannot be directly applied in the case of freeway traffic where service facilities are difficult to define precisely. The second method makes use of a very simple relation which states that any amount of travel-time over a given limit constitutes delay; this limit may be defined in terms of modal speed and measured, or actual, travel by transforming equation 16:
\[ \text{TTT}_{\text{lim}} = \frac{\text{TT}_{\text{actual}}}{U_{\text{modal}}} \] (23)

and the delay will be given by

\[ \text{Delay} = \text{TTT}_{\text{actual}} - \text{TTT}_{\text{limit}} = 0 \] (24)

The delay rate defined by Miller (35) is simply the ratio of delay over actual travel time:

\[ \text{Delay Rate} = \frac{\text{Delay}}{\text{TTT}_{\text{actual}}} \] (25)

**Adjustment Techniques** - The development of the various parameters was accomplished under the hypothesis of continuous counts on a closed system. This section will further develop this technique by stressing several adjustments: sources of errors, distribution of errors, methods of initializing and ending a study, use of automatic detectors, and use of aerial photographs.

**Sources of Errors** - There are two principal sources of error, one involving the counting of vehicles and the other the recording of time intervals. More specifically these errors are: vehicles are not counted, either at the input or at the output; the input and output counts are not synchronized in time; or the cumulative counts are not recorded exactly at the right time.

A very small error in determining \( N_t \) may result in large relative errors in the total travel time, the average speed and the kinetic energy. If there were actually ten vehicles in the system \( (N_t) \) and only eight vehicles were counted, only a two vehicle error results. However this represents a 20% error and when applied to typical data may result in errors of 15% or more in \( \text{TTT} \), speed and kinetic energy.

It can happen, also, that some vehicles will not be counted at some time during the study. As pointed out above, this can result in significant error calculating the desired parameters.

It can be seen that errors in the number of vehicles in the system have a greater importance when they are made at the beginning of the study than at the end. This is, of course, due to the fact that cumulative counts are used to determine total travel time accruing to the vehicles in the system at any time.

Another type of error is the situation where one of the counts is not recorded at exactly the right time, but, say, one minute before, so that the time intervals are no longer equal.

The computations, of course, will be made using equal intervals, so that the error in travel-time will result in significant errors, either positive or negative, in calculation of the parameters. Here again one minute seems small but it represents 20% of the five minute period.
If the counts were not synchronized in time, the error would be similar to the one just described; in particular, if the time interval between the beginnings of the counts is reduced, the initial number in the system is decreased, and the total travel time is decreased. Conversely, if the time interval is increased, these parameters are increased.

Distribution of Errors - The only means to detect errors is to compare the inputs to the outputs: for the whole study period, their respective sums should be equal, and at no time should the number in the system be negative. This is fairly obvious, but a problem arises when, according to the data, either the total output is different from the total input, or the number in the system is negative. The closure error is given by:

\[ E = \sum_i V_{in,i} - \sum_i V_{out,i} + P \]  

(26)

where \( P \) is the algebraic sum of vehicles overtaking or overtaken by the signal car.

Assuming that the correct volume is the higher of the two, \( \sum V_{in} \) or \( \sum V_{out} \), the lower figure should be adjusted, unless there is evidence to the contrary, by double-checked counts for instance.

It would be logical to distribute the errors so as not to increase the travel-time unduly. Since the error can occur anywhere in time, the least biased error distribution technique is probably to distribute the error evenly among the different time intervals.

If, after this correction \( N(t) \) is still negative at some point, several alternate solutions could be used: one can discard the data, which is not a very good solution in view of the painstaking efforts made to collect it; one can compute the parameters, keeping the negative values of \( N(t) \), and thus obtain lower values than expected for travel-time; one can also use the fact that \( N(t_0) \) cannot be less than zero to make it equal to zero and pursue the computations from there on. Obviously, if \( N(t) \) is larger than it should be, it will not be noticed, unless it is larger than permitted by the maximum density on the link under study. The second alternative, accepting negative \( N(t) \) appears to be the most appropriate.

The errors in \( N(t) \) will affect travel-time, and errors in volume \( V_{in}(t) \) and \( V_{out}(t) \) will affect travel. Because of count errors and storage in the system the difference between \( V_{in}(t) \) and \( V_{out}(t) \) is not always equal to zero. A correction term can be used:

\[ TT_{cor} = TT + \frac{V_{in}(t) - V_{out}(t)}{2} \cdot L \]  

(27)

It must be emphasized that the purpose of this discussion is to define a means to use data that is incorrect. The discussion also points out the most serious flaw of the input-output method is that the
SYSTMS I and II

SYSTEM III

Figure 7. System Description
number of vehicles in the system at a given instant is never known directly, but must be inferred from cumulative counts.

Methods of Initializing and Ending an Input-Output Study - In a straight pipe section, the use of a signal-car, as described above, to initialize and end a study, does not present any particular problem, assuming that the observers use the same time basis and that the driver of the signal-car notes the number of vehicles overtaken or overtaking while he is driving through each subsystem. This method is easily applicable to any number of subsystems in series, if all inputs and outputs are taken into account.

However, as seen in Figure 7, this method cannot be applied when several subsystems converge at a node, since the signal car can only go through A, D, or E, before reaching a2, which is also d2 and e2. One solution would be for the observers at d and e to begin their respective counts when they see the signal-car at a2, and add the number of cars in their respective subsystems D and E at that time. However, the node a2 will not always be visible from d1 or e1, and the observers will have to walk from d2 to d1, and from e2 to e1, counting the vehicles on the links at the same time. To close the study, the process is reversed in that observers at d2 and e2, when they see the signal car, walk back to d1 and e1 counting the vehicles on these links, which will be subtracted from the input counts at d1 and e1.

A different procedure was used successfully in the Detroit study. When the signal-car passes a2, a radio signal instructs d1 and e1 to begin their count (d2 and e2 do so at the same time as does a2; b1 is redundant and will not be used except if a check is needed). The counters at d1 and e1 immediately radio back a description of the first vehicle they counted. Then, d2 and e2 note the number of vehicles counted when those vehicles described pass their locations. The same procedure is followed to close the system. These numbers are then added to d1 and e1 when opening the system, and subtracted from d1 and e1 when closing it. This procedure, of course, offsets the times when the counts on the different subsystems begin, in particular subsystems D and E, but this is not important if it is assumed that traffic does not vary greatly during this time interval.

Use of Automatic Detectors - As defined in this paper, an input-output study could easily be performed on a routine basis, were it not for the large number of observers needed and the difficulty to log the volumes at exactly the right time. An obvious solution is to use automatic detectors that can record data on real-time basis. Two different solutions will be discussed.

In the first case, a technique is needed that may be used at different locations for short periods of time - measured in minutes, at most a few hours - which implies portable equipment. A 20-pen recorder could be used, but about 10,000 feet of wire would be needed to cover all but the most simple cases.

In the second case, it is desired to obtain data for the purpose of
traffic surveillance and control, which implies fixed equipment. In Detroit, on the National Proving Ground TV Control area, overhead mounted ultra-sonic vehicle detectors are used to obtain directly the volume of traffic. A digital computer receives the information from several detectors defining a closed system.

One of the first tasks of NCHRP Project 20-3 was to have a computer program written that could give more information from the collected data, in particular travel, travel-time, kinetic energy and relative delay. However, it was felt that the automatic detectors actually in use elsewhere on the freeway were not accurate enough, for use in this study, and the relative error is much higher than by using observers. This should not be a deterrent to study the possibility of using automatic detectors at other locations, even if much research and development is needed to perfect a reliable and exact detector or sensor.

As noted by Haynes (26), a detector should be able to send information on the density of traffic flow. Loop detectors can be used to give an estimate of density, as defined above; or long series of loop detectors could provide an exact measure of density. Whichever sensing components are used, the information can be input to a central computer that can tabulate all the data and compute any parameter needed. The continuous series of loop detectors has the properties of both point studies (volume counts, time headways) and space-time continuous studies (real density, space headways, and speed) thus enabling the investigation to perform a systematic evaluation of a network.

Besides the automatic detection system used in Detroit, three similar systems, one in New York (36), one in Chicago (37), and one in Houston (38), exist from which input-output studies can be made, on a routine basis to give information to the traffic surveillance and control systems used at these locations.

Use of Aerial Photographs - In some cases, it may be convenient to use data obtained from aerial photographs to perform input-output studies. The circling airplane technique has been well described by Williams et al. (7), and extensively used with much success on different projects by the Texas Transportation Institute.

The method will be described using a general example. Assume that a plane is circling over the merging point 0 (Figure 8), taking continuous pictures at one-second interval. This point 0 is always visible on the film. Every time the plane has made a complete circle, the same area is visible, say the link a₁-a₂, if the flight pattern is consistent.

The continuous count of vehicles at the merging point 0 (location a₂) gives the total number of vehicles that used the link a₁-a₂ during the study period. The volume of traffic in (vehicles) multiplied by the length, l₀, of the link will give the travel in that section for the time the volume has been measured:
Continuous Count at $a_2$

Flow $= q$

$TT = q \cdot L$

Intermittent Counts on $a_1 - a_2$

Number in the System $= N(t)$

$TTT = \int_0^t N(t) \cdot \Delta t_i$

---

Figure 8. Use of Aerial Photographs to Obtain Travel and Travel Time
\[ TT = n \cdot L_k \]  \hspace{1cm} (28)

The count of the vehicles over the link \( a_1-a_2 \) when it is entirely visible on a photo gives the number of vehicles in the system \( N(t) \) at a particular time, which can be used to determine the total travel-time by simple integration if the time interval \( dt \) are equal, or by summation over all \( \Delta t_i \) if they are not: (Figure 9)

\[
TT = \int_{0}^{T} N(t) \, dt
\hspace{1cm} (29)
\]

\[
TT = \sum_{t=0}^{T} N(t) \Delta t_i
\hspace{1cm} (30)
\]

It is a simple matter to define the other parameters: average speed, kinetic energy, relative delay and interchange ratio.

The major assumption is that the output volume from one link is equal to the input volume to this link during a certain time interval, since the count is made at one location only. This may possibly give some variations in the results if the time interval is quite short, say five minutes, but it has no effect if the interval used is one hour or more, the difference between the total input and the total output being nearly always less than 1\% (39).

It was noted that aerial photographs have serious limitations as a method of study, related particularly to ground coverage, enlargement of picture, flight altitude and response-time, or lag between film-taking and analysis. In some circumstances, this method can be used when a study is needed of special problem areas, such as left-hand merging ramp, a ramp with a high volume of trucks, etc. It could be used when manpower is not readily available, or when the interchange configuration makes it difficult to post observers at any desired location. It would be possible to correlate system studies of this type with the previous point studies made on gap acceptance characteristics (7), and presumably define a relation between these functions and the conditions of traffic, both on the ramp and on the freeway, to supplement the known effects of geometrics.

Possible use of Digital Computers - Although aerial photographs have proved quite effective when used for research purposes, this method may become expensive and time consuming in surveying a large system. A study procedure will be described that eliminates many of the inconveniences found in the different methods discussed above, and has the advantage of being well adapted to research purposes (where data are needed from different freeway systems, involving different combinations of entrance and exit ramps, to determine experimentally a feasible range of optimum combinations.)
Area Under the Curve is Total Travel Time

\[ TTT = \sum_{t=0}^{t} N(t) \cdot \Delta t \]

Figure 9. Travel-Time From Sample Traffic Counts
Briefly, observers log all input and output vehicles in the usual fashion, but instead of recording the cumulative total every five minutes, a major source of errors, they use relay counters. Their signals are transmitted through leased telephone lines to a central computer programmed to process real-time information, and rented a few hours every day for the duration of the field study.

Studies are initialized through a special procedure, to eliminate initial errors: the driver in the signal car sends a radio message to the computer every time he passes by a counting station. The procedure can be repeated as often as necessary, thus defining in time several input-output studies inside a larger one, each one delimited by the passage of the signal car. It has the advantage of freeing the observers from all paperwork, especially cumulative counts and beginning and ending times of the studies.

Computers should be readily available in the cities where studies of this type are necessary, and it should be relatively easy to rent the necessary telephone lines to transmit the signal from the counters to the computer. Some interface equipment is needed between the counter and the telephone line itself, but it should not be difficult to develop. Finally, a computer program could be written to output the required results on any time basis, thus affording an extra measure of flexibility.

Obviously, the costs of such studies may prove to be higher than using the pencil-and-paper approach, but the fact that it virtually eliminates all possibilities of errors should be taken into consideration when preparing an experimental plan.
IV. APPLICATION OF TECHNIQUES

Description of Study Sites

Originally, the Traffic Control and Instrumentation System of the National Proving Ground was located in a 3.2 mile area between the major interchanges of the Lodge Freeway with the Davison Freeway and the Edsel Ford Freeway. Since it was felt that these two interchanges were in a large measure responsible for the congestion on the Southbound Lodge Freeway during most of the day, it was proposed that "detailed operational studies of these two major interchanges (...) be conducted to determine the nature of the problem and the possibilities for its solution" (40).

Three different systems were chosen, and each one is representative of a peculiar condition existing in these two interchanges.

At the Davison-Lodge interchange, two entrance ramps, one from the right side (from eastbound Davison), and one from the left side (from westbound Davison), enter the Freeway simultaneously and immediately downstream, the Glendale entrance ramp is added. To complicate the operations of this bottleneck further, the large volume of trucks entering the Lodge Freeway from the left-hand on-ramp has to weave across three traffic lanes to satisfy the local regulations that heavy trucks have to use the two right lanes.

The same description applies to the Lodge-Ford interchange, where westbound traffic on Ford is successively increased by two simultaneous entrance ramps from the Lodge Freeway and one entrance ramp from Trumbull Street.

The third system is somewhat different, since it involves an on-ramp, Milwaukee, on the southbound Lodge Freeway immediately preceding two simultaneous exit ramps to the Ford Freeway, one to the left and one to the right.

At the first two locations, data were collected for three consecutive days and for two days at the third locations. The studies were conducted for at least one hour, extending from a few minutes before 10:00 A.M. to a few minutes past 11:00 A.M. in every case (Table 1), in order to make sure that the studies lasted for at least one hour.

Flow maps for average traffic conditions (from 10:00 to 11:00 on weekdays) are given in Appendix B.

Data Reduction and Processing

Two different data systems are analyzed: conventional input-output studies and aerial photographs, and this section is divided accordingly.
<table>
<thead>
<tr>
<th>STUDY DAY</th>
<th>LOCATION</th>
<th>SYSTEM NUMBER</th>
<th>TIME</th>
</tr>
</thead>
<tbody>
<tr>
<td>42</td>
<td>SB Lodge-Davison</td>
<td>IV-A</td>
<td>10:00-11:00</td>
</tr>
<tr>
<td>42</td>
<td>SB Lodge-Glendale</td>
<td>IV-B</td>
<td>11:18-12:18</td>
</tr>
<tr>
<td>78</td>
<td>SB Lodge-Davison</td>
<td>I</td>
<td>09:55-11:05</td>
</tr>
<tr>
<td>79</td>
<td>SB Lodge-Davison</td>
<td>I</td>
<td>09:50-11:05</td>
</tr>
<tr>
<td>81</td>
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<td>I</td>
<td>09:56-11:07</td>
</tr>
<tr>
<td>85</td>
<td>WB Ford-Lodge</td>
<td>II</td>
<td>09:51-11:03</td>
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<tr>
<td>86</td>
<td>WB Ford-Lodge</td>
<td>II</td>
<td>09:53-11:03</td>
</tr>
<tr>
<td>87</td>
<td>WB Ford-Lodge</td>
<td>II</td>
<td>10:00-11:05</td>
</tr>
<tr>
<td>89</td>
<td>SB Lodge-Ford</td>
<td>III</td>
<td>09:56-11:03</td>
</tr>
<tr>
<td>90</td>
<td>SB Lodge-Ford</td>
<td>III</td>
<td>09:58-11:06</td>
</tr>
</tbody>
</table>
Conventional Input-Output Studies - Each of the three systems analyzed are comprised of six links: three of these six links are always completely defined by an input count and by an output count; two of the links are defined by either an input or an output, and one link is not defined at all. It is possible to obtain values of any parameters on the three completely defined links, and an estimate of the same on the three other links taken together. Of course, it is possible to obtain these values for the total system. Briefly, there are eight counts and four subsystems, plus a total system. The characteristics of each subsystem are shown in Tables 2 and 3 which give respectively the locations of the observers and the lengths of the links.

A computer program was written to perform the computations in the particular case where there are up to six input counts, up to ten output counts, up to six links and up to fifty time intervals. The program could be made more general by increasing the fields for input and output counts, number of links, and time intervals, which is relatively easy to do; and also by enabling the program to process any system configuration, or any combination of input and output counts, which could rapidly become a problem if the system is complicated and built in a free-form instead of a trunk-form. The program will not perform any sensitivity analysis other than setting back to zero a negative number of vehicles in the system. Finally, because of the impossibility for the program to build the system configuration from the input data, the initial number of vehicles on each link has to be given as input information (Table 4). However, this is not a major restriction, since this initial number is a good indication of the value of a particular set of data, and has to be known before the data are processed.

The program provides the following information for each five-minute interval and for each subsystem: number of vehicles in the subsystem, travel, travel-time, average speed, kinetic energy and density. Summation of these parameters, where appropriate, is made over the total system at each five-minute interval: total inflow to the system, total outflow from the system, accumulation and total number of vehicles in the system, travel, travel-time, average speed, kinetic energy and density. Summation is also made over the total study period on each subsystem and on the total system, giving a grand total inflow, a grand total outflow, and accumulation, in addition to the other parameters mentioned above.

Since this paper is concerned mainly with the feasibility of input-output studies, delay rates and interchange ratios have not been computed. They would be used in a before-and-after study, where the effects of some changes in the systems need to be evaluated.

A major problem in reading and processing the data is to detect counting and timing errors, and correct them. Table 5 gives closure errors using typical data. The errors appear quite small, especially when all vehicles are considered, and a brief examination of the data will show that other errors may be more important than the closure errors. For instance, on day 89, the closure error for the total system
TABLE 2

OBSERVATION POINTS

<table>
<thead>
<tr>
<th>SYSTEM</th>
<th>NODE</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>a₁</td>
<td>Lodge Freeway at Nose of SB to EB ramp</td>
</tr>
<tr>
<td></td>
<td>a₂</td>
<td>Lodge Freeway at Nose of EB to SB ramp</td>
</tr>
<tr>
<td></td>
<td>c₂</td>
<td>Lodge Freeway at Monterey Overpass</td>
</tr>
<tr>
<td></td>
<td>d₁</td>
<td>WB to SB ramp at Davison</td>
</tr>
<tr>
<td></td>
<td>d₂</td>
<td>WB to SB ramp at Lodge</td>
</tr>
<tr>
<td></td>
<td>e₁</td>
<td>EB to SB ramp at Davison</td>
</tr>
<tr>
<td></td>
<td>e₂</td>
<td>EB to SB ramp at Lodge</td>
</tr>
<tr>
<td></td>
<td>f₂</td>
<td>Glendale on-ramp at Lodge</td>
</tr>
<tr>
<td>II</td>
<td>a₁</td>
<td>Ford Freeway at Nose of WB to SB ramp</td>
</tr>
<tr>
<td></td>
<td>a₂</td>
<td>Ford Freeway at Nose of SB to WB ramp</td>
</tr>
<tr>
<td></td>
<td>c₂</td>
<td>Ford Freeway at Fourteenth Street Bridge</td>
</tr>
<tr>
<td></td>
<td>d₁</td>
<td>NB to WB on-ramp at Lodge</td>
</tr>
<tr>
<td></td>
<td>d₂</td>
<td>NB to WB on-ramp at Ford</td>
</tr>
<tr>
<td></td>
<td>e₁</td>
<td>SB to WB on-ramp at Lodge</td>
</tr>
<tr>
<td></td>
<td>e₂</td>
<td>SB to WB on-ramp at Ford</td>
</tr>
<tr>
<td></td>
<td>f₂</td>
<td>Trumbull on-ramp</td>
</tr>
<tr>
<td>III</td>
<td>a₁</td>
<td>Lodge Freeway at Milwaukee Overpass</td>
</tr>
<tr>
<td></td>
<td>c₁</td>
<td>Lodge Freeway at Nose of SB to WB off-ramp</td>
</tr>
<tr>
<td></td>
<td>c₂</td>
<td>Lodge Freeway at Nose of EB to SB ramp</td>
</tr>
<tr>
<td></td>
<td>d₂</td>
<td>Milwaukee on-ramp (SB)</td>
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<td></td>
<td>e₁</td>
<td>SB to WB off-ramp at Lodge</td>
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<tr>
<td></td>
<td>e₂</td>
<td>SB to WB off-ramp at Ford</td>
</tr>
<tr>
<td></td>
<td>f₁</td>
<td>SB to EB off-ramp at Lodge</td>
</tr>
<tr>
<td></td>
<td>f₂</td>
<td>SB to EB off-ramp at Ford</td>
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<td>SYSTEM</td>
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<td>B</td>
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<td>--------</td>
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<td>-----</td>
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<tr>
<td>I</td>
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<td>1400</td>
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<tr>
<td>IV-A</td>
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</tr>
<tr>
<td>IV-B</td>
<td>1700</td>
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注释：
- IV-A: (WB to SB On-ramp on Lodge)
- IV-B: (SB Lodge from Nose of WB to SB On-ramp on Lodge)
TABLE 4
INITIAL NUMBER OF VEHICLES

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<tr>
<th>SYSTEM</th>
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<th>LINKS</th>
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<th>SYSTEM</th>
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<td></td>
<td></td>
<td></td>
<td>A</td>
<td>C</td>
<td>D</td>
</tr>
<tr>
<td>I</td>
<td>78</td>
<td>All</td>
<td>-32</td>
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<td>0</td>
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<td></td>
<td></td>
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<tr>
<td></td>
<td>79</td>
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<tr>
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<td>1</td>
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<td></td>
<td>Trucks</td>
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<td>-1</td>
</tr>
</tbody>
</table>

\(a\) All denotes all vehicles  
\(b\) T denotes Trucks, excluding panels and pickups  
\(c\) \(\text{Sum} = a_2 + d_2 + e_2 - f_2 - c_2\) (LINK 4)  
\(d\) \(\text{Sum} = a_4 + d_4 - c_1 - e_1 - f_1\)  
\(e\) \(\text{Total} = a_1 + d_1 + e_1 + f_2 - c_2\)  
\(f\) \(\text{Total} = a_4 + d_4 - c_2 - e_2 - f_2\)
<table>
<thead>
<tr>
<th>SYSTEM</th>
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<th>LINKS</th>
<th>TOTAL SYSTEM</th>
<th>% OF TOTAL</th>
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<td>A</td>
<td>C</td>
<td>D</td>
</tr>
<tr>
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<td>T</td>
<td>-9</td>
<td>3</td>
<td>-1</td>
</tr>
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</table>

^a All denotes All vehicles, including trucks
^b T denotes Trucks excluding panels and pickups
^c Error = \(a_1 + d_1 + e_1 + f_2 - c_2\)
^d Error = \(a_1 + d_2 - c_2 - e_2 - f_2\)
is 10 vehicles, a relative error of 0.32%; but the initial number in the total system is negative, and unless this number is made equal to zero, the subsequent values for the number in the system will always be negative, giving negative travel time, speed, density and kinetic energy. When it is set initially equal to zero, the subsequent values are so low -- they never catch up with the initial negative value -- that fantastic speeds and extremely low densities are obtained (Table 6).

In this latter case, one probable course of error is an error of timing by the observer at $a_1$, since, between 10:10 and 11:05, the number of vehicles in the system is always zero on link 4 (subsystems A, B and D on Figure 7). The same explanation holds for day 90, where high system speeds (between sixty and two hundred miles per hour) may be due to the fact that travel-time is null on link between 10:10 and 11:05.

Errors may also occur when the initial number in a subsystem is too high: for instance, on day 78, there are initially 39 vehicles on link A, which increase travel-time on this link and on the whole system, thus decreasing speeds to almost half of what they are on days 79 and 81.

Aerial Photographs - The subsystem analyzed is located at the Davison-Lodge interchange, and comprises the area visible around the nose of the entrance ramp from the left into the southbound Lodge. Filming time extended for one hour, and the plane took approximately one minute to complete a circle around the designated point.

The data collection, reduction, and analysis techniques have been described in the previous section. A computer program was written to define the travel, the travel-time, the average speed, the kinetic energy and the average density at every five-minute interval over the left-hand entrance ramp from westbound Davison to Southbound Lodge.

Contrary to the conventional type of input-output study, this method (if filming technique is carried out successfully) is practically fool-proof. The major source of error would be that the central point would disappear from the camera field for a few seconds so that the counts would no longer be continuous. Another error source would be vehicles hidden from view by structures such as underpasses.

Significance of Results

Despite the fact that the data were unusable on some days and that they were somewhat inexact and imprecise, this study has shown that much system information can be gathered from an input-output study. It may be possible, for instance, to determine the effect of a ramp closure on a freeway section by studying the variations in travel and travel time on the part of the freeway and on the street system that would be affected by this change. An increase in travel, a decrease in travel time, or both, may indicate a sensible amelioration of the traffic
<table>
<thead>
<tr>
<th>STARTING TIME</th>
<th>78</th>
<th>79</th>
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NOTE: The data from days 81, 85, 89, and 90 were voided by procedural or counting errors by the field personnel.
flow on the freeway, but it may also indicate a worsening of the operations on the street system by a decrease in travel and increase in travel time. However, the algebraic sum of the changes may show a real benefit. For instance travel time on the whole system may be decreased.

The results show that the input-output study is very sensitive to the conditions of traffic on any subsystem: the various parameters of travel, travel time, speed, density, kinetic energy, are much more variable when taken on a short, light-traveled ramp, where relative errors in counting or initializing have the greatest importance than on a long stretch of freeway. A direct consequence of this property is that continuous input-output counts can be used to monitor traffic flow if the time lag is short enough, say a few seconds time lag being the sum of the collection time and the computation time. Obviously, detectors must be highly reliable, since the shorter the time interval used, the more weight has a single vehicle on the values of the different parameters.

Aerial photo techniques provide the more accurate means for determining the number of vehicles in a system, N(t), and therefore the more accurate means of measuring total travel time, TT. Ground observers, without the necessity of recording counts and times, provide the more accurate means of measuring volume inputs and outputs, Vin and Vout, and therefore total travel, TT. It would seem, therefore, that the most desirable technique for a study of a major interchange would be a combination of the two methods.

The aerial photos would provide a measure of the vehicles in a system or subsystem but not necessarily on a continuous basis as would be required for a volume counts. Therefore, a flight might record data for several subsystems by making several passes over the system under study during the study period.

In summary, the recommended study technique would be one where ground observers or highly accurate detectors, feed count data directly to a computer for collection and processing. Aerial photos would provide data on the number of vehicles in the system. Knowing total travel and total travel time from the above data collected in the above-described techniques, an accurate determination is possible for density, speed, and kinetic energy.

Effect of Trucks on Traffic Flow

The effect of trucks on the traffic flow was tentatively evaluated by taking a separate count of trucks, and performing all computations for trucks exclusively (Table 7). The average speeds should be lower, and in general, they seem to be lower than when all vehicles are considered. But the closure errors for trucks are consistently higher than for all vehicles, pointing to an unreliable method of counting trucks and to the insufficient size of the sample.
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**NOTE:** The data from days 78, 89, and 90 were voided by procedural or counting errors by the field personnel.
The average speeds of trucks on system I (days 79 and 81) are consistently lower than on system II (days 85, 86, and 87), which is probably due to the fact that a large number of trucks are entering the southbound Lodge Freeway through the left hand entrance ramp from westbound Davison, and have to weave across two lanes of traffic once they are on the freeway to comply with the local regulation that trucks have to travel in the shoulder lane. This problem is not new, at least not in Detroit: since the early fifties, Detroit has tried to live harmoniously with its truck population (41). At that time, interested parties: city traffic engineers, trucking firms and their principal clients, the auto-makers, were called at a conference to solve the "truck problem". Evidently, the same problems still exist, even after fifteen years, and the best and ultimate solutions have not yet been found.
V. CONCLUSIONS

This section will give a brief resume of the paper, and will point out improvements in the study methods.

a) The input-output study is essentially a systems analysis, and as such is not limited to the study of any single component of the traffic flow. Rather it permits the measurement and evaluation of traffic flow as a whole, whatever the location, type and geometrics of the roadway, and whatever the kind and composition of traffic.

b) Two basic methods have been investigated. Both are capable of measuring the behavior of a system, both permit the investigator to look at a large area in a continuous fashion. But each technique has drawbacks. The conventional input-output studies rely too much on the observers to take precise note of both time and number of vehicles to be of much use for research purposes. Aerial photographs have inherent "mechanical" technique problems. Further, the aerial photos may present problems on a large system.

c) This paper has pointed out that major errors can result from small counting errors, and it has been shown that observers alone can not make the counts sufficiently precise and exact so that the final errors can be neglected. It should not be concluded that detectors would solve this problem, since in at least one instance, they have been shown to be inferior to observers.

d) This paper has also suggested that attention be given to the units of the different parameters used, particularly travel, travel-time, speed, and kinetic energy. It should be remembered that travel is an expression of vehicle-miles over a certain length of roadway, but that is has to be measured over a unit of time interval, be it five minutes or one hour. Similarly, travel-time, expressed in vehicle-hours, has to be measured over a unit length of roadway, say one mile. This will ensure that speed is measured both in time and in space, while kinetic energy, being a point variable, has to be converted to unit time and unit distance.

e) The most desirable technique in the input-output analysis would be one where aerial photographs are used for determination of total travel time and ground counts, fed directly into the computer, are used for total travel. This technique may be too costly for some purposes but in view of the accuracy of the data, it most certainly has application possibilities.
VI. REFERENCES


APPENDIX A

\( t \) - time

\( t_A \) - time when A begins his count

\( t_B \) - time when B begins his count

\( t_0 \) - beginning time (first time after \( t_A \), multiple of 5 minutes)

\( t_i \) - time \( i \) minutes after \( t_0 \)

\( T_x \) - time interval of \( x \) hours, unless otherwise indicated

\( N(t) \) - number of vehicles in the system at time \( t \)

\( \text{CUMin}(t) \) - cumulative input volume at time \( t \)

\( \text{CUMout}(t) \) - cumulative output volume at time \( t \)

\( \text{Vin}(t) \) - input volume during period ending at \( t \)

\( \text{Vout}(t) \) - output volume during period ending at \( t \)

\( K_T^\ell \) - average density during time period \( T \) over section \( \ell \)

\( L^\ell \) - length of section \( \ell \)

\( T_T^\ell \) - total travel over section \( \ell \) for time period \( T \)

\( TTT_T^\ell \) - total travel time over section \( \ell \) for time period \( T \)

\( U_T^\ell \) - average speed during time period \( T \) over section \( \ell \)

\( \text{KE}_T^\ell \) - average kinetic energy during time period \( T \) over section \( \ell \)

\( q \) = flow in vehicles per hour

\( k \) = concentration in vehicles per mile

\( u \) = average speed in miles per hour

\( n \) = number of vehicles during study period \( T \) (hour)

\( d \) = constant (no units)
APPENDIX B

Figure B-1. Traffic Flow Map

Study Site I (10:00 to 11:00 A.M.)
Upper Figure: Total Hourly Flow
Lower Figure: Percentage of Trucks

Study Site II (10:00 to 11:00 A.M.)

Figure B-2. Traffic Flow Map
Figure B-3. Traffic Flow Map

Study Site III (10:00 to 11:00 A.M.)

Upper Figure: Total Hourly Flow
Lower Figure: Percentage of Trucks