A Quantitative Evaluation of Traffic in a Complex Freeway Network

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The proposition that travel time is a fundamental dependent variable in the analysis of transportation systems is developed along with several corollary concepts. The proposition and some of the derived concepts are then put to test in a detailed investigation of traffic in a part of the freeway network in downtown Los Angeles. The network of interest includes two "input" freeways (the Santa Ana and San Bernardino Freeways), three "output" freeways (the Harbor, Hollywood, and Pasadena Freeways), and three intervening on-ramps and one off-ramp which come into the network between the input and output freeways.

License plate methods, including dictation into portable tape and wire recorders and high-speed photography, are used to obtain both travel time and the relative percentages of traffic flow in all the combinations of input-output freeways as well as freeway-ramp combinations. Speeds and headways are measured by lane at the output boundary of the network of interest which is on a freeway proper. Other covariates are classified volume counts which also are by lane on the output boundary. A novel mailing questionnaire is used to establish the surface street paths drivers pursue to get to the on-ramps of the network. In light of a response of the order of 60 percent of the original mailing of 400 questionnaires, the particular techniques used, appear to be quite promising for application to more extensive networks.

Representative of the hypotheses tested are: the effect of on- and off-ramp traffic on network travel time; the effect of multi-axle vehicles on network travel time; (deduced) effects that opening planned additional links of the freeway system will have on the existing network; (deduced) effects that closing a ramp would have on the network as well as the adjacent surface streets.

Besides providing a quantitative description of traffic in the selected network, the study demonstrates that mathematical models based on travel time can be applied to real situations. Although there can be no formal proof of the importance of these models, the fact that they yield useful information in this case suggests that more general applications might be considered.

●A NUMBER OF SITUATIONS have recently been reported in various parts of the country in which decisions have had to be made to change some operational aspect or physical feature of an existing high-performance transportation facility such as a freeway network. Many more decisions of a similar nature will, no doubt, have to be made in the future, partly because the state of the art of land-use planning has not progressed to where evolving land use can be reliably predicted, and partly because the transportation art has not progressed to where the interactions between freeway networks and changing land uses in a burgeoning metropolitan region can be understood.

An emergent need, therefore, will be for increasingly rigorous measurements of freeway systems. These measurements will represent mandatory inputs into any decision-making process to alter the facilities in any way.

The immediate purpose of this paper is to present methods for quantitatively evaluating the performance of a freeway network or a section thereof pursuant to decision-making on changes to improve network performance. The methods are then demonstrated in a study performed in a relatively complex section of a heavily traveled freeway network in downtown Los Angeles. The underlying operational decision in this study concerns the closing of a particular on-ramp, but the ultimate disposition of this problem is not germane to this paper; it is only the methodology that is being emphasized here.

Included in the methodology are certain field techniques that were developed specifically for measuring freeway performance under high-speed, high-volume conditions with minimum disturbance, if any, of traffic. The measurements are inputs into a mathematical model of traffic flow in a network with travel time as the fundamental dependent variable. This concept is not entirely new, for a number of studies have been published which in essence treat traffic in this, or some related manner (1, 2, 3, 4, 5, 6, 7). The difference lies in the manner in which the concept is applied to the movement of ensembles or collections of vehicles through complex networks of flow paths rather than to the movement of a single vehicle.

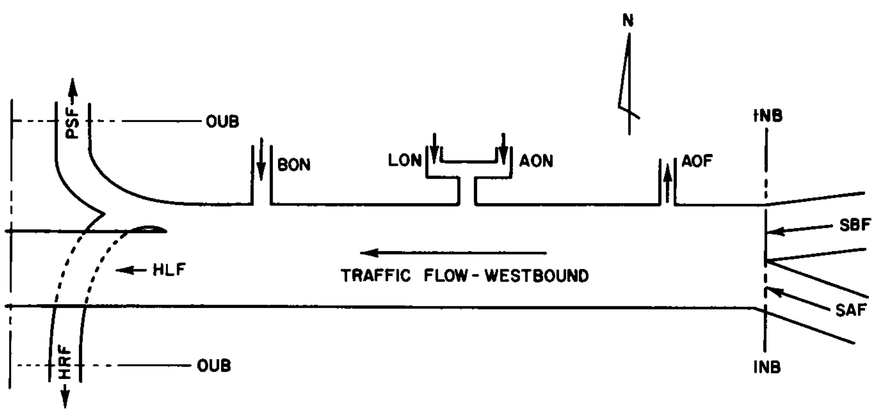
Finally, a more or less peripheral purpose of this paper is to demonstrate a nomenclature that was directly suggested by FORTRAN language used in writing programs for the IBM 709 computer. This computer was used in this study for computing speed, headway, and several other properties of the observed traffic.

NOMENCLATURE

A section of the freeway network in Los Angeles is designated as the "system-of-interest" or simply "system" as shown in Figure 1, and approximately to scale in Figure 2. Figure 3 shows the freeway links which either are under construction or are programmed in the Los Angeles area, and the completion of which might affect the performance of the system of interest.

The primary traffic flow in the system is from east to west so that an imaginary line to the east is defined as the input boundary, INB, of the system, whereas an imaginary line to the west is defined as the output boundary, OUB, of the system.

Input traffic at INB is from either of two freeways, the Santa Ana Freeway, SAF, or the San Bernardino Freeway, SBF. Output traffic is to either of three freeways: the



OUB - Output Boundary
PSF - Pasadena Freeway
HLF - Hollywood Freeway
HRF - Harbor Freeway

BON - Broadway Avenue On-Ramp
LON - Los Angeles Street On-Ramp
AON - Alameda Avenue On-Ramp
AOF - Alameda Avenue Off-Ramp

INB - Input Boundary
SBF - San Bernardino Freeway
SAF - Santa Ana Freeway

Figure 1. Schematic diagram of system of interest.

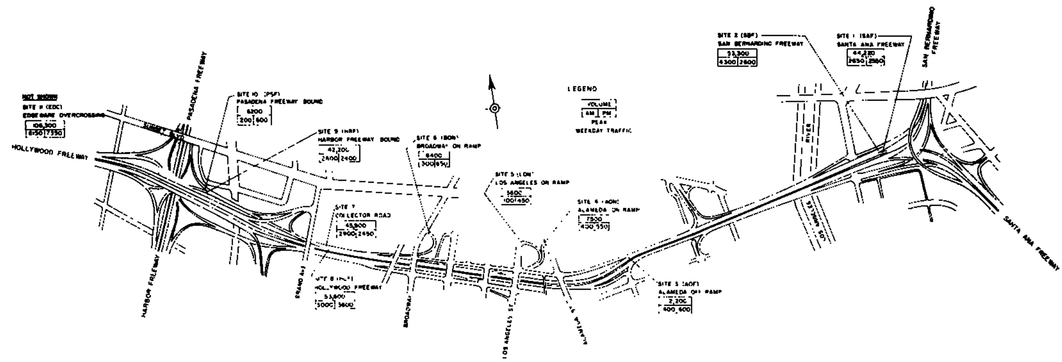


Figure 2. The system of interest as a part of the freeway network.

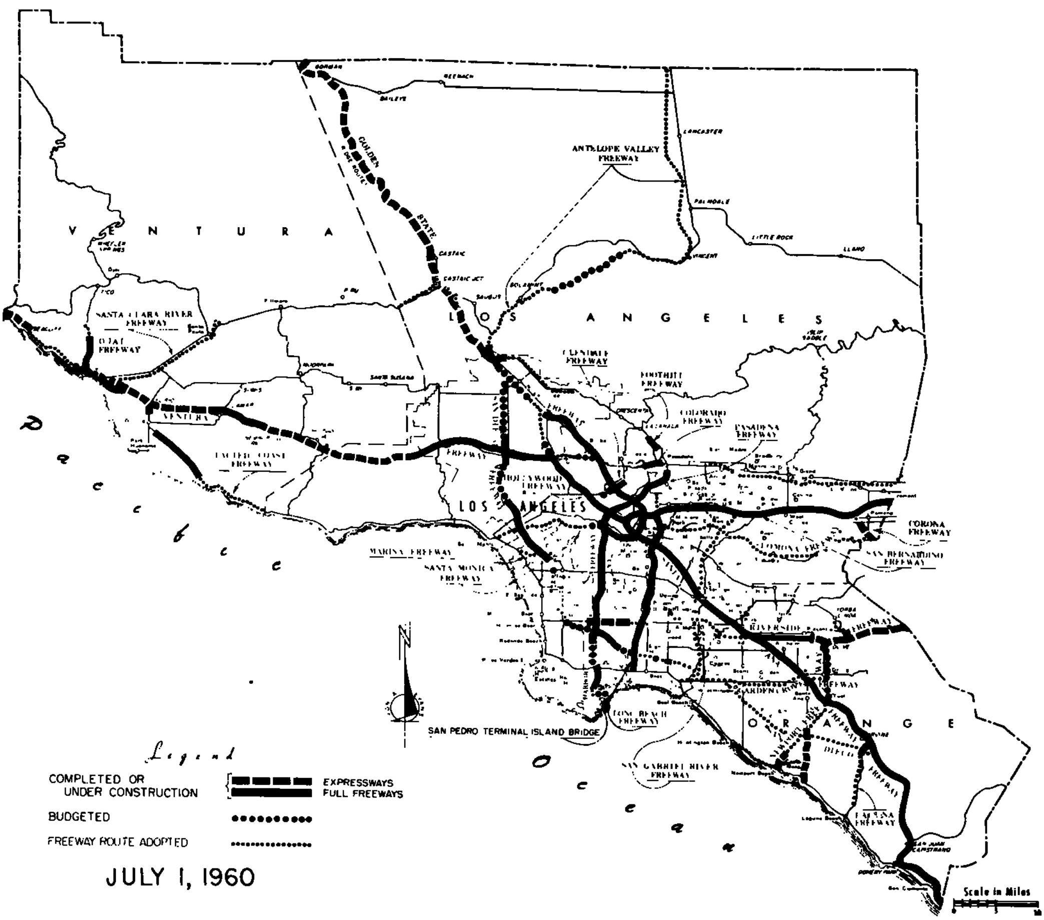


Figure 3. District VII freeways, State of California.

Hollywood Freeway, HLF; the Harbor Freeway, HBF; the Pasadena Freeway, PSF. The HLF traffic continues westbound, PSF traffic is northbound, HBF traffic is southbound. The additional input traffic into the system is via three on-ramps: Broadway Avenue, BON, Alameda Street, AON, and Los Angeles Street, LON. Additional output traffic leaves the system at the Alameda off-ramp, AOF. All three on-ramps and the one off-ramp are between INB and OUB.

Traffic of interest is identified in two ways: first, according to input and output sites; and second, by performance expressed in travel time.

General

System boundaries

INB	input boundary
OUB	output boundary

On-ramps of interest

BON	Broadway on-ramp
LON	Los Angeles on-ramp
AON	Alameda on-ramp

Off-ramp of interest

AOF	Alameda off-ramp

Freeways

SBF	San Bernardino Fwy
SAF	Santa Ana Fwy
HRF	Harbon Fwy
HLF	Hollywood Fwy
PSF	Pasadena Fwy

Ramp status

O	ramp open
C	ramp closed (hypothesized)

Examples:

BONO	Broadway on-ramp open
BONC	Broadway on-ramp closed

Compound attributes (examples)

(SAF) (HRF)	traffic going from SAF to HRF (Santa Ana Fwy to Harbor Fwy), or traffic at SAF going to HRF.
(HRF) (SAF)	traffic at HRF coming from SAF, or traffic going from HRF to SAF.

Operators

N ( )	"number of" operator; specifically, number of vehicles (volume) having attribute shown in parentheses.
P [( ) ( )]	"percentage of" operator; specifically, percentage of vehicles having attribute shown in first parentheses also having attribute in second parentheses.

Examples:

N (SAF) (HRF)	number of vehicles going from SAF to HRF.
P (SAF) (HRF)	percentage of vehicles at SAF that go to HRF.

Vehicle Attributes

I	the I^{th} vehicle.
CLT	clock time, or time of day.
TRT	travel time.
RSP	reciprocal speed, where if travel time is measured over a distance C:

$$RSP = \frac{(TRT)}{C} = \frac{[CLT\ (OUB)] - [CLT\ (INB)]}{C}$$

CLT (I. INB) = clock time at which the I^{th} vehicle crosses the input boundary of the system; that is, the time of day the I^{th} vehicle enters the system.

CLT (I. OUB) = clock time at which the I^{th} vehicle crosses the output boundary of the system; that is, the time of day the I^{th} vehicle leaves the system.

RSP (I. OUB) = reciprocal speed of I^{th} vehicle measured at output boundary; the distance C over which the travel time is measured is sufficiently small to justify treating RSP as applying to point OUB.

TRT (I. INB-OUB) = travel time of I^{th} vehicle in moving from input to output boundary of the system:

TRT (I) (INB=OUB) = CLT (I. OUB) - CLT (I. INB)

MEASURE OF EFFECTIVENESS

The measure of effectiveness in this study is the summation of individual travel times for all vehicles arriving at the system or the adjacent surface street network during some arbitrarily chosen interval of clock time to clear the output boundary of the system or surface street network (whichever applies). Symbolically:

CLT (1-2) CLT (1) to CLT (2) (1)

N (INB. CLT 1-2) number of vehicles arriving at INB during CLT 1-2 (2)

N (BON. CLT 1-2) number of vehicles arriving at BON during CLT 1-2 (3)

N (SSN. CLT 1-2) number of vehicles arriving at SSN (surface street network) during CLT 1-2 (4)

TRT (I. INB) travel time of the I^{th} vehicle arriving at INB of the system to clear OUB of the system

CLT (I. OUB) - CLT (I. INB) (5)

$$\text{TRT (INB. CLT 1-2)} \quad \sum_{I=1}^{I=N\text{ (INB. CLT 1-2)}} \text{TRT (I. INB)} \tag{6}$$

MOE (CLT 1-2) the measure of effectiveness for CLT 1-2

$$\sum_{\text{all sets}} \text{TRT (set. CLT 1-2)} \tag{7}$$

where the sets include:

N(INB. CLT 1-2), N(LON. CLT 1-2), N(AON. CLT 1-2)
N(BON. CLT 1-2), N(SSN. CLT 1-2)

OVER-ALL STRUCTURE OF THE STUDY

The measure of effectiveness as defined in Eq. 7 is to be quantified by direct field measurements and certain questionnaire techniques for what would normally be regarded as "before" performance of the system. The "before" here means prior to some operational decision; for example, to close an on-ramp. However, there are no complementary "after" experimental measurements because all operational decisions here are only hypothetical. Accordingly, "after" performance can be arrived at solely by analysis. The general study will, therefore, compare a measured MOE with one arrived at by analysis.

The general study is comprised of several sub-studies, each of which provides one or more of the required inputs to the general problem of the MOE comparisons. However, each sub-study essentially is a complete study within itself, and could be profitably pursued in less general contexts. The sub-studies are listed here briefly to show how they fit into the general plan, and are detailed more fully in the next section.

Sub-study 1—ascertains the spectrum of trip lengths originating at on-ramps of interest.
Sub-study 2—ascertains the pattern of surface street routes traffic follows in getting to the various on-ramps of interest.
Sub-study 3—seeks to estimate properties of the traffic stream at the output boundary of the system.
Sub-study 4—seeks to establish travel time needed to negotiate the "system" over various paths (that is, input-output combinations) and any attendant TRT diseconomies.
Sub-study 5—seeks to estimate the relative traffic volumes using the different possible input-output combinations of the freeway network.

Field measurements were conducted on two days, a Sunday and a weekday. On each of these days the sampling was limited to four 15-min periods in the off-peak hours and a single 1-hr period during the afternoon peak. Because the primary purpose of this paper is to present the technique and underlying logical framework, the data analysis is limited to one 15-min off-peak period and one 1-hr peak period. Clearly, pursuant to any actual operational decision-making (which is not the purpose here), the sampling would have to be broadened.

CONCEPTUAL FRAMEWORK

The "Collection"

The measure of effectiveness as stated in Eq. 7 pertains to a specific group of vehicles; namely all vehicles arriving at the system or at the adjacent surface street network during a specified time interval. This group of vehicles will be referred to as "the collection". The collection is specific to the specified time interval which may be arbitrarily varied to reflect any given operational problem or situation. For example, there could be "the afternoon peak collection" which would include the vehicles arriving during the 2-hr interval corresponding to the afternoon peak.

It is assumed here that the total number of vehicles in the collection remains constant once the defining clock time interval is established. There might be some redistribution of the vehicles in the collection among the different route possibilities after some operational change. For example, some freeway users might become surface street users, or users of a given ramp might use a different ramp, etc. But the total number of vehicles, although redistributed, would be the same for that clock interval. A higher order analysis would, of course, permit the size of the collection to change as a consequence of the operational change, but this study is limited to the more simple analysis.

Inasmuch as the analysis is centered on the properties of the collection rather than of the single vehicle, it is referred to here as "macroscopic"; the single-vehicle type of analysis, in contrast, could be referred to as "microscopic". There already has been extensive theoretical work on microscopic flow as, for example, the movement of the individual vehicle in the stream as reported in various publications on car following theory (8, 9, 10). However, very little work has been done on macroscopic theory as defined here.

(It is interesting to note that macroscopic analyses of physical systems in the classical thermodynamic mode have been yielding highly useful engineering solutions to practical problems for many years, well before the microscopic treatments of statistical mechanics were conceived. There are, of course, many problems today which can be attacked only with statistical mechanics. However, the results are accepted as valid when they do not conflict with whatever classical measurements can be made of macroscopic properties such as temperature or pressure.)

(In transportation theory, on the other hand, microscopic treatments have preceded macroscopic. Accordingly it might be speculated that the absence of macroscopic work is one explanation why theorists have not produced many solutions to immediate problems confronting planners, designers, and ultimately the operators of vital transportation systems.)

Because the collection is defined by a specified time interval, its size (number of vehicles) is a random variable which could have been taken as the measure of effectiveness instead of travel time. In fact, such "volume" models generally characterize much of the work in transportation theory and practice; for example, the volume of traffic clearing a system within a specified time period. There are, however, several reasons why volume is not selected as the measure of effectiveness in this analysis, although it still enters as a covariate to the selected measure, travel time.

Ambiguous Meaning of Low Volume.—A low flow rate expressed as vehicles per unit time can mean that either of two situations prevail: first, there is not much demand no matter how congested or uncongested the system might be; second, there is a high degree of congestion. To identify the situation, additional information is needed, usually involving some form of time measurement.

Non-Definitive Meaning of High Volume.—In the analysis of traffic flow in a network, a high volume or flow rate at the output boundary of the network gives no indication of network conditions, any number of which could be compatible with the high output rate. Although all would be equivalent in this regard, they might be vastly different from the standpoint of over-all network performance. For example, suppose that the flow at some output boundary of a freeway were at the maximum possible rate of 2,200 vehicles per lane per hour, but at the same time the queue of traffic waiting to enter the system continued to lengthen as a result of input rates upstream being greater than the maximum possible output rate at the output boundary. From the volume standpoint, the network would be operating at maximum capacity. However, it could well be that short trip users of the system could be causing an unreasonable increase in the travel time of the long trip users. Thus, from the travel time viewpoint the network would not be operating optimally, even though the output flow was at a maximum rate.

Insufficiency of Volume as a Network Variable.—The critical transportation problem today in metropolitan regions involves the daily home-to-work travel cycle of drivers on surface street and freeway networks. The volume demands on the network on any given day are essentially constant; sooner or later, that collection of vehicles is serviced (that is, all drivers get to their destinations). Therefore the size of the collection—that is, the volume of traffic—cannot possibly be sufficient for describing network performance. The variable aspect is the travel time that each vehicle devotes to its homework travel cycle, or the aggregate travel time for the collection as a whole.

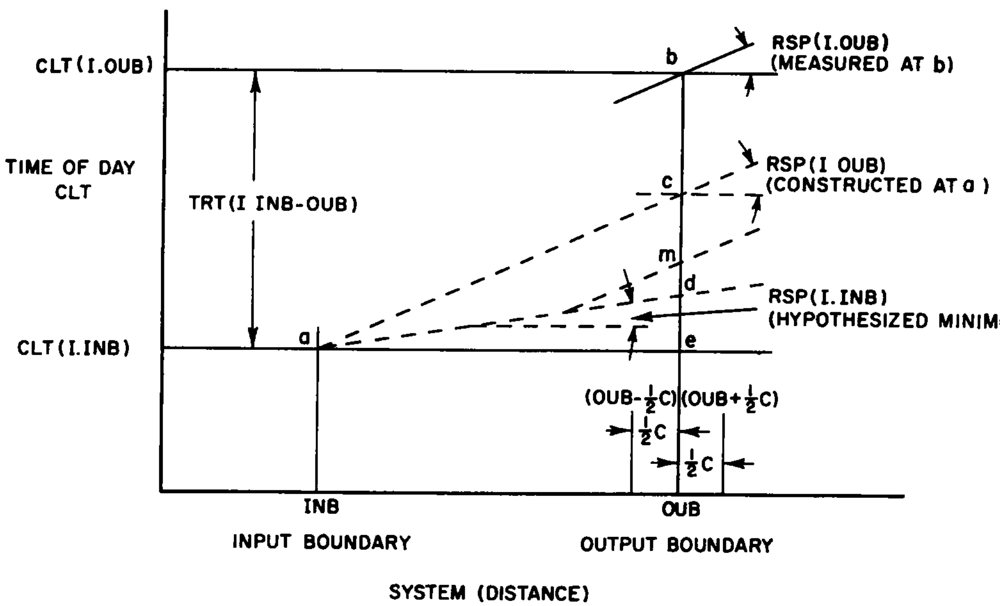


Figure 4. Travel time of the I[th] vehicle in the system.

Average speeds that can be maintained are often used to describe this variable aspect of network performance. However, the travel distance in the aggregate for the collection is also a constant because the large masses of people do not change their home or place of work from one day to the next. Therefore, including the distance-traveled aspect into the argument, as is implicit in determining average speeds, adds nothing to the analysis.

"TRT" Diseconomies

Consider that the I^{th} vehicle, in entering some system of interest, crosses the defined input boundary INB of the system at some clock time CLT (I. INB). This is represented by point a in the "time-system" space shown in Figure 4. The vehicle later leaves the system, crossing the output boundary OUB at CLT (I. OUB) as represented by point b. By definition, its TRT (the elapsed time while it was negotiating the system) is given by:

$$\text{TRT (I. INB(OUB)} = \text{CLT (I. OUB)} - \text{CLT (I. INB)} \tag{8}$$

The sub-system now is defined as being centered on OUB, with its input boundary at (OUB - ½ C) and its output boundary at (OUB + ½ C). If C is sufficiently small relative to the distance between INB and OUB, then the travel time of the I^{th} vehicle over the sub-system may be considered as the travel time at OUB. This will be assumed to be the case here, so that the reciprocal speed RSP (travel time per unit distance) measured over C can be treated as the RSP at OUB.

$$\text{RSP (I.} \left[(\text{OUB} - \tfrac{1}{2}\text{C}) - (\text{OUB} + \tfrac{1}{2}\text{C})\right]) = \text{RSP (I. OUB)} \tag{9}$$

if

$$\text{C} << (\text{INB} - \text{OUB})$$

In Figure 4, line ac constructed at point a with slope RSP (I. OUB), intersects the OUB ordinate at point c. Line ad is also constructed at point a, but with slope RSP (I. INB). If RSP (I. INB) is a minimum, which would identically imply that speed was a maximum, then point d at the intersection of ad with the OUB ordinate would identify the minimum time it would take a vehicle to travel from INB to OUB. Because the vehicle actually arrives at some later time signified by point b, the length db represents a travel time diseconomy that somehow was incurred by the I^{th} vehicle. The order of magnitude of this diseconomy is an immediate barometer of the performance of the system. Furthermore, defined as it is for an individual vehicle, this diseconomy can readily be summed for all vehicles in the collection to yield a warrant (for more detailed probing into the operation of the system) that is specific to the clock time interval over which the collection was defined. This essentially characterizes the work of Rothrock and Keefer (2), and as they report, represents a very direct approach to the problem.

To analyze the performance of the system more deeply, it is necessary to factor the total diseconomy into parts which can be identified with specific operational aspects of the system. A prior requirement is to identify how much of the total diseconomy is due to internal aspects of the system, and how much is due to external aspects. For example, and an obviously limiting case, if a barrier were placed across the output boundary of the system such that no vehicles could cross it, the ensuing TRT diseconomy could hardly be ascribed to the operation of the system; it would have to be due to the downstream (and hence external) barrier to the system.

In the case shown in Figure 4, the actual arrivel time at the output boundary, point b, does not coincide with what it should have been, point c, had the I^{th} vehicle been able to maintain RSP (I. OUB) throughout the system as well as at OUB. But if the vehicle had been able to maintain RSP (I. OUB), it still would have incurred the diseconomy dc. Thus RSP (I. OUB) is a constraint on performance of the vehicle in the system, and the diseconomy dc may be properly considered as being due, in significant measure, to factors external (that is, downstream) to the system. The diseconomy cb, on the other hand, must be due primarily to occurrences or situations within the system. In this context, therefore, point c splits the total diseconomy into external and internal components.

With point d, by definition, coinciding with maximum possible performance, both dc and db must always be positive. The case dc > db (not shown) implies that the diseconomy cb (which would be negative in this case) is due to factors external to the system. This case is of interest when the analysis deals with conditions downstream of the system. On the other hand, the case dc < db (Fig. 4) implies that the diseconomy cb (which is positive) is due to factors within the system. Inasmuch as the objectives of this study involve analysis of the performance of the system, and not of downstream conditions, the latter case of positive cb is of primary interest.

Effects Producing "Within" TRT Diseconomies

Two factors contributing to the system "within" diseconomy TRTD are considered: (1) the number of cars in the system at the instant any given car in the collection reaches INB, and (2) the number of cars which enter the system after the given car passes INB, but before it crosses OUB. (The "within" diseconomy here, aside from a few minor differences, is the same as the "travel time delay" as defined by Berry and Van Til (5): ".... This type of delay for an individual vehicle is the difference between its actual time required to traverse some fixed distance at the approach to an intersection, and the travel time which would have been required had the vehicle been able to continue at the average approaching speed of traffic....") An analytical construct of "the leading ensemble" or simply "ensemble" used to treat these factors is defined in the following manner.

At the instant CLT (I. INB) that the I^{th} car crosses the input boundary of the system, there exists in the system some set of vehicles. As this vehicle proceeds through the system, the set of vehicles ahead of it changes; some of the vehicles in the original set leave the system at the output boundary or at intervening off-ramps, while other vehicles join the set from intervening on-ramps. The hypothetical summation of the set of vehicles ahead of the I^{th} car at all instants between CLT (I. INB) and CLT (I. OUB) is defined here as its "ensemble", and is illustrated in Figure 5, although this figure pertains to the special case of all vehicles moving at the same speed which will be discussed in detail presently.

The ensemble of the I^{th} car is comprised of three classes of vehicles: (1) some number of vehicles N (INB. OUB) that crossed INB ahead of the I^{th} car (the assumption of uniform speed precludes the possibility of a car entering the system after the I^{th} car, and later passing it to become a part of the ensemble of the I^{th} car), (2) some number of vehicles N (LON. OUB) that come into the mainstream from LON some time after CLT (I. INB), and (3) some number of vehicles N (BON. OUB) that come into the mainstream from BON some time after CLT (I. INB). The travel time of the I^{th} vehicle is considered to have some functional relationship with these three numbers:

$$\begin{aligned} \text{TRT (I)} &= f\ [\text{ENS (I)}] \\ &= f\ [\text{N (INB. OUB), N(LON. OUB), N (BON. OUB)}] \end{aligned} \tag{10}$$

It can be seen from Figure 2 that to the (SAF. HLF) traffic, the (BON. HLF) traffic represents merging movements, while to the (SAF. HRF) traffic, the same (BON.-HLF) traffic represents weaving movements. Similarly, the (SBF. HLF) traffic is weaving across the (SAF. AOF) traffic. It thereby becomes possible to quantify the effects of weaving and merging movements to and from ramps, the separate effects being measured in travel time decrements. Thus, the effects associated with the function (Eq. 10) begin to have general meaning although they are measured in a specific situation.

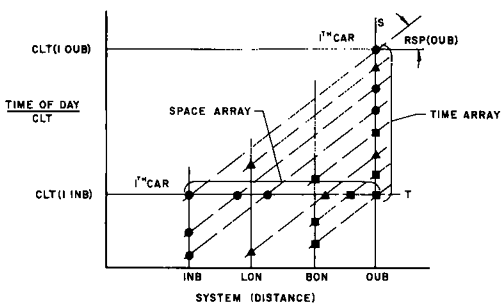


Figure 5. The laminar ensemble.

Another way of classifying the vehicles in the ensemble is by wheelbase, so that the N (INB. OUB) in Eq. 10 could be considered to be comprised of four groups; namely, the four classes of vehicles given under "Nomenclature—Vehicle Attributes". The function in Eq. 10 can then be expanded to

$$\text{TRT (I)} = f\ [\text{N (INB.WBC4.OUB), N (INB.WBC2.OUB)}, \ldots \ldots \ldots \ldots \text{N (BON.WBC4.OUB)}] \qquad (11)$$

which would then permit evaluating the "truck" effect. For example, if the Ith vehicle in the collection is heading for HRF, and if OUB in the last term in Eq. 11 is HLF, then

$$\text{TRT (I)} = f\ \left[\text{N (BON.WBC4, HLF)}\right] \qquad (12)$$

describes the effect of weaving trucks. Or, if the Ith car was heading for HLF, Eq. 12 would describe the effect of merging trucks, etc.

Returning to the special case of all vehicles moving at the same uniform and unchanging speed, the locus of each vehicle would be a straight line in the system-time space shown in Figure 5, and would be parallel to the loci of all other vehicles. In this case, which will be called "laminar", the array of vehicles in time at the point OUB can be direcly mapped into the array of vehicles in space at a given instance in time. The time domain of interest at OUB is shown on SS and extends from CLT (I. INB) to CLT (I. OUB); the space domain of interest at CLT (I. INB) is shown on TT and extends from INB to OUB (to wit, the "system").

A large number of laminar situations are possible in any given system, there being a different one for every hypothesized uniform speed. Also, for every laminar case, a large number of different ensembles are possible because for any given number of vehicles in the ensemble, there would be a different ensemble for every different possible spatial (or time) arrangement of input and output vehicles. The particular laminar case of interest here has an average respeed of traffic at the OUB as its hypothesized uniform speed, the average RSP being taken over some clock time domain at OUB, and being of the form

$$\text{Mean (RSP)} = \frac{\sum_{I=1}^{N} \text{RSP (I)}}{N} \qquad (13)$$

This study is not concerned with speed as such, but rather with its reciprocal RSP. Aside from this difference, Eq. 13 coincides with what Walker (4) expresses as "Time mean speed":

$$\text{Time mean speed} = \frac{\sum \frac{\text{distance}}{t}}{n}$$

in which t is the travel time for each individual vehicle and n is the number of vehicles.

The array in time realized at OUB rather than the array in space at CLT (I. INB) is treated as defining the ensemble, although the space array seemingly has greater physical meaning as an influence on the travel time for the Ith vehicle to negotiate the system. However, this array is relatively difficult to measure in the field as contrasted with that for time, and because with the laminar assumption it becomes possible to map into the space array from the time array, it becomes feasible to use the more easily measured time array.

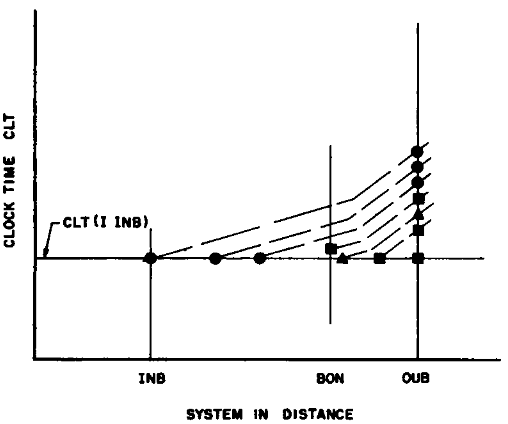


Figure 6. Modified laminar flow yielding MIN TRT (I).

A modified form of laminar demand on OUB is treated here as yielding the minimum "within" travel time for a given size of ensemble. A uniform respeed is assumed at OUB. A fruther assumption is that for this RSP there always is the same time gap GAP (RSP) between successive vehicles leaving the system at OUB. A final assumption, which is not necessary if N is sufficiently large, is that the first of the N vehicles in the ensemble is at OUB at CLT (I. INB). Under these three assumptions, minimum TRT (I) will be

$$\text{MIN TRT (I)} = \text{N} \times \text{GAP (RSP)} \tag{14}$$

This construction is demonstrated in Figure 6, and deviates from the defined laminar ensemble in that it requires each vehicle to move at a lesser respeed than the hypothesized uniform RSP at OUB until it is at the GAP (RSP) behind the vehicle ahead of it and both are moving at RSP (OUB).

There is no formal proof here that Eq. 14 may be correctly identified as the minimum and, in fact, it might be better stated that the correct minimum is at least as small as Eq. 14. The argument is plausible by analogy with laminar flow of some fluid in a pipe, in which case the entropy of the fluid would be a minimum. Departures from laminar flow would result in entropy production, and hence a reduced capability of the stream to do useful work. Departures from the defined laminar ensemble would produce local turbulences, or turbulences some other place in the system (that is, not necessarily at the point where the departure from laminar flow takes place) such that the aggregate travel time would be increased over what it would have been for the laminar case, notwithstanding any local decrease in travel time. This concept, although suggested directly by the Second Principle of Thermodynamics, is highly speculative.

(Whether or not this concept of aggregate travel time increasing with departures from laminar ensembles always holds is a matter of speculation. Seemingly, it would hold for high densities of traffic, but it might hold for low densities. The implications here are quite broad if this concept is ever elevated to the status of a "law" or "principle". For example, a passing or lane-changing maneuver is one form of departure from laminar flow. The concept would then assert that even though the particular vehicle changing lanes in passing achieves a reduction in its travel time, somewhere in the system there is at least an equal increase in travel time. Clearly, if there are no vehicles in the lane into which the passing vehicle moves, there would be no travel time decrement anywhere, and the concept would be violated. On the other hand, if the density were sufficiently high, the likelihood would be low that there would be no cars in the adjacent lane, and the concept could hold. Similar "Second Principle" type of arguments could be offered for ramp locations, multi-axle vehicles, and other factors causing local disturbances in the ensemble.)

In Figure 4, point m is established by Eq. 14 for a given N (ENS), and in turn establishes the minimum travel time of the Ith car, em, for this size ensemble. The minimum travel time is comprised of ed, which is the limiting value for the hypothesized min RSP, and dm, which is due to the size of the ENS (I). Depending on the distance between INB and OUB, there could be some non-zero N (ENS) for which m would coincide with d. However, this case is not of interest here.

It can be seen that dm is the minimum diseconomy for a jointly specified N (ENS) and RSP (OUB). It can be varied by changing N (ENS) as, for example, by diverting some traffic from the system of interest, or by changing RSP (OUB) as, for example, by adding more freeway lanes downstream of OUB. Such changes involve operational decisions which essentially are external to the system of interest. Thus because dm is amenable to change only by external (to the system) decisions, it will be referred to as the "external diseconomy". The remainder of the total diseconomy db is mb and can be due only to factors "within" the system, and accordingly will be referred to as the "within diseconomy". This differs from the earlier statement in this paper wherein point c in Figure 4 was asserted as defining the "within" diseconomy. Because point c can never fall below point m, then cb can never be greater than mb. Or, for the most part cb will not represent the entire "within" diseconomy. It nevertheless represents a gross, first approximation type of warrant as to the need for operational decisions that directly concern the system of interest.

FIELD METHODS

The field data inputs required for the various sub-studies all stem from a single set of field measurements comprised of: (1) license plate identifications at various input and output boundaries of the system, and (2) performance of the traffic stream at a given output boundary. A parallel requirement was that a reference framework of clock time be vigorously coordinated among all of the sites where data were to be collected. Finally, there was a somewhat unusual need for safety precautions as a consequence of the location of sites at which measurements were to be made.

License Identification

License identifications were required for three separate purposes: (1) to obtain travel time for vehicles to clear the network via different combinations of input and output boundaries, (2) to estimate the relative volumes of traffic moving over the different flow paths, and (3) to identify the "ensembles". These multi-purpose uses justified using somewhat more detailed field methods than would normally be needed to obtain licenses. In fact, in certain aspects, redundant identifications were deliberately obtained at sites where identifications had to be very precise.

Two methods were used to obtain licenses: (1) direct visual observation followed by voice dictation into tape recorders, and (2) photography. The tape recorder method was used for on-ramp and off-ramp sites; the photographic method was used for primary identification of licenses on the freeway proper. However, dictation methods were used redundantly on the photographic sites to correlate time-of-day with the time at the other sites in the network. They were also used (and again redundantly) to obtain a check on respeed at the output boundary. Detailed descriptions of the two methods follow.

Dictation Method.—In this method, the observer dictated the license numbers of passing vehicles directly into the microphone of a tape (or wire) recorder. Alphabetic characters were dictated with the phonetic alphabet; for example, "able" for a letter "A", etc; out-of-state cars were identified as such by the observer dictating "out-of-state" into the record; and all other pertinent information bearing on the study, location of the observer, his name, etc., were also dictated into the record. In this manner a relatively large amount of information could be readily and compactly stored in the field for later transcription and analysis in the office.

Portable, transitorized tape recorders were used at the relatively inaccessible ramp sites, highlighting another advantage in the dictation method; namely, the absence of an AC power requirement. This afforded the investigation an unusual degree of flexibility in placing observers at strategic points throughout the network.

Possibly the most important advantage of the dictation method was that time-of-day at which vehicles arrived at the recording sites could be established with a high degree of accuracy. It was found in a pilot study that high-quality tape recorders maintained essentially constant tape speed, even when battery-powered. (The special pilot study on tape recorder methods was conducted to determine the order of magnitude of the discrepancies in measurements of time-of-day that could be expected in using this technique. A total of 107 randomly arriving licenses were dictated into one of the machines in a 10-min period calibrated with five stop watches. In eleven later playbacks of 10-min recording, the maximum discrepancy for the known 10-min interval was 20 sec; the average was 5.5 sec. The median discrepancy in the time of arrival for a given license was found to be 3 sec. Notwithstanding the fact that the results pertained only to the machine tested, the order of magnitude of the discrepancies appeared to be well within the requirements of the study, particularly because time reference checks were to be dictated at known 5-min intervals). Accordingly, the recorders were run continuously once a study was under way. At 5-min intervals, the observer, referring to his watch, dictated the time-of-day into the microphone. In the later playback of the tapes in the laboratory, it was possible to establish the real time of arrival of a vehicle by relating the audible message of its license to the audible message of the real time reference points. To do this the data were transcribed in several runs. In the first run, the transcriber concentrated solely on the license numbers. In the second, he started a stop watch the instant he heard the first timing reference point, and allowed the watch to run for the remainder of the study with the tape recorder running simultaneously. He then established the time of arrival of a vehicle by relating the auditory license message to the visual stop watch reading, and entering the watch reading next to the already entered license number. For heavy traffic conditions, a third transcribing run was used to check the accuracy of both the license and its time of arrival.

Finally, an adjusted time of arrival was established by linear interpolation of the transcribed time of arrival between the dictated time reference points. As an example, if the auditory messages indicated that exactly 5 min had elapsed between two timing reference points, while the stop watch showed 5 min and 10 sec (indicating that the tape speed was slower in the transcription process than it had been in the dictation process in the field) the 10-sec discrepancy would be distributed throughout the 5-min period: every time-of-arrival in the first minute would be reduced by 2 sec, in the second minute by 4 sec, etc.

It is difficult to estimate precisely the accuracy with which the time-of-day was established with these techniques. That there was a high degree of accuracy is suggested by the fact that independent transcribers produced time-of-arrivals which rarely differed more than 3 sec from values for the same arrival (that is, vehicle) produced by other independent transcriptions of the same dictated record. However, there is no way of knowing whether or not field observers dictated licenses of vehicles at precisely the same point, notwithstanding the fact that they were instructed to do so. The best estimate of accuracy, taking all factors into account, but which nonetheless must be considered as speculative, is of the order of 10 sec.

Photographic Method.—This method involved photographing licenses of passing vehicles with pulse-type cameras from overhead structures. Aside from the advantages inherent in photography (permanent visual record of license, visual display of clock time, automatic actuation, and others), the method presented difficult problems, and was used only after pilot studies indicated that problems associated with using dictation methods at multi-lane freeway sites would be more difficult to overcome. (Pilot studies indicated that dictation methods would not be too satisfactory for multi-lane freeway traffic. If an observer were located on an overhead structure, it was quite difficult for him to read and then dictate the licenses of a large sample of the vehicles passing below him because of distance and his angle of view, particularly when vehicles were moving at high speeds. It was found that the number of vehicles licenses a trained observer could pick out of a fast-moving stream of freeway traffic was not sufficiently large for flow pattern work (although more than adequate for travel time measurements alone). Placing observers on median strips or on the shoulders to reduce the sight distance and provide a better angle of view was ruled out because of danger to the observers, and because of the deleterious effect that their presence would have on the traffic flow. This effect was observed in some work reported earlier (11), so that as a general policy, observers were to be kept out of view of the passing motorists as much as possible.)

The difficult problems in photographing licenses of fast-moving vehicles so that the separate license characters could later be read on magnifying film readers related to an entire complex of factors: film speed and grain, camera angle relative to angle of inclination of license plate which in turn depended in large measure on grade of the road and whether the front or rear plate was being photographed, changing ambient light, glare reflected off the plate, or shadow falling across the plate, and others. These will not be described in detail here; the net effect however was to limit the coverage of single cameras to single lanes at the all-important output boundary.

The primary camera system in the study used Kodak Cine Special 16-mm movie cameras that were set for single-frame operation. (When a movie camera is used as a pulse camera, as in this study, its shutter never reaches full speed due to starting inertia. Consequently, the smallest shutter opening is not sufficiently small to give an exposure fast enough to resolve the license detail of a fast-moving car. A special adaptor had to be designed that gave the camera a shutter speed of approximately 1/400 sec.) In 16-mm film, there are 40 frames per foot, so that the Cine with its 100-ft magazine has a capacity of recording licenses of approximately 4,000 cars without reloading. This was the principal reason for selecting this camera for freeway work. However, there was a major disadvantage; namely, with this size of film, there are significant problems of image size which necessitated using a separate camera for each lane.

The cameras were triggered manually; that is, by an observer watching for the instant a car came into the camera field. (In the new photographic system under development at ITTE, cameras will be triggered electrically by car wheels rolling over pressure-actuated detectors.) Prior to the beginning of the study, and with traffic temporarily by-passed around the given lane, two strips of adhesive tape were placed on the road at the beginning and end of the field of view of the camera with the lens properly focused. The observer thus was able to determine when a vehicle was in the field of view (after the license crossed the first lane and before it crossed the second). This eliminated having him continuously looking through the camera viewfinder which is extremely fatiguing.

A total of seven cameras were simultaneously used in this study. In two cases, a small watch movement was placed in the field of view, and brought into focus by a system of lenses external to the camera. (This system was designed and operated by Stephen Craig, photographic consultant to the project.) The time base for the other cameras was provided by superimposing (redundantly) independent dictation of licenses into tape recorders at the same site. These time-identified licenses were later matched with the photographed licenses to establish time reference points for the remaining (unmatched) photographed licenses. Times-of-day for the unmatched licenses were then established by linear interpolation between the nearest reference points. Although only approximately 25 percent of the licenses could be obtained via dictation (as contrasted with virtually 100 percent with the photography), there were sufficient time-identified licenses (and hence reference points) to establish time to within an estimated 5 sec.

ITTE is now developing a 35-mm camera system specifically for photographing licenses of fast-moving vehicles on a freeway. The system is being designed around a Robot Recorder - E 35-mm camera having a film magazine capacity of 200 ft, or approximately 2,400 frames. In contrast with 16-mm film, the larger size image will permit a single exposure to cover two, or possibly more lanes of traffic. A special collimating prism adaptor having its own light source, has been designed that superimposes an instrument panel on the image of the vehicle. A watch and other instrument displays can be included in the panel. The system was tested in this study, and although it performed satisfactorily, it was not sufficiently reliable to be included as a part of the basic instrumentation. Once the system is fully developed, it should significantly simplify the task of recording licenses and time of fast-moving vehicles.

Properties of Traffic Stream at Output Boundary

An important study objective was the identification of traffic factors "within" the system that were influencing travel time from those occurring "downstream"; that is, beyond the output boundary. This was accomplished by a combination of a set of speed-headway measurements and a classified count of traffic, both at the output boundary, and both carefully controlled so as to be on the same clock time base. Ideally, these control measurements should have been made over the entire output boundary. In this study, they were limited to the output boundary at site 8 (the Hollywood Freeway) because of the amount of equipment required.

Cross-Coupling of Recorders.—Two pairs of Esterline-Angus 20-Pen Recorders were located at site 8 (the Grand Avenue Overcrossing overlooking the Hollywood Freeway). The first pair was used for respeed-headway measurements; the second for classified volume counting. In a given pair, one recorder would be in operation while the other was on stand-by. The set of signal inputs to a given pair was via an external control unit. By throwing a single selector switch on the external control unit, the complete set of signal inputs could be transferred from the operating recorder to the stand-by recorder, with the operating recorder being simultaneously changed to stand-by while the stand-by unit went into operation. The reason for this provision was that for accurate respeed measurement, it was necessary to have the paper at maximum travel speed or 3 in. per second; a roll of paper would be used in approximately six min. The switching arrangement allowed an instantaneous shift from one recorder to the other without losing any data. While the second unit was in operation, a fresh roll of paper would be inserted in the first recorder which would then be ready to be switched on when paper ran out on the second unit. The arrangement also permitted switching recorders when any common recorder malfunctions occurred—paper jamming, pens running dry, etc.

Speed and Cross-Reference Truck Classification.—Two pressure-type, vehicle-actuated detectors, similar in some respects to those reported by Mathewson, Brenner, and Reiss (12), were installed directly on the roadway, parallel to each other and 4 ft apart. As the wheel of a vehicle rolled over a detector, mechanically separated contacts would be closed and a pen on the recorder energized. By calibrating the paper speed of the recorder, it was possible to measure the time gap between successive pips and accordingly establish the vehicle speed (actually respeed), headway, wheel base, and several interrelated functions. With three lanes of traffic at site 8, it was mandatory that the electrical signal coming with the closure of the contacts in any detector in any lane be completely independent of the signal coming with actuation of any other detector. A multi-lane detector was accordingly designed and built that met this requirement of independent lane-by-lane detection of traffic. There were, therefore, six pens assigned to traffic detection.

A parallel requirement to speed-headway measurements by lane was to identify these measurements by type of vehicle. This identification, which was needed to measure the "truck" effect as well as the "compact car" effect reported by Burch (13), could be accomplished to a certain extent by studying the pip pattern. For example, a three-axle truck would produce a definitive array of three pips on one channel (corresponding to the first of the parallel detectors) translated from three pips on a parallel channel (the second detector). However, under high density conditions, ambiguous patterns occur quite frequently. As an example, a pattern for a two-axle, long wheelbase vehicle (specifically, busses), ahead of a five-axle truck trailer combination, is easily interpreted as a three-axle truck followed by two compact cars, etc.

Accordingly, an independent, direct input was designed whereby an observer actuated two sets of buttons on a control panel, with each button energizing a separate pen on the recorder. There were three buttons in the first set, one for each lane. In the second set, there were five buttons, one each for: a truck-full-trailer combination, a truck-semi-trailer combination, a three-axle truck, a two-axle truck, and a bus. The observer depressed the proper lane button and the proper truck classification button as he saw the first wheel of the particular vehicle cross the first detector in the given lane.

The complete pen use is shown in Figure 7 which is a facsimile of an actual record obtained in this speed measurement cross referenced to vehicle classification. A ninth button on the control panel (actuating pen No. 20) was used for time calibration purposes, being depressed every minute (on the minute) by the observer who for this purpose was provided with a continuously running sweep second watch.

The procedures followed in reducing these data, the subsequent computer analyses, and specimen results are described later in this paper.

Classified Volume Counting.—The second pair of Esterline-Angus recorders (also at site 8) were used for classified counting of multi-axle vehicles, and two-axle trucks and busses. As with the speed measurement use of the recorders, observers depressed buttons on a control panel for lane indication. The type of vehicle, however, was indicated by multi-counts on an indicator button on the control panel; for example, one count signified a bus or two-axle truck, two counts indicated a truck-semi-trailer combination, three counts indicated a truck-full-trailer combination.

There were two reasons for using the Esterline-Angus equipment for this volume counting. The first was to reference the presence of multi-axle vehicles, two-axle trucks and busses on the clock time scale. This was redundant with the classification being accomplished in the speed measurement system at the same time. The second reason was to have on hand a stand-by pair of Esterline-Angus recorders ready to be connected into the speed measuring system in the event of failure of either one of the

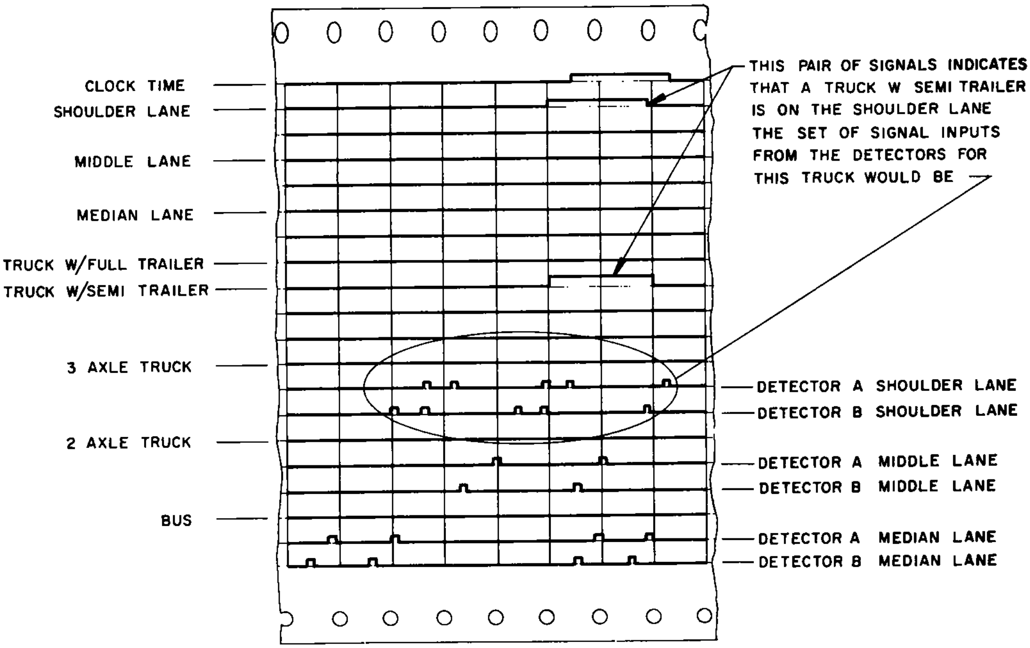


Figure 7. Facsimile of Esterline-Angus record for speed and cross-referenced truck classification.

pair originally set up for speed measurement. To meet this latter eventuality, both pairs of recorders with their control panels, interconnecting circuitry connectors, etc., were wired identically, and hence were completely interchangeable. However, the pair used for the classified volume counting was set to operate at a much slower paper speed, 1 ft per minute as compared to 3 in. per second. The low speed, which could be instantaneously switched to high speed, was used for the classified volume counting because there was no need to time the gap between successive pips.

Redundant "RSP" Measurement.—In view of the importance of the RSP measurement at the output boundary, provisions were made in the experimental plan for its being measured redundantly. The first (and primary) method used the previously described equipment system (multi-lane detectors, Esterline-Angus Recorders, etc.). The second method required that licenses be identified (on a sampling basis) at some secondary point downstream of the output boundary. Matching licenses identified at the secondary point with those identified at the output boundary would establish travel time between the output boundary and the secondary point. With the intervening distance known, an RSP pertaining to the section of freeway immediately downstream of the section of interest could be computed. This RSP would not necessarily have the same value as the RSP measured over the 4-ft distance at the output boundary, and although it probably would not be as closely correlated with system performance as would be the spot RSP, it nevertheless would provide an order of magnitude indication of downstream effects.

For site 7, the downstream secondary control points were sites 9 and 10 which happened to be required for separating HRF and PSF traffic. It later developed that enough detectors could not be provided in time for the study to equip both sites 7 and 8 for RSP measurement. The decision was made to limit the RSP measurement to site 8. Thus the secondary RSP measurement (via the travel time between site 7 and sites 9, 10) was the only RSP measurement at site 7.

For site 8, the downstream secondary control point was at site 11 (Edgeware Overcrossing) which is approximately ½ mi downstream (west) of site 8. (There are no intervening overcrossings.) But, aside from providing for the redundant RSP measurement, the license identification at site 11 was used to test the power of the license matching technique for establishing flow patterns with low sampling ratios.

General Network Control

An overriding problem was to synchronize the clock time base for all measurements (dictation of licenses, photographing licenses, RSP measurements, classified volume counting) throughout the network. This was done in part by assembling all observers at the start of the day in a briefing period, and having each synchronize his watch with an electric clock mounted permanently in the assembly area. Thereafter during the course of the day, repeated time checks were made over a special radio network provided through the courtesy of the Los Angeles Police Department. Five police walky-talky ratios were loaned to the project, and were set on an infrequently used police channel. The radios were then distributed to personnel in charge of the most widely dispersed sites (sites 1, 2, 8, 9, and 11).

Radio communication of this nature was considered to be mandatory, not only because of the time check requirement, but also (and more important) because of safety considerations. Several of the sites were essentially inaccessible except at high risk due to the high-speed traffic. Police protection was required to get field personnel into and out of these sites. Personnel were relatively safe once they were at their sites, but there always was the possibility of an accident. The radio network was made available to communicate any untoward happenings to the field director. Several motorcycle officers and other police officers in squad cars were on a stand-by basis through the course of the day.

SPECTRUM OF TRIP LENGTHS ACCORDING TO ON-RAMP OF ORIGINATION

Increasing consideration has been given in recent years to determining the origin and destination of traffic on modern freeways and data are available on the vehicle-miles being driven on freeways. However, there has been relatively little work done on apportioning this mileage to specific on-ramps or off-ramps, although such information would serve to demonstrate in part whether a ramp was being used principally for long-trip or for short-trip purposes. Limited-access facilities are not intended for short-trip purposes, so that if the short-trip use of a particular ramp is sufficiently high, a decision to close the ramp might readily be made without further analysis as to any detrimental effects the short-trip use would have on the long-trip freeway user. There, of course, would have to be prior analyses as to suitable alternate ramps and surface street paths to them. Therefore, an immediate screening type of study would be to ascertain the spectrum of trip lengths on the freeway proper originating at the different on-ramps of interest.

The conventional roadside-interview type of survey undoubtedly would be adequate for determining the length of freeway trips originating at a given on-ramp (or terminating at a given off-ramp) provided the volume of ramp traffic was not too high. In this particular study, however, the three ramps of interest carry considerable traffic during peak hours; the traffic back-up that would have resulted from roadside interviews would have created intolerable inconveniences to the drivers, and would also have resulted in incorrect travel times. Consequently, a somewhat novel questionnaire technique was developed. Although the technique was used in on-ramp situations in this study, it can be applied to situations on the freeways proper.

Licenses of vehicles coming on to the ramp were recorded by voice dictation. It was not necessary to stop the vehicle or impede its travel in any way. In fact, observers were hidden from the motorists' direct view as much as possible. Later, the licenses were taken to the Department of Motor Vehicles which in turn supplied the addresses of the registered owners to whom a questionnaire was to be mailed.

The mailing to the registered owners consisted of a letter explaining the study objectives, a special map type of questionnaire, and a self-addressed, stamped, business reply envelope. Specimen cover letters and questionnaires are shown in Figures 8 and 9, respectively. The information sought in the questionnaire related to: (1) freeway trip length of the ramp user, (2) the specific freeway to which the ramp user was

Institute of Transportation and Traffic Engineering
UNIVERSITY OF CALIFORNIA
LOS ANGELES 24, CALIFORNIA

Registered Owner of
Vehicle License No. ____________

Dear Sir:

We are a research group in the Institute of Transportation and Traffic Engineering of the University of California, and need and earnestly seek your help in a special study we are conducting on freeway operation in the Los Angeles area.

Our problem is to find out how the freeways are being used, where cars get on and leave the freeways, the city streets they use to get to the freeway. Our method is to record licenses of vehicles we observe on different freeway ramps throughout the city. We then write directly to the registered owners at addresses we obtain from the license records of the Department of Motor Vehicles of the State. This is how we obtained your address. Specifically, a vehicle registered in your name was observed:

DATE:

TIME:

PLACE:

We ask you to fill in the enclosed questionnaire and mail it back to us immediately in the addressed envelope. If you were not, but know who uas driving the vehicle we observed, would you still complete the form, please?

You will note that we do not ask you to sign the questionnaire or otherwise identify yourself. We do this on purpose to insure that your privacy will be respected.

May we thank you in advance for your needed cooperation in this work that is so important to all of us; the information you supply will no doubt result in long-range benefits to all freeway users.

Yours truly,

Robert Brenner

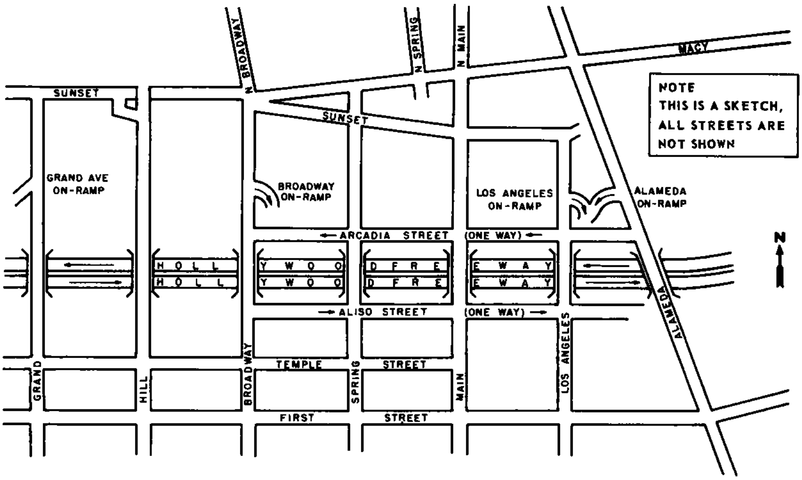
Robert Brenner, Project Engineer
The Institute of Transportation and
Traffic Engineering

Encl.

Figure 8. Cover letter used in mailing questionnaire study.

INSTITUTE OF TRANSPORTATION AND TRAFFIC ENGINEERING
UNIVERSITY OF CALIFORNIA LOS ANGELES 24 CALIFORNIA

FREEWAY RESEARCH PROJECT



1 YOUR CAR WAS OBSERVED HERE ON THE ________________ ON RAMP ON MAY ____

2 DRAW A LINE DIRECTLY ON THIS MAP SHOWING HOW YOU GOT TO THIS RAMP

3 ON THAT DAY, WAS YOUR VEHICLE HEADING FOR (MARK ONE)
HARBOR FREEWAY? ☐ HOLLYWOOD FREEWAY? ☐ PASADENA FREEWAY? ☐

4 AT WHAT RAMP DID YOUR VEHICLE LEAVE THE FREEWAY? __________________

AS SOON AS YOU HAVE COMPLETED THIS FORM PLEASE RETURN IT TO US IN THE ENVELOPE WE HAVE SUPPLIED IF YOU HAVE ANY QUESTIONS, YOU MAY PHONE US AT BRADSHAW 2-6161 EXTENSION 551 THANK YOU FOR YOUR COOPERATION

Figure 9. The mailing questionnaire.

headed, and (3) the surface street path followed in getting to the ramp. The discussion here is limited to trip length; the latter two classes of results are treated in the next sub-study.

At the outset, it was recognized that the questionnaires would have to be in the mails as quickly as possible if there was to be a satisfactory return and if the results were to be reliable. Consequently, extraordinary measures were taken to assure that the questionnaires would be posted within 24 hr after the vehicles were observed. In fact, the study was deliberately scheduled (for a Tuesday) so that there would be no weekend intervening between the date the vehicle was observed and the date the registered owner received the questionnaire. The transcription of licenses from dictated records, cross-checking, and alphabetic-numeric sorting (required for locating addresses) began within 3 hr after the field work was completed and continued throughout the night of the study. The addresses of the registered owners were on hand by noon of the following day. Addressing of letters and envelopes was completed by 5 p.m., and the questionnaire in the mails by 6 p.m.

The initial listing was limited to licenses observed between 4 and 4:30 p.m., and was comprised of 200 licenses at the Broadway on-ramp, and 100 each at the Los Angeles and Alameda on-ramps. The sampling ratios (licenses used for mailing vs total volume) were 99 percent at BON, 45 percent at LON, and 52 percent at AON. The sampling was heavier at BON because this was the on-ramp of primary operational interest.

Addresses could not be located for 36 of the original listing of 400 licenses, so that the mailing went out to 364 persons. Of these, there were in all 213 usable replies, and 17 non-usable (person had moved; car was leased; car sold new, registered owner unknown; etc.). The useful reply percentage (of the entire mailing) was approximately 59 percent.

The gratifyingly high percentage return can be ascribed to any of a number of factors: speed in getting the questionnaire into the mail, wording of the cover letter, assurance of anonymity, respective prestige values of the names of the University and the Division of Highways, the fact that the communication was personal, novelty, etc. There were, however, numerous additional commentaries in the replies: detailed descriptions of routes, reasons why particular routes are selected, offers to be of further assistance, even a few discussions of "poor" ramp design. These unsolicited commentaries coupled with the high percentage of returns indicate a high degree of public interest in research projects on freeway operations. This, of course, could also explain the high return.

The results shown in Figure 10 are the spectra of trip lengths, and Figure 11, the cumulative frequency distribution of trip lengths. The median trip lengths are BON—5.1 mi, LON—7.0 mi, AON—8.4 mi. The 75th percentiles are BON—2.6 mi, LON—4.4 mi, AON—4.4 mi.

Any judgment as to what constitutes a "short" trip on a freeway would be completely arbitrary. An equally arbitrary judgment would bear on how high the percentage would have to be before being considered to be excessive, how low to be acceptable, etc. There are no norms for either of these judgments. To the authors, it appears that use of all three ramps during the period sampled is compatible with the intent in freeway construction. There is limited indication of excessive short-trip use, certainly not to any degree that would preclude more detailed analysis of the total network problems prior to any decision to close any one or all of the ramps.

Another way of interpreting the results is that, were any of the three ramps to be closed, not many of the motorists presently using these ramps would be dissuaded from using the freeways, albeit by entering via another on-ramp. Closing the ramps would thus raise problems of how the diversion of traffic from one on-ramp to another would affect the intervening surface street network. This is the subject of the next sub-study.

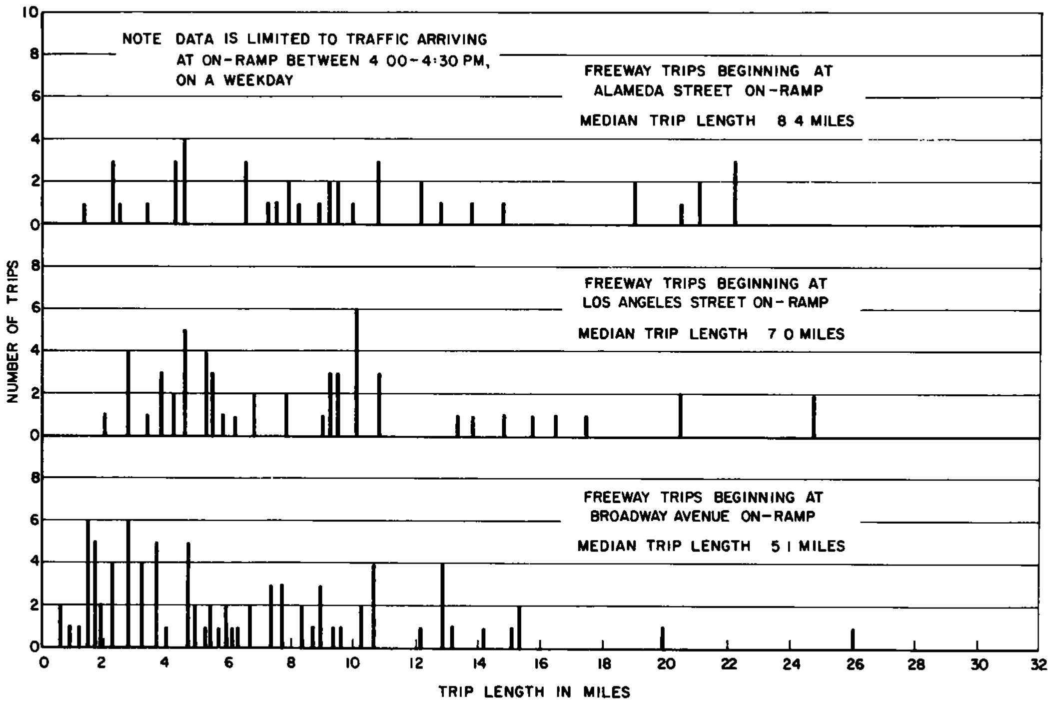


Figure 10. Distribution of trip lengths as obtained from mailing questionnaire.

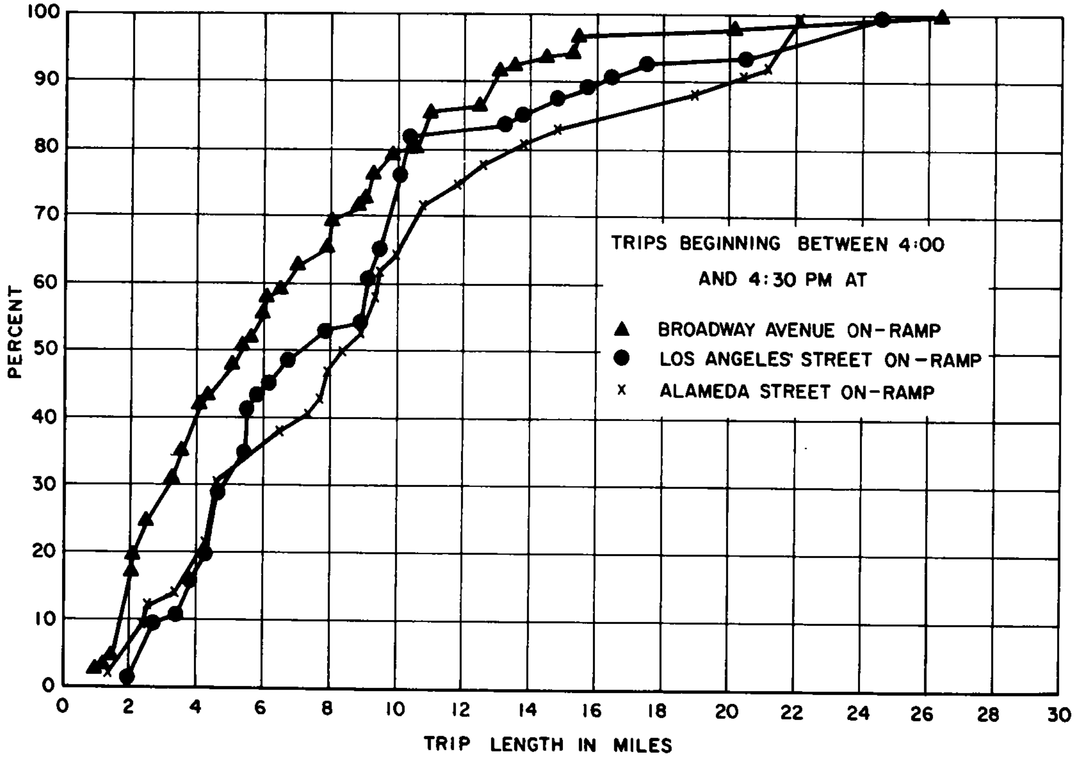


Figure 11. Cumulative distribution of trip lengths over all freeways.

SURFACE STREET TRAVEL PATTERNS OF RAMP USERS

The questionnaire described in the previous sub-study was devised in the form of a schematic map of the surface streets specifically to yield at once both the surface street paths and a general idea of the point of origin of ramp users. Because the questionnaire was sent only to ramp users, the information was automatically keyed to specific on-ramps. Also, keyed to the on-ramp use would be the freeway to which the respondent was heading, this being one of the questionnaire items. It was considered mandatory to have all of this information for subsequent analysis of alternate ramps and surface street routes that would be used in the event of ramp closings, or opening of new freeway links.

It was recognized at the outset that there would be problems in evaluating the reliability of the data, because no completely suitable statistical method could be identified. Consequently, a somewhat oblique split-half reliability procedure was followed. The replies were arranged in nine groups, one for each combination of on-ramp and freeway (destination). Through use of random number tables, each group was divided into two samples. The samples were then tabulated separately and the totals compared with each other. Although the data actually identify the point of origin of the traffic and the complete surface street pattern followed in getting to the on-ramps, the statistical analysis was limited to treatment of the cardinal directions from which traffic had come upon reaching the on-ramps. The data are given in Table 1, and are shown schematically in Figure 12. To simplify the presentation here, these data are limited to cardinal directions. The actual data (questionnaire replies) show the complete surface street route traffic followed in getting to the different ramps.

The sole case where there appears to be any inconsistency between the "A" and "B" samples is for the BON to HLF case. The null hypothesis was tested for this case using a chi square technique, and was not rejected. (The experimental chi square value

TABLE 1

CARDINAL DIRECTIONS FROM WHICH RAMP USERS APPROACH THE RAMP

On-Ramp	To Freeway	Sample	Direction of Approach Via Surface Streets, From the: North	East	South
Broadway (BON)	Hollywood (HLF)	A	3	12	1) 31
		B	3	6	6)
	Harbor (HRF)	A	1	16	7) 47
		B	2	16	5)
	Pasadena (PSF)	A	1	4	1) 12
		B	3	2	1)
Los Angeles (LON)	Hollywood (HLF)	A	1	-	21) 42
		B	1	-	19)
	Harbor (HRF)	A	4	-	-) 9
		B	3	-	2)
	Pasadena (PSF)	A	1	-	-) 2
		B	1	-	-)
Alameda (AON)	Hollywood (HLF)	A	9	-	4) 24
		B	9	-	2)
	Harbor (HRF)	A	5	-	4) 16
		B	3	-	4)
	Pasadena (PSF)	A	1	-	-) 3
		B	2	-	-)

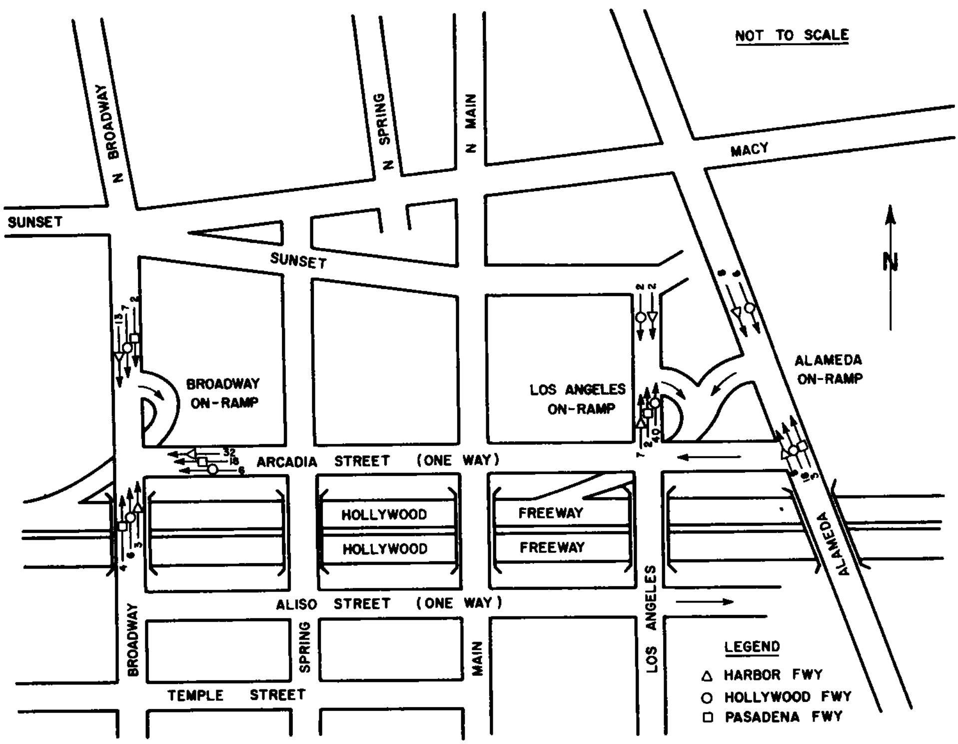


Figure 12. Cardinal directions from which traffic came in getting to on-ramps of interest.

uncorrected for continuity is 5.533. The chi square, 2 DF values at the 10 and 5 percent levels of significance are 4.605 and 5.991, respectively.) This may be interpreted as meaning that although the A and B patterns differ, the discrepancies are not sufficiently large to be ascribed to anything other than chance. A somewhat heuristic interpretation of the discrepancy would be that the variability of the BON - HLF pattern is high, which in turn would imply that more data would have to be taken to lessen the uncertainty as to this particular flow pattern.

The results, in the main, demonstrate a high degree of self consistency, and show that the principal flow to the on-ramp of interest is from the south. In the case of the LON - HLF pattern, 18 of the 21, and 15 of the 19 northbound vehicles (coming from the south), originated south of First Street. This result (which comes from detailed tabulations of travel patterns which are not presented in this paper) demonstrates the potential power of the questionnaire technique for determining more precise surface street patterns.

The principal reason for determining the surface street paths (which essentially was the principal reason for the questionnaire itself) was to establish a basis for estimating the effect that closing a particular on-ramp would have on its present users. There are questions of: (1) will the present ramp user continue to use the freeway, albeit by taking a different on-ramp; (2) under these circumstances, which ramp will be chosen; (3) what new route will be taken on the surface streets to get to his new on-ramp. Inferential judgments such as these are inherently difficult, and can never be made with certainty. But they can be made with a greater degree of confidence if the present points of origin within the surface street network are known for the ramp users along with the actual routes they take.

To estimate the surface street patterns that would prevail after projected ramp changes took place, a secondary questionnaire was constructed specifically directed toward traffic experts and others who were knowledgeable of traffic conditions in the downtown Los Angeles area. The experts were from three independent organizations: (1) Traffic Department, City of Los Angeles; (2) Police Department, City of Los Angeles; and (3) Traffic Department of District VII, California Division of Highways. Selection of the experts who were to receive the questionnaire was left to the heads of the separate organizations.

The "expert" questionnaire was constructed directly from the replies received from the general "mailing" questionnaire. This is to say that the routes the motorists indicated they were taking to get to the specific on-ramps were identified in the "expert" questionnaire. Each route was identified by a sequence of intersection numbers which were assigned arbitrarily to every intersection in the adjacent downtown area. The routes (sequence of intersection numbers) were further cross referenced to on-ramps, there being in all 60 route-ramp combinations. Illustrative of the instructions to the experts:

> "...Judge as best as you can how a vehicle would change from the given route if the ramp for which it was originally heading were closed. List the new ramp and the new route in the space provided next to the given route, and in the same manner, that is by the intersection numbers...."

To minimize any bias the "mailing" questionnaire might have on the "expert" questionnaire, the number of vehicles following each route was not disclosed to the experts. It was recognized that this might result in some aspect of the diversion pattern being inconsistent with traffic conditions. However, the investigators judged that if such an inconsistency did arise, they could reconcile it.

As was anticipated, the replies were consistent with each with a few exceptions, and from the results of this and the mailing questionnaire, the ramp diversions were deduced as given in Table 2. The diversion pattern appears to be reasonable with the exception of the ramp traffic headed for the Harbor Freeway. The present load and resulting back-up of traffic on the collector road to the Harbor Freeway during the evening break is so high, that the 210 vehicles shown as going to the Harbor Freeway (having been diverted from the Broadway on-ramp) would probably get to the Harbor Freeway via a ramp (3rd Street) which is not a part of the system of interest in this study.

TABLE 2

ADDITIONAL TRAFFIC VOLUME ON ADJACENT ON-RAMPS WITH THE CLOSING OF THE BROADWAY ON-RAMP
(Figures Pertain to 1-hr Volume 4-5 p.m.)

Ramp	Volume with Broadway On-Ramp Open	Vehicles Diverted From the (Closed) Broadway On-Ramp	Total Volume When Broadway On-Ramp is Closed
Broadway Avenue On-Ramp	620	0	0
Grand Avenue On-Ramp to:			
Hollywood Fwy	745	150	895
Harbor Fwy	300	210	510
Pasadena Fwy	240	15	255
Castellar Street On-Ramp	1,670	70	1,740
Alameda Street On-Ramp	540	95	635
Los Angeles Street On-Ramp	385	80	465
		620	

PROPERTIES OF TRAFFIC STREAM AT OUTPUT BOUNDARY OF SYSTEM

If the input and output boundaries of the freeway system of interest were placed at locations where entering and exit speeds, respectively, were at the maximum legal limit (specifically, 65 mph in California), performance measured at the boundaries could be said to be due to factors "within" the boundaries. In this study, however, the boundaries are defined so as to include only the section of freeway that is of operational interest, and at these locations, speeds are anything but maximum during the period of the study. Performance measured at these boundaries must accordingly include effects due to the freeway network downstream (that is, beyond) the OUB, effects due to factors upstream (that is, ahead) of the INB, and finally effects which could be said to be due primarily to factors within the boundaries. It is these latter effects with which the project is concerned, and a general objective is to isolate them from the downstream and upstream effects. Upstream factors are removed from the analysis by having the MOE measured for the "collection" defined on the basis of clock time at the INB. Downstream factors are taken care of in some measure by relatively precise measurement of traffic at the OUB. This measurement is the subject of this particular sub-study.

The field techniques used in the speed-headway measurements at the output boundary have already been described as involving multi-lane detectors in combination with the Esterline-Angus recorders, and the resulting Esterline-Angus record is shown in Figure 7. Figure 13 shows a facsimile of the Esterline-Angus record in sufficient additional detail to facilitate descriptions of the data reduction procedures and subsequent computer analysis.

Data Reduction Procedures

There were three primary "times" to be identified for each vehicle. These are, referring to Figure 13:

A_{2I-1} = time the first wheel of the vehicle crossed the first detector;

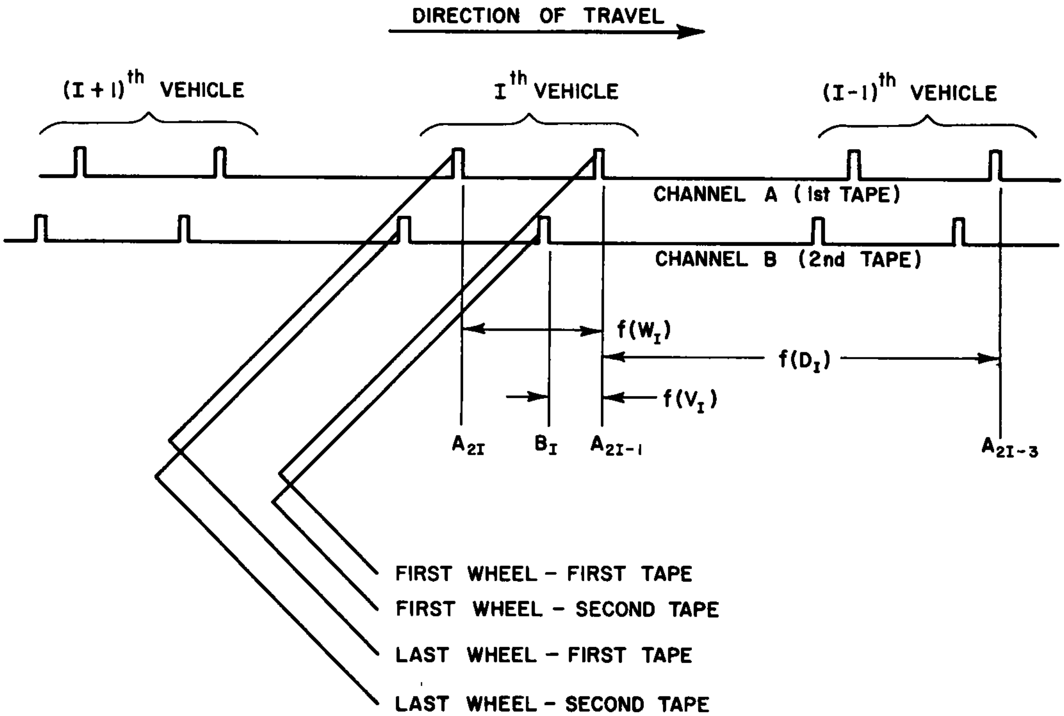


Figure 13. Nomenclature used in speed and headway study.

A_{2I} = time the last wheel of the vehicle (or truck-trailer combination) crossed the first detector; and

B_I = time the first wheel of the vehicle crossed the second detector.

A fourth "time", B'_I, was used only to demonstrate that this technique could yield an acceleration measurement.

Inasmuch as one channel (number 20) of the chart record was used as an independent clock time indication, it was possible to convert each of the "time" measurements (A_{2I-1}, A_{2I}, B_I) to "clock time" measurements by relating them to the nearest time indication. The time indications were made every minute on the minute. The analysis accordingly was set up in 1-min blocks; that is, from one time indication to the next. Paper speed was 3 in. per second, or 15 ft of paper travel in the 1-min block.

To facilitate the "reading" of the time pips over the 1-min interval, a special 16-ft long wooden channel was designed with paper take-up reels at each end. The channel was marked off in 3-in. units, each unit corresponding to 1-sec of real time. The units were subdivided into 100-millisecond (Distances) increments. A vernier scale was constructed to be used in conjunction with the channel board which further increased the accuracy of the reading to 10 milliseconds by direct reading of the vernier scale, and to 1 millisecond by estimation of the vernier scale.

The procedure was to line up the first time pip with the zero time point on the channel and scotch tape the record in place. The vernier, which was made of transparent lucite, was then placed on top of the record, and indexed on successive pips simply by sliding it along the channel.

Additional Nomenclature

Two sets of additional nomenclature are required to describe the properties of the traffic stream as measured at the output boundary. The first set identifies attributes of individual vehicles in their respective positions in the moving stream crossing the output boundary of the system. The criterion for establishing the attribute of following-too-closely (FTC) is the widely quoted ¾-sec brake reaction time. The criterion for the attribute of closing-too-rapidly (CIG) is 8 ft/sec^2 which stems in part from the judgment of Gazis, Herman, and Maradudin (14) who use ⅓ g (approximately 10.7 ft/sec^2) as a maximum "comfortable" deceleration. Thus, the 8 ft/sec^2 value used in this study is more conservative than that of Gazis and the others. Different criterion constants can be used at will, and which ones are appropriate are strictly matters of opinion.

FTC (I)	following too closely, (Ith: car following the (I-1)th car too closely), where: $\text{FTC (I)} = \left[\text{D (I)} \leq \left\{\text{V (I) ft/sec}\right\} \left\{\tfrac{3}{4}\text{ sec}\right\}\right]$
NFTC (I)	not following too closely, where: $\text{NFTC (I)} = \left[\text{D (I)} > \left\{\text{V (I) ft/sec}\right\} \left\{\tfrac{3}{4}\text{ sec}\right\}\right]$
DFV (I)	difference between speeds of Ith and (I-1)th cars, where: DFV (I) = V (I) - V (I-1)
CLG (I)	closing too rapidly (Ith car is closing too rapidly on the (I-1)th car), where: $\text{CLG (I)} = \left[\left\{(\text{DFV})^2 \text{ (I)} / 2 \text{ D (I)}\right\} \geq 8.0 \text{ ft/sec}^2\right]$
NCLG (I)	not closing too rapidly, where: $\text{NCLG (I)} = \left[\left\{(\text{DFV})^2 \text{ (I)} / 2 \text{ D (I)}\right\} < 8.0 \text{ ft/sec}^2\right]$
FTC. CLG	following too closely and closing too rapidly (compound attribute), where: (FTC. CLG) (I) = both FTC (I) and CLG (I) hold for the Ith car
$\left\{\text{N (FTC. CLG)}\right\} \left\{\text{(I)}\right\}$	the property FTC. CLG does not hold for the Ith car, or: $\left\{\text{N (FTC. CLG)}\right\} \left\{\text{(I)}\right\}$ = either NFTC (I), or NCLG (I), or both hold for the Ith car.

The following additional nomenclature is used to describe properties of a group of vehicles (as contrasted with the preceding nomenclature, which pertains to individual vehicles).

N(J)	total number of cars recorded in the Jth time group
N(WBC-)(J)	number of cars of wheel base classification WBC1, WBC2, etc., recorded in the Jth time group
N(FTC)(J)	number of cars following too closely in the Jth time group
N (NFTC)(J)	number of cars not following too closely in the Jth time group
N(WBC-. FTC)(J)	number of cars of wheel base classification WBC1, WBC2, etc., that were following too closely in the Jth time group
$\text{P} \left\{\text{N(J)}\right\} \left\{\text{(WBC-)}\right\}$	percentage of the cars in the Jth time group that were of wheel base classification WBC1, WBC2, etc. $\text{P} \left\{\text{N(J)}\right\} \left\{\text{(WBC-)}\right\} = \dfrac{\text{N(WBC-)(J)}}{\text{N(J)}}$
$\text{P} \left\{\text{(WBC-)}\right\} \left\{\text{(FTC)}\right\}$	percentage of the cars of wheel base classification WBC1, WBC2, etc., that were following too closely $\text{P} \left\{\text{(WBC-)(J)}\right\} \left\{\text{(FTC)}\right\} = \dfrac{\text{N(WBC-. FTC)(J)}}{\text{N(WBC-)(J)}}$
MEAN V(J)	mean speed of all cars in the Jth time group; alternately, $\overline{V}_J$

MEAN D(J)	mean following distance of all cars in the J^{th} time group; alternately, $\overline{D}_J$
VAR V(J)	variance of speeds of all cars in the J^{th} time group; alternately, $S^2_{V,\ J}$
VAR D(J)	variance of following distance of all cars in the J^{th} time group; alternately, $S^2_{D,\ J}$
MEAN V(WBC-)(J)	mean speed of all cars of wheel base classification WBC1, WBC2, etc., in the J^{th} time group; alternately, $\overline{V}_{(WBC-)(J)}$
VAR V(WBC-)(J)	variance of speeds of all cars of wheel base WBC1, WBC2, etc., in the J^{th} time group; alternately, $S^2_{(WBC-)(J)}$
MEAN D(WBC-)(J)	mean following distance of all cars of wheel base WBC1, WBC2, etc., in the J^{th} time group; alternately, $\overline{D}_{(WBC-)(J)}$
VAR D(WBC-)(J)	variance of following distance of all cars of wheel base WBC1, WBC2, etc., in the J^{th} time group; alternately, $S^2_{D(WBC-)(J)}$
MEAN V(WBC-.FTC)(J)	mean speed of all cars of wheel base WBC1, WBC2, etc., and following too closely in the J^{th} time group; alternately, $\overline{V}_{(WBC-.FTC)(J)}$

The grouping of vehicles was according to predetermined (clock) time intervals at the output boundary. The interval in this study is 1 min and is identified by the letter J in relation to a reference time. Thus J = 9 means the 9^{th} minute after the reference time. In this study the beginning of each separate study was considered as the reference time for that study.

Computer Analysis

A program was written for the computer to perform the necessary mathematical operations on the set of time data, and to output the results in a directly readable form. This latter objective is one of the principal reasons why the FORTRAN-like language was used to describe the variables in the study. The machine used in the study is a part of the facilities of the Western Data Processing Center located on the Los Angeles Campus of the University of California. Specimen outputs of the computer program are shown in Figures 14 and 15.

Results

The results, which essentially are enumerative in nature, are read directly from the computer output. The output of primary interest to the general study is the distribution of MEAN (RSP) according to clock time as given in Eq. 13. With the MEAN (RSP) known, the macroscopic "within" TRT diseconomy can accordingly be identified. The detailed computations of the diseconomies are given in the analysis section.

Several interesting additional observations may be made which suggest the possibility of much more general uses of this coordinated field and computer technique. In Figure 14, the first three vehicles are moving at fairly high speeds (48, 46, 52 fps); the 4th vehicle, which measures 617 in. from its first to last axle, is a truck moving at a speed of 20.5 fps. All vehicles behind this truck are moving at the greatly reduced speed. The speeds proceed to build up until the arrival of what appears to be an Isetta type of vehicle (the 7th vehicle in the 15th min in Figure 15), whereupon speeds again are reduced.

Referring again to the 14th minute (Fig. 14), the following distances of the high-speed vehicles are 184, 150, 171 ft, whereas that for the truck (4th vehicle in line) is 583 ft. Thereafter, the following distances are 82, 62, 88 ft, etc. The picture conveyed by the data, therefore, is a large space gap ahead of the truck followed by a relatively tightly bunched platoon of slow-moving vehicles.

Figures 14 and 15 pertain only to the shoulder lane. However, the general study

THE FOLLOWING IS FOR DATA COLLECTED AT SITE 8 LANE 3

DATA IS FOR MINUTE NUMBER.14

V(I)	W(I)	D(I)	WBC(I)	B(I)	FTC	CLG	FTC.CLG
48.193	102.940	184.000	2	7.035	NO	NO	NO
45.977	113.655	149.880	3	10.149	NO	NO	NO
51.948	109.714	171.172	2	13.962	NO	YES	NO
20.513	617.108	583.376	4	25.210	NO	NO	NO
18.957	115.564	82.380	3	29.242	NO	NO	NO
18.433	507.429	61.725	4	32.504	NO	NO	NO
14.440	126.845	87.834	3	37.329	NO	NO	NO
18.265	116.822	36.022	3	39.904	NO	YES	NO
15.267	120.000	40.201	3	42.148	NO	NO	NO
13.072	115.765	27.405	3	43.987	NO	NO	NO
13.652	115.167	33.255	3	46.518	NO	YES	NO
24.390	112.976	76.997	3	52.029	NO	YES	NO
28.777	126.389	58.463	3	54.401	NO	YES	NO
25.157	112.000	58.763	3	56.463	NO	NO	NO
22.989	126.621	89.912	3	60.052	NO	NO	NO

```
              N= 15.              N(FTC)=  0.             N(CLG)=  5.       N(FTC.CLG)=  0.

       N(WBC1)=  0.             N(WBC2)=  2.            N(WBC3)= 11.          N(WBC4)=  2.
   N(WBC1.FTC)=  0.         N(WBC2.FTC)=  0.        N(WBC3.FTC)=  0.      N(WBC4.FTC)=  0.
   N(WBC1.CLG)=  0.         N(WBC2.CLG)=  1.        N(WBC3.CLG)=  4.      N(WBC4.CLG)=  0.
N(WBC1.FTC.CLG)=  0.     N(WBC2.FTC.CLG)=  0.    N(WBC3.FTC.CLG)=  0.  N(WBC4.FTC.CLG)=  0.
    P(N)(WBC1)=  0.         P(N)(WBC2)= 13.33       P(N)(WBC3)= 73.33     P(N)(WBC4)= 13.33
  P(WBC1)(FTC)=  0.       P(WBC2)(FTC)=  0.       P(WBC3)(FTC)=  0.     P(WBC4)(FTC)=  0.
  P(WBC1)(CLG)=  0.       P(WBC2)(CLG)= 50.00     P(WBC3)(CLG)= 36.36   P(WBC4)(CLG)=  0.
P(WBC1)(FTC.CLG)=  0.   P(WBC2)(FTC.CLG)=  0.   P(WBC3)(FTC.CLG)=  0. P(WBC4)(FTC.CLG)=  0.

        TNVNC=  0.               N= 15.              ALLV= 15.     FVNC=TNVNC/ALLV=  0.
        MEANV= 25.335        MEAND=110.226          VARV=167.399
        SAVEV= 35.003        SSUMN=107.

  MEANV(WBC1)=  0.      MEANV(WBC2)= 50.070     MEANV(WBC3)= 21.904   MEANV(WBC4)= 19.473
  MEAND(WBC1)=  0.      MEAND(WBC2)=177.586     MEAND(WBC3)= 67.555   MEAND(WBC4)=322.551
   VARV(WBC1)=  0.       VARV(WBC2)=  7.051      VARV(WBC3)= 91.247    VARV(WBC4)=  2.162
```

Figure 14. Specimen output of the computer program used for computing properties of the traffic stream at the output boundary in the 14th minute.

THE FOLLOWING IS FOR DATA COLLECTED AT SITE 8 LANE 3

DATA IS FOR MINUTE NUMBER,15

V(I)	W(I)	D(I)	WBC(I)	B(I)	FTC	CLG	FTC.CLG
22.787	130.229	90.917	3	3.536	NO	YES	NO
32.000	122.112	80.852	3	6.905	NO	NO	NO
32.000	123.643	31.008	3	8.349	NO	NO	NO
26.030	129.277	69.000	3	11.010	NO	YES	NO
25.714	121.296	60.108	3	13.224	NO	NO	NO
25.398	127.434	103.679	3	16.128	NO	NO	NO
12.945	45.049	79.540	1	19.581	NO	NO	NO
27.397	120.658	25.139	3	20.300	NO	YES	NO
40.816	117.551	21.097	3	21.104	YES	YES	YES
37.037	122.667	120.735	3	24.072	NO	NO	NO
35.398	109.593	116.000	2	27.209	NO	NO	NO
34.783	112.276	49.097	3	28.598	NO	NO	NO
37.037	111.111	73.635	3	30.708	NO	YES	NO
40.816	115.102	57.778	3	32.252	NO	YES	NO
37.037	137.778	84.041	4	34.227	NO	NO	NO
41.667	137.000	105.000	4	37.150	NO	YES	NO
42.105	132.700	69.042	3	39.286	NO	YES	NO
41.237	126.185	115.074	3	42.021	NO	NO	NO
43.011	122.645	60.345	3	43.338	NO	YES	NO
42.553	116.930	64.633	3	45.143	NO	NO	NO
37.363	120.672	56.255	3	45.478	NO	NO	NO
42.553	137.301	73.421	4	45.429	NO	YES	NO
37.352	109.000	43.657	2	49.408	NO	NO	NO
44.944	138.000	40.729	4	50.700	NO	YES	NO
47.059	145.694	64.000	4	52.565	NO	YES	NO
47.619	125.714	72.500	3	54.120	NO	YES	NO
52.632	107.369	127.714	2	56.300	NO	YES	NO
41.667	127.000	81.158	3	58.302	NO	NO	NO
43.011	125.741	63.167	4	59.375	NO	YES	NO

N= 29　　N(FTC)= 1.　　N(CLG)= 15.　　N(FTC.CLG)= 1.

N(WBC1)= 1.　　N(WBC2)= 3.　　N(WBC3)= 19.　　N(WBC4)= [illegible]
N(WBC1.FTC)= 0.　　N(WBC2.FTC)= 0.　　N(WBC3.FTC)= 1.　　N(WBC4.FTC)= [illegible]
N(WBC1.CLG)= 0.　　N(WBC2.CLG)= 1.　　N(WBC3.CLG)= 9.　　N(WBC4.CLG)= [illegible]
N(WBC1.FTC.CLG)= 0　　N(WBC2.FTC.CLG)= 0　　N(WBC3.FTC.CLG)= 1.　　N(WBC4.FTC.CLG)= 0.
P(N)(WBC1)= 3.45　　P(N)(WBC2)= 10.34　　P(N)(WBC3)= 65.52　　P(N)(WBC4)= [illegible]
P(WBC1)(FTC)= 0.　　P(WBC2)(FTC)= 0　　P(WBC3)(FTC)= 5.26　　P(WBC4)(FTC)= 0
P(WBC1)(CLG)= 0　　P(WBC2)(CLG)= 33.33　　P(WBC3)(CLG)= 47.37　　P(WBC4)(CLG)= [illegible]
P(WBC1)(FTC.CLG)= 0.　　P(WBC2)(FTC.CLG)= 0.　　P(WBC3)(FTC.CLG)= 5.26　　P(WBC4)(FTC.CLG)= [illegible]

THVNC= 0.　　N= 29.　　ALLV= 29.　　FVNC=THVNC/ALLV= [illegible]
MEANV= 37.340　　MEAND= 77.037　　VARV= 52.537
SAVEV= 35.702　　SSUMN=130.

MEANV(WBC1)= 12.945　　MEANV(WBC2)= 41.204　　MEANV(WBC3)= 37.753　　MEANV(WBC4)= [illegible]
MEAND(WBC1)= 79.540　　MEAND(WBC2)= 75.791　　MEAND(WBC3)= 74.252　　MEAND(WBC4)= [illegible]
VARV(WBC1)= 0.　　VARV(WBC2)= [illegible].907　　VARV(WBC3)= 24.177　　VARV(WBC4)= [illegible]

Figure 15. Specimen output of the computer program used for computing properties of the traffic stream at the output boundary in the 15th minute.

includes analyses for the middle and median lanes as well, with all three analyses being on the identical time base. This permits correlating properties of the traffic stream in one lane with those in the adjacent lanes. For example, an analysis (not shown here) of traffic in the middle lane shows that this traffic was moving quite rapidly at the instant the truck in question in Figure 14 presumably was causing the shoulder lane traffic to move much more slowly. The computer output thus easily discloses the widely recognized situation: a truck moving slowly up a grade followed by a long line of cars which are prevented from passing the truck by high-speed traffic in the adjacent lane.

The major significance of the work is that, through the use of the relatively simple multi-lane detector field techniques coupled with the high-speed computer analysis, it becomes possible and economically feasible to quantify in a highly precise manner a wide variety of properties of interacting traffic streams. Readily recognized are the implications this has for theoretical and applied traffic research.

TRAVEL TIME REQUIRED TO NEGOTIATE SYSTEM OF INTEREST, AND ANY INFERRED DISECONOMIES

License matching was selected as the method for determining travel time in this study for three reasons. First, it was mandatory that travel time be measured as accurately as possible, and, in the words of Highway Research Board Committee on Operating Speeds in Urban Areas (4):

> "..... The license matching method has been accepted by the Committee as being a reliable standard upon which to base the accuracy of other methods..........."

Second, it was known from the inception of the study that a large number of travel time measurements would be required at fairly close (clock) time intervals. Repeated trials in pilot studies indicated that something of the order of three to four runs could be made by a single floating car during the afternoon peak hour. Thus, it did not appear that any of the variations of floating-car techniques would be practical. As it developed with the license matching method, the equivalent of approximately 5, 000 floating-car runs were obtained in a 1-hr period.

Third, this study required travel time measurements over 38 input-output combinations, with each of the lanes at the primary output boundary being treated as separated sites for purposes of lane-to-lane comparisons. Furthermore, the measurements had to be made essentially at the same (clock) time. It was out of the question to attempt this set of measurements with anything but license matching methods.

Notwithstanding these strong arguments favoring the license method, there were the difficulties associated with the method, as pointed out by Walker (4), of obtaining matchings, subtracting time of passage, and eliminating spurious matchings. These difficulties were minimized in large measure by using computer method that was reported earlier by Brenner, Mathewson, and Gerlough (11). A technical memorandum outlining the program will shortly be published (15).

The input to the computer included the individual licenses, site at which they were identified, and (clock) time at which they were identified. The license encoding was limited to the first five characters (3 alphabetic, 2 numeric) to reduce card punching costs. However, obviously spurious matchings occurred with the five-character identification. Suspicious matchings were apparent from unusual travel times, and could easily be confirmed as spurious by reference to the original field data. Consequently, in future studies, all six characters will probably be used.

Although the clock time was recorded in the field to the nearest second, it was encoded by minute for computer analysis because the computer program permits a five part linear interpolation of time which could yield interpolated answers to 12-sec accuracy. This was considered adequate for purposes of this study. Also, this procedure of outputting travel time in units of ⅕-min significantly simplifies enumeration of results.

The computer output of interest included the license that was a matching, its input site, its output site, the input clock time, output clock time, and finally the difference in clock time; that is, travel time.

A specimen graph of travel time plotted against clock time at the input boundary is shown in Figure 16. This particular figure pertains to travel from site 1 to site 8, and hence represents the primary freeway traffic; that is, "the slot" traffic. Each point on the curve represents the average of the travel times for all vehicles arriving at the input boundary in the given minute. The minute input volumes vary from 28 to 42 vehicles, and the graph represents in all 960 vehicles. Similar graphs have been prepared for every input-output combination but are not shown here.

It can be seen in Figure 16 that distinct travel time peaks occurred at approximately 4:10 p.m. and 4:40 p.m. for the movement from sites 1 to 8. The same double peak picture occurs in all of the other flow path combinations; for example, sites 2 to 8, 1 to 7, 2 to 7, etc. It is a matter of considerable interest to examine some of the possible explanations for the two peaks occurring, instead of a single uniform p.m. peak, as would be normally expected.

The first possibility is that there was coincident traffic congestion downstream of the section of interest. However, an examination of RSP (OUB) failed to disclose any unusual build up at the same time the two TRT peaks occurred. This may be seen in Figure 16 in which the inferred mean TRT curve is plotted on the same (clock) time scale as the realized mean TRT curve. The inferred curve is deduced directly from, and is a linear function of RSP (OUB). Each point on it, as with the realized curve, represents an average of the RSP (OUB) performance of upwards of 20 vehicles. It can be seen that RSP (OUB) is generally increasing during the course of the hour, but there are no peaks that could be related to the realized TRT peaks. The only distinct peak, at CLT (INB) = 1,651, was due to a minor bumper-to-bumper accident which occurred downstream of OUB at 1,657.

A second possible explanation of the TRT peaks is volume of traffic at the output boundary. In Figures 17 (a) and (b), 1-min lane volumes and 1-min totals of all traffic of the output boundaries are plotted on the same (clock) time scale as the TRT. Also plotted are 5-min totals of truck volumes for all trucks, busses, and 5-min totals for

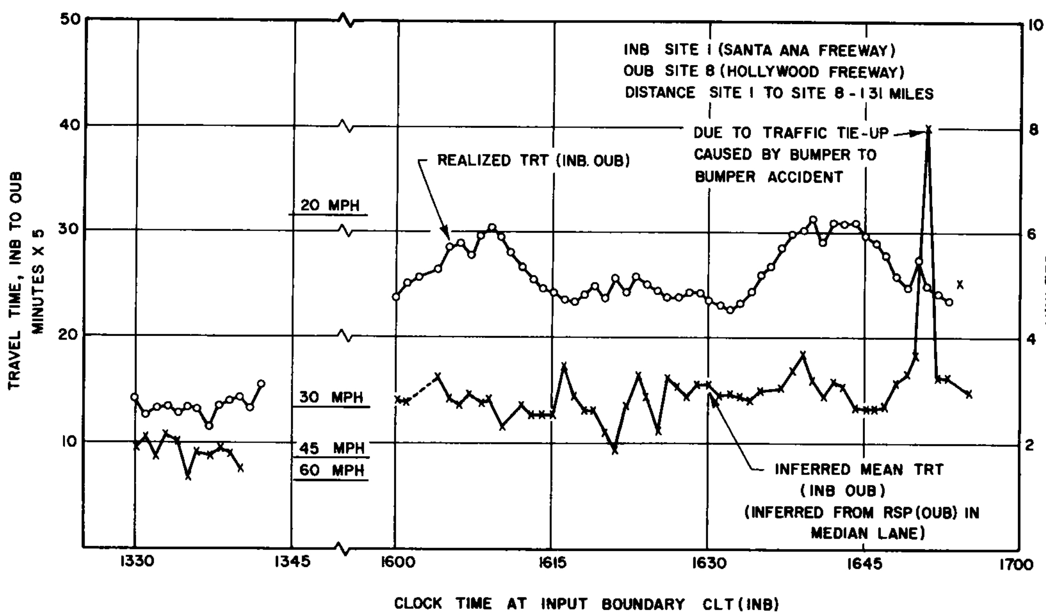


Figure 16. Specimen graph of travel time as a function of clock time at the input boundary.

the "heavy" trucks; that is, trucks with semi or full trailers. It can be seen that the total volume curve essentially remains flat over the hour. Both truck curves, if anything tend to drop from 4 to 5 p.m. Therefore, from these curves, there is little indication that the TRT peaks coincide with the volume factors (total volume, lane volumes, truck volumes).

A particularly interesting result is seen by comparing the curve of shoulder lane volume with the truck curves. The shoulder lane volume is in a decided upward trend from 4 to 5 p.m. while there concomitantly is a definite downward trend for both truck curves. Most of the heavy trucks (73 percent) are in the shoulder lane. Thus the paired trends could be construed as an argument on the reduction of capacity with truck

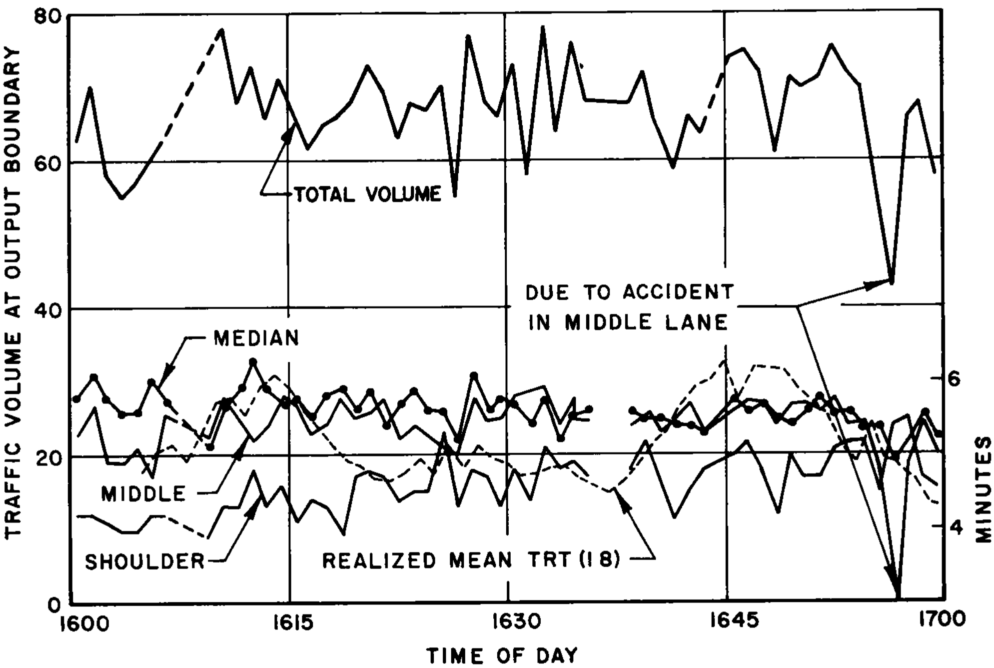


Figure 17(a). Lane-by-lane volumes, total volume, truck volume at the output boundary as a function at clock time.

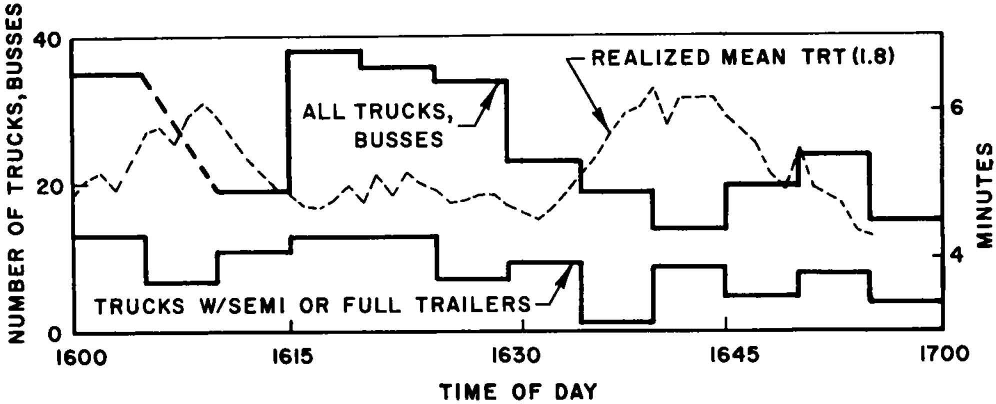


Figure 17(b). Lane-by-lane volumes, total volume, truck volume at the output boundary as a function at clock time.

traffic. On the other hand, the volumes in the middle and median lanes are essentially constant for most of the hour, and hence might represent the practical capacities. The build up in the shoulder lane might therefore be due to a build up in total demand on the system, with the incremental volume appearing in the shoulder lane because the other two lanes were operating close to practical capacity. The concomitant decrease in truck volume might not therefore be the dominant reason for the increase in shoulder lane total volume. (The capacity results obtained at site 8 are in relatively close agreement with those reported by Webb and Moscowitz (17) on observations made near this site in August 1956. They suggest using the volume during the highest 5-min period as a basis for estimating the peak hour volume. The essentially flat nature of the median and middle lane curves in Figure 17 support their view completely. It also appears that a slightly more refined estimate might be obtained by taking separate 5-min estimates for the middle and median lane, and then applying a correction factor for the shoulder lane based on a "least squares" straight line. First, however, further studies would be needed to establish the generality of the linear coefficients.) The important conclusion here in the travel time context, is that the TRT peaks occur contrary to capacity factors—indications that the TRT variable relates to more complex factors than capacity alone.

The only data in this study which appear to be closely related to the travel time peaks are the number of vehicles coming onto the freeway proper from intervening on-ramps. The on-ramp movements are plotted in Figure 18 on the same (clock) time scale as travel time. There are three distinct on-ramp peaks, approximately at 4:12 p.m., 4:22 p.m., and 4:37 p.m. The 4:37 peak of on-ramp traffic could be causing the 4:35 to 4:48 TRT peak; the 4:12 peak of on-ramp traffic could be related to the 4:05 to 4:12 TRT peak; the 4:22 on-ramp peak might be related to the (small) 4:20 to 4:25 TRT peak.

In the absence of more detailed information, these observations as to possible relationships between the on-ramp movements and through travel time can only be treated as conjectures. It is known, however, that there are at least two distinct "waves" of on-ramp traffic during the afternoon peak hour coincident with the two quitting times, 4:00 p.m. and 4:30 p.m., for many governmental workers in the civic center. It accordingly is at least a plausible consideration that the TRT peaks are related to on-ramp movements as shown.

ESTIMATES OF FLOW PERCENTAGES FOR DIFFERENT INPUT-OUTPUT COMBINATIONS OF THE SYSTEM

This sub-study deals with estimating the percentages of traffic at a given input site moving through the system to exit at a given output site. Quantifying the relative volumes of traffic moving between the various input-output combinations is referred to as a "flow pattern analysis", and has a wide variety of uses. The immediate use in this study is for obtaining travel time for the "collection" as defined earlier, with the make-up of the "collection" being directly deduced from the flow patterns. Another important reason for determining flow patterns is to provide one of several bases required for estimating the amount of traffic that will be diverted from the "system of interest" as additional links in the total freeway network are completed.

Some of the present SAF - HRF, and SBF - HRF traffic will use the Santa Monica Freeway (now under construction) and by-pass the "slot" which presently is a necessary link in its freeway path; some of the SAF - HLF, and SBF - HLF traffic will also be diverted from the "slot" when the Golden State Freeway is completed. Conceivably, the amount of diverted traffic might reduce the load on the "system" to a point where the system would operate without undue congestion even with ramps remaining open that are now being considered for closing. Any relief afforded by closing the ramp would thus only be needed for a relatively short period of time, and might not be worth whatever negative publicity could come with closing the ramp. More important than negative publicity, however, would be the expenditure of significant sums of money to relieve a present bottleneck in the face of some likelihood that the bottleneck would automatically be relieved with the completion of additional links of the network.

Knowledge of the flow patterns is invaluable for evaluating this likelihood that the problem will correct itself as the planned-for network links are completed.

The problem of estimating the volume of traffic at a given on-ramp that proceeds to a particular off-ramp of a freeway system has been treated in detail in an earlier work by Brenner, Mathewson and Gerlough (11). In a later work, Mathewson and Brenner apply the same technique to estimating through traffic on a surface street network (16). The technique is particularly well suited to the present study because of the difficulty in obtaining a 100 percent sample at some of the sites coupled with the fact that the technique permits sampling of traffic. The formula used for estimating the flow percentages in this technique (derived in the earlier work (11)) is:

$$P\left\{(A)\ (B)\right\} = \frac{[NM\ \{(A)\quad (B)\}]\quad [TV\ (B)]}{[NI(A)]\quad [NI(B)]} \tag{15}$$

in which

$P\left\{(A)\ (B)\right\}$ = percentage of vehicles at A going to B;

NI (A) = number of vehicles identified at A;

NI (B) = number of vehicles identified at B;

TV (B) = total volume of traffic at B; and

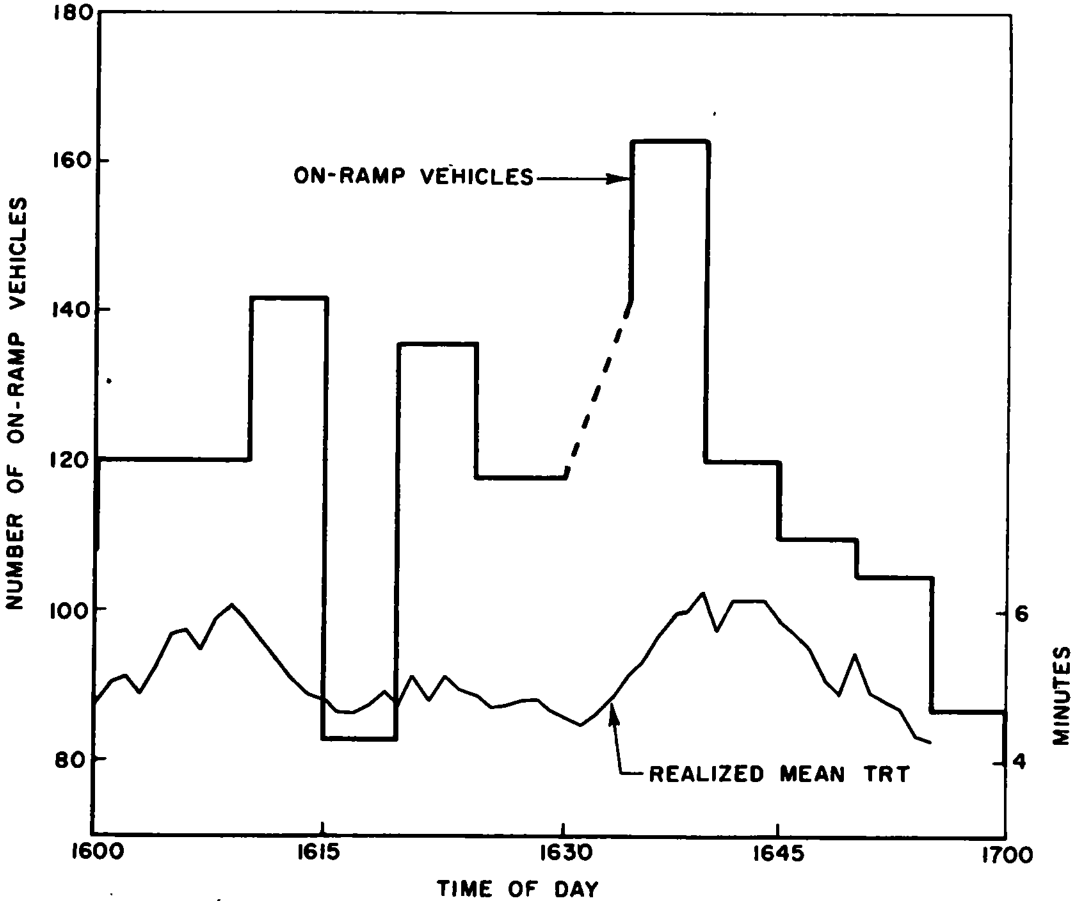


Figure 18. On-ramp movements as a function of clock time at on-ramp.

NM $\{(A)(B)\}$ = number of license matchings between the NI (A) and NI (B) identifications.

All of the factors in Eq. 15 had to be measured experimentally to determine network travel time as discussed in "Travel Time Required to Negotiate System of Interest, and any Inferred Diseconomies." Thus, the flow percentages could be obtained at no extra experimental cost, and the flow pattern analysis can accordingly be regarded as an immediate by-product of the travel-time analysis, or vice versa. However, not nearly as many license matchings are needed to produce a travel time analysis of fairly high percision as are needed for a precise flow pattern analysis.

The results shown in Figure 19 concern the percentage of traffic at specific input sites that proceed to specific output sites—P (INB. OUB). The results shown in Figure 20 concern the percentage of traffic at specific output sites that come from specific input sites—P (OUB. INB). Both sets of percentages were computed in two ways. In the first, Eq. 15 is the basis of the first method which essentially seeks to correct for the sampling ratios. The second method is based strictly on the distribution of matchings and became necessary after it was found that with the first method, the total percentages were significantly lower than the expected summation for a set of probabilities; namely, unit.

Some of the discrepancies between the percentage totals and unity can be explained by traffic to the unmanned intervening sites. The greater part of the discrepancy,

AT ↓ / TO →		OUTPUT SITES: Off-Ramp 3	Freeways 8	Freeways 9	Freeways 10	Primary Total	Auxiliary to Site 11
INPUT SITES: Freeways	1	.01 / .01	.48 / .78	.10 / .16	.04 / .05	.63 / 1.00	.45 /
	2	.03 / .07	.20 / .45	.21 / .47	.05 / .01	.49 / 1.00	.19 /
INPUT SITES: On-Ramps	4		.45 / .71	.14 / .23	.05 / .06	.64 / 1.00	.35 /
	5		.49 / .81	.08 / .12	.05 / .07	.62 / 1.00	.47 /
	6		.25 / .39	.32 / .52	.07 / .09	.64 / 1.00	.31 /

Flow percentage as estimated with sampling ratio adjustments. / Flow percentage as estimated from matchings, without considering sampling ratios.

Figure 19. Percentages of traffic at input sites that proceed to output sites P(INB.OUB).

AT → / From ↓		OUTPUT SITES: Off-Ramp	Freeways		
		3	8	9	10
INPUT SITES: Freeways	1	.10 / .25	.33 / .55	.11 / .24	.18 / .50
	2	.40 / .75	.14 / 21	.24 / .49	.02 / .07
INPUT SITES: On-Ramps	4		.05 / .09	.03 / .07	.04 / .12
	5		.05 / .09	.01 / .03	.04 / .11
	6		.04 / .06	.08 / .17	.07 / .20
Total		.50 / 1.00	.61 / 1.00	.47 / 1.00	.35 / 1.00

Flow percentage as estimated with sampling ratio adjustments. — / — Flow percentage as estimated from matchings, without considering sampling ratios.

Figure 20. Percentages of traffic at output sites that come from input sites P(OUB.INB).

however, can only be interpreted as stemming from licenses being incorrectly identified. These errors prevent licenses from being matched (missed matchings) resulting in flow percentages computed according to Eq. 15 being lower than they should be. Furthermore, the ultimate estimate of the percentage is lowered by erroneous identifications at the input site independently of erroneous identification at the output sites, and by errors at the output site independently of those at the input site. Identifying licenses incorrectly is known to be the major bias in applying Eq. 15 to a real traffic situation, and is discussed in detail by Brenner, et al. (11).

Using the matchings (which would have to be correct identifications) as reference points, it was possible to isolate obvious errors in the (unmatched) identifications, and to estimate that something of the order of 5 percent of the identifications could be suspected as being in error, and this number of erroneous identifications would easily explain the flow extimates being low. But, rather than proceed through the entire set of data in the extremely laborious checking for incorrect identifications, a more gross estimation procedure was used. In this procedure, flow percentages were estimated by the relative percentages of matchings within a total set of matchings. For example, of the 1,766 matchings among the site 8 traffic, 960 were site 1 matchings, and the ratio of 960 to 1,766 or 0.78 was treated as the flow percentage of site 8 traffic from site 1.

This procedure based on matchings, although not precise, is not as gross as might be suspected at first glance. For one thing, it is exact if the sampling ratios at the output sites are the same. The sampling ratios at sites 8 and 9 are 0.84 and 0.83, respectively. Thus the respective number of matchings site 1 to site 8, and site 1 to site 9 are essentially in direct proportion to the respective flow percentages. Because the flows to these output sites from the input sites 1 and 2 represent the major part of the traffic through the system, accurate percentage estimates for these two primary patterns cause the patterns for the system as a whole to be fairly accurate.

Additional support for the belief that the gross procedure has yielded results that are sufficiently accurate for purposes of this study may be seen in the ramp data. From the mailing questionnaire, the flow percentages of BON traffic to HRF, PSF, and HLF are 50.0 percent, 11.8 percent, and 38.2 percent, respectively. The same percentages as obtained from the gross matching procedure for the same traffic are 52.0 percent, 39 percent, and 9 percent, respectively. Similar agreement exists for the other on-ramps.

Notwithstanding the fact that the number of matchings obtained in this study were sufficiently high (and the sampling ratios at the output boundary for the primary traffic happened to coincide) to yield what appear to be sufficiently accurate estimates of the flow percentages for the major flow patterns, it nevertheless is necessary to examine the present and ultimate usefulness of the techniques based on Eq. 15. The identification errors could have occurred anywhere in the total process beginning with the observer dictating the license, continuing through the data reduction process, and to the ultimate encoding of the data onto punched cards. Errors obviously occurred in the dictation in the field; there is evidence of this in a by-product investigation which will be described presently. There also is evidence of errors in the photographic reading due mainly to changing light conditions under which the licenses were originally photographed. Furthermore, the investigators detected encoding errors, notwithstanding the fact that the card punching was also verified.

These three major sources of error can be remedied at least in part. The observers used in the study were not experienced in the dictation methods and with more training and experience would undoubtedly perform better. Since the date of the study, there has become available a new film (18) designed to give more than twice the speed of the film used in the study without a significant increase in graininess. It appears that with the new film a much sharper picture of the license plate will be obtained, with the result that errors in license identification should be reduced. Finally, there are several controls on the data handling procedures that would further reduce errors. It, therefore, appears that Eq. 15 will prove to be more effective for freeway work than shown in the present study. At the present state of the art, however, the technique probably should be applied principally at ramp-to-ramp types of freeway pattern analysis.

The by-product investigation mentioned earlier involved computing two independent sets of flow percentages for traffic heading for the Hollywood Freeway. Site 8 (Grand Avenue overcrossing) is the output boundary in one set; site 11 (Edgeware Avenue overcrossing) is the output boundary in the second set. The input boundaries are identical for the two sets. Both sites are on the Hollywood Freeway, and are approximately ½ mi apart, with traffic of interest reaching site 8 first.

Site 8, being the primary OUB of the study, had relatively complete coverage; namely, a camera on each of its three lanes together with the observer using a tape recorder for time check purposes. The over-all sampling ratio, licenses identified to total volume of traffic, was 84 percent. Site 11, on the other hand, had the much lower sampling ratio of 16 percent for several reasons. This site was included in the experiment plan principally as the downstream control point for site 8; that is, to provide an RSP (OUB) measurement in the event of equipment failure at site 8. Inasmuch as relatively small number of license identifications would suffice for this purpose, identifications were limited to whatever identifications two observers, each with his own tape recorder, could make of the very heavy traffic on the four lanes at this site. Also contributing to the depressed sampling ratio was the fact that the volume of traffic was much higher at site 11 (ADT = 106,300) than site 8 (ADT = 59,100) because all of the traffic bound for the Hollywood Freeway from the Harbor Freeway

(ADT = 36,000) and Pasadena Freeway (ADT = 11,200) passes site 11, but not site 8.

Because all of the traffic at site 8 has to pass site 11 (there being no intervening off-ramps), the percentage of traffic at a given on-ramp going to site 8 is identically the same as the percentage from the same on-ramp going to site 11. By treating sites 8 and 11 as two independent output boundaries in the license matching formulas, two independent estimates are obtained of the same variable. The question is how well the two estimates will agree with each other.

It may be seen in Figure 19, that the two sets of flow percentage estimates are in close correspondence, indicating that two observers, equipped with nothing more than tape recorders, were able to produce a flow pattern that is essentially the same as that produced by the more expensive camera technique. The far-reaching implication is that with the portable tape recorder technique, it should be possible to map complete time gradients for a freeway network and at the same time obtain reasonably accurate estimates of flow patterns—both at relatively low cost. The photographic method, particularly with the new film, would continue as the more desirable in those situations where the flow patterns have to be determined more accurately.

GENERAL ANALYSIS

The general analysis seeks to estimate a priori how closing a particular on-ramp, the Broadway Avenue On-Ramp in this case, will affect the travel time the "collection" requires to clear the system of interest, with the "collection" being comprised basically of three classes of traffic: (1) the freeway traffic, (2) the surface street traffic, and (3) the ramp traffic that will have to go to a different ramp. The analysis brings together the results of the previously described sub-studies, seeking only order-of-magnitude estimates. Furthermore, the analysis is limited to a 1-hr p.m. peak period. The extrapolations of these data to a full day, week, or month period are not performed here because they contribute nothing additional to the presentation of the analytical techniques. Clearly, it would be necessary to extrapolate the data in actual practice.

Effect on Present Ramp Users

The "mailing" questionnaire and the subsequent "expert" questionnaire established that most of the present Broadway Avenue On-Ramp (BON) traffic would head for the Grand Avenue On-Ramp (GON) in the event BON was closed. The most conservative treatment is assumed, specifically, that all of the BON traffic would head for GON, because this condition would cause the greater decrement to surface street patterns as well as to the diverted traffic.

A total of seventeen points of origin of BON users were identified in the surrounding surface street network. For each point of origin, a new route was traced out on the surface street network to the freeways via GON. The new route was then compared with the present routes to BON. From the known differences in distance between the routes to GON and BON, a travel time decrement was estimated considering that the average speed of traffic was 15 mph on surface streets and 30 mph on the freeway. The realized average spot speed on the freeway (median lane) was 26.5 mph, so that using the 30-mph speed is conservative. The travel time decrement for each route was then weighted by the number of vehicles using that route, the (weighting) numbers being determined from the replies to the mailing questionnaire. The weighted decrements were finally added to yield an estimated total decrement for all traffic during the hour. This amounted to 1,070 vehicle-minutes.

The analysis was then repeated considering that freeway traffic was moving at 15 mph, instead of 30 mph. The results show a time saving of 585 vehicle-minutes in the hour if BON traffic took the alternate routes via GON to the freeway as contrasted with the time loss of 1,070 vehicle-minutes in the previous analysis. Thus, if freeway traffic is moving at the slow speed, it pays the BON traffic to stay on the surface streets a bit longer and enter the freeway network at the GON ramp. If the freeway traffic is moving at the faster speed, the BON traffic experiences a time loss by having to delay getting onto the freeway until GON. The point of indifference for the BON traffic is not computed here, but would have freeway traffic moving at some speed between 15 mph and 30 mph. Instead, the 30-mph figure is used and the time loss considered to be 1, 070 vehicle-minutes.

Effect on Present Surface Street Traffic

For each of the seventeen points of origin in the surface street network, a distance decrement had to be computed between the two alternate paths to the freeway network (via BON or GON) to establish the time decrement. As was done with the time decrement, the distance decrement was also weighted by the relative number of ramp users taking the present (BON) path according to the mailing questionnaire. The weighted sum was +10. 7 miles which shows that by using the alternate path via GON, present BON traffic in the p. m. peak hour would save this aggregate distance. In other words, present BON users are driving slightly longer distances on the surface streets to get to the freeway in order to obtain the time benefit of driving on the freeway. This exemplifies the widely recognized pheonmenon of drivers traveling greater distances (in this case both on the surface streets and the freeway) to reduce their over-all travel time. A problem of major interest would be to determine these trade-off curves (distance for time) under a wider variety of conditions.

Taken at face value for the purposes here, the results suggest that diverting the BON traffic to GON will not be detrimental to present surface street traffic because, if anything, the diversion will reduce the mileage being driven on surface streets. This is an oversimplification, of course, for there might be local disturbances that would cause the surface street traffic to suffer travel time decrements in spite of the aggregate vehicle mileage being reduced. In any case, it does not appear that the effects on present surface street traffic will be severe.

Effect on Present Users of the Alternate Ramps (s)

The most critical local disturbance resulting from diverting traffic from one ramp to another is expected to be at the alternate ramp. If the alternate ramp is lightly loaded, the disturbance will be minimal, but if it is already heavily loaded, the additional traffic would undoubtedly cause a severe local disturbance. As stated earlier, in the most conservative analysis (that is, to produce the most severe local disturbance) all of the BON traffic would be considered to be diverted to the one alternate ramp, GON. However, from the "expert" questionnaire it is judged that were the Broadway On-Ramp to be closed, the present BON. PSF traffic would go to the Castellar On-Ramp, not to the Grand Avenue On-Ramp. This amounts to 9 percent of the BON traffic. Also, the back-up on the collector road of traffic heading for the Harbor Freeway during the peak hours usually extends beyond the point where the GON traffic merges with the collector road. It accordingly is judged that BON. HRF traffic would head for GON for the first few days after BON is closed, but after encountering the back-up at GON, would seek out the more logical ramp to get on to HRF at 3rd Street. (This ramp is not shown in any of the figures because it is not a part of the defined "system", but should now be included in the over-all analysis. Required is the effect that present BON. HRF traffic will have on the surface street network which intervenes between points of origin and the 3rd Street On-Ramp. To simplify the presentation here, this iteration is omitted, and the assertion made that the BON. HRF traffic will create far less disturbance using this as the alternate ramp rather than GON.) From the flow pattern analysis, the BON. HRF traffic is 52 percent of the BON traffic.

Thus, the net effect closing BON would have on GON at the outset would be an additional loading comprised of 61 percent of the present BON traffic or 400 vehicles. This would drop to 39 percent of the present BON traffic, or 250 vehicles after the system became stabilized. The Grand Avenue On-Ramp presently carries 1, 400 vehicles during the evening peak hour, so that its ultimate peak hour volume will rise to 1, 800 vehicles immediately after the BON is closed, and drop off to 1, 650 vehicles after several weeks.

It is difficult to estimate precisely the travel time decrement that the increased loading of 250 vehicles per hour (or 4 to 5 vehicles per minute) will produce on a one-lane ramp. However, with several minor adjustments, Wingo's (3) ingression model can be applied to the problem. In his model

$$Y = \frac{N^2}{2C} \tag{15}$$

in which

Y = total ingression loss for the inflow phase of a cycle;
N = number of vehicles constituting the cyclic demand on the ramp; and
C = cyclic capacity of the ramp.

If N_1 and N_2, respectively, represent the cyclic demands on GON before and after BON is closed, the incremental ingression loss per cycle will be

$$\Delta Y = \frac{N_2^2 - N_1^2}{2\,C} \tag{16}$$

To simplify the arithmetical computations here, 1 min is arbitrarily set as the cycle length as a basis for treating the cyclical demand on GON, and the total change in the ingression loss for the 1-hr period is considered to be 60 times the value for the 1-min cycle. For a more precise analysis, the actual cyclic demand (which would be directly related to the cycle length, division, phase relationships of the traffic signals at adjacent intersections) should be considered, as well as variations in demand from cycle to cycle.

Using the simplifying assumptions, and considering that the capacity of the ramp is 1,000 vehicles per hour in Eq. 16, the change in ingression losses during the peak hour at GON due to increased demand is found to be 246 vehicle-minutes.

Effect on Present Users of the Freeway

Based on the pattern analysis described in the section on "Estimates of Flow Percentages for Different Input-Output Combinations of the System," the nature of the 4 to 5 p.m. "collection" can be approximated (Table 5). The problem here is to estimate how eliminating BON traffic will affect the travel time the remainder of the "collection" requires to negotiate the "system". As discussed in the section on "Travel Time Required to Negotiate System of Interest, and Any Inferred Diseconomies," the two realized travel time peaks in Figure 16 appear to be related most directly to ramp movements; capacity-type arguments do not appear to correlate too closely. Whatever caused them, the two peaks demonstrate that significant travel time diseconomies are being generated in the system.

To quantify the diseconomies, some "normal" travel time must be selected as a base from which the diseconomy is to be established. Several possible bases are plotted in Figure 16 including horizontal lines which portray speeds of 20, 30, and 60 mph being uniformly maintained by a vehicle proceeding from INB to OUB, and an inferred travel time curve based on RSP (OUB). Each point on this inferred TRT curve is a point C in Figure 4, and was determined by adding the TRT (INB. OUB) to CLT (INB) to obtain a CLT (OUB). The RSP was then measured at this CLT (OUB) and used to find the ordinate of the inferred TRT curve at the CLT (INB) abscissa. The inferred TRT curve thus is shifted on the clock time axis by the amount of the TRT (INB. OUB) for the collection at CLT(INB).

From the standpoint of the over-all concept, it is a matter of indifference whether one of the constant speed curves or the inferred curve is selected as the base from which the diseconomies are to be established. The method in every case would involve measuring the travel time difference between the realized curve and the base curve, and then weighting the difference by the number of vehicles that experienced that travel time decrement. The inferred TRT curve is used because it is keyed into actual measurements, RSP (OUB), while any constant speed curve would have been more or less arbitrarily selected.

It must be recognized that there also is an arbitrary aspect to the inferred TRT curve. Specifically, the curve is a direct function of the location of the output boundary. For example, if the boundary was at the beginning of an upgrade, one curve would have resulted, but there would have been a different one had the boundary been on a level tangent section, etc. However, the output boundary was chosen to fit the problem of operational interest (that is, performance of the "slot"), and not because of geometry of the freeway at that point. Thus the use of the inferred TRT curve is not completely arbitrary.

With the inferred TRT curve as a base, the macroscopic TRT diseconomy was found to be 11,451 vehicle-minutes during the hour 4 to 5 p.m. Remaining to be answered is the difficult question of how much of this is due to traffic from the on-ramp in question, and how much is due to the other ramps and different factors such as the presence of trucks, the grade (maximum 4.8 percent) of the freeway, lane changing, and others. The question will be answered indirectly in the next section by estimating how much the reduction in travel time would have to be to match the different increases in travel time associated with the hypothesized ramp closing.

Summary Analysis

The total negative travel time saving (that is, increase in travel time) is 1,316 vehicle-minutes in the 1-hr period. This is due to the ingression losses of the waiting stream at GON, and to the (maximum) time loss that present BON traffic will experience with the closing of BON. The total number of vehicles in the collection is approximately 6,000, so that the "break-even" point for the ramp-closing decision is that the average vehicle in the collection realizes a minimum TRT saving of 13 sec with the closing of BON.

At this point, and until the planned-for detailed statistical analysis actually partials the total "within" diseconomy of 11,451 vehicle-minutes into the components due to truck effects, volume effects, and effects of the separate ramps, it is strictly a matter of opinion as to whether or not the break-even point was reached in these data. The authors are of the opinion that the break-even point was substantially exceeded because: (1) most of the total diseconomy appears to be due to the two peaks, (2) ramp movements are the only factors which peak in the same manner, and (3) BON traffic represents approximately one-third of all of the ramp movements.

TABLE 3

THE "COLLECTION" DURING THE HOUR 4 TO 5 P.M.

Item	BONO	BONC	ΔTRT[1] (veh-min)
N (BON)	620	0	-
N (SAF.HLF)	1,990	1,990	5,337
N (SAF.HRF)	408	408	956
N (SAF.PSF)	128	128	300
N (SBF.HLF)	1,170	1,170	1,703
N (SBF.HRF)	1,220	1,220	2,360
N (SBF.PSF)	27	27	57
N (AON.HLF)	390	390	529
N (LON.HLF)	364	364	
N (AON.HRF)	127	127	154
N (LON.HRF)	54	54	
N (AON.PSF)	33	33	55
N (LON.PSF)	32	32	
Total			11.451

[1]ΔTRT is computed using the inferred TRT curve as the base.

Diversion Analysis

There remains one other consideration to complete the analysis; namely, how any present operational decision might be affected by completion of additional links of the programmed freeway network. By estimating the amount of traffic that will be diverted from the system of interest, the traffic volume that the system will have to handle presumably will be known. The issue then becomes one of deciding whether the present operational decisions still would be indicated under the ultimate volume conditions.

Based on the flow pattern analysis in the section on "Estimates of Flow Percentages for Different Input-Output Combinations of the System", it is estimated that with the completion of the freeway network in the Los Angeles region, 25 percent of the SAF traffic and 15 percent of the SBF traffic will be diverted from the "system of interest". Or, 17 percent of the present "system" traffic will be diverted, including 14 percent of the present truck traffic. Diversion patterns such as these have been estimated for many years; it is expected that with the flow pattern analyses providing additional information, the reliability of the estimates can be improved.

As discussed in the section on "Travel Time Required to Negotiate System of Interest, and Any Inferred Diseconomies", the relationships of TRT diseconomies to volume of traffic are not clearly recognized in the data obtained in this study. Consequently, it is difficult to estimate the amount by which the TRT diseconomy will be reduced even though it is possible to estimate that something of the order of 31, 000 vehicles will be diverted from the system.

One other point must be emphasized here. It is clear from the sections on "Spectrum of Trip Lengths According to On-Ramp of Origination", "Surface Street Travel Patterns of Ramp Users", and "Estimates of Flow Percentages for Different Input-Output Combinations of the System", that motorists trade distance for time in the region in question. If travel time through the system of interest is improved either as a consequence of traffic being diverted to other freeway links, or as a consequence of additional capacity being provided, additional traffic will be attracted to the "system" from the adjacent surface streets. This would mean more ramp traffic as well as through traffic. Thus, if the ramp effect observed at the present is real, it can be compounded rather than relieved with the completion of the links of the programmed network.

SUMMARY AND CONCLUSIONS

This paper presents a series of interrelated sub-studies which together comprise one approach to quantifying freeway performance. The fundamental dependent variable is travel time for an individual vehicle to negotiate any given link of a freeway network, the link being referred to as the "system" and being defined by a pair of arbitrarily-set boundaries. The measure of effectiveness is the summation of travel time that each of a group of vehicles requires to clear the system. The group of vehicles, called the "collection", is comprised of all vehicles arriving at all "input" boundaries of the system within some specified interval of clock time.

The quantification requires two basic classes of field measurements: first, the clock time identifications of vehicles at input and output boundaries of the system; second, closely controlled spot-speed and headway measurements at the output boundary. Derived from the license identifications is a questionnaire technique involving a direct mailing to registered owners of vehicles observed at specific ramp locations. The questionnaire serves to establish surface street paths that ramp users take in getting to or from ramps and the freeway use emanating from (or to) specific ramps. With these data, it becomes possible to extend the "system of interest" to include the adjacent surface streets, and to examine the effect of a change in one sub-system (for example, the freeway) on the total system.

Numerical results are obtained in the study for a part of the freeway network in downtown Los Angeles, but cannot be construed as representing the "system" for any period other than the day of the study. Furthermore, they are not necessarily representative of other sections of the freeway network in Los Angeles or elsewhere. Nevertheless, they are of more than passing interest insofar as they demonstrate that travel time models can produce unambiguous answers to real problems, and thereby suggest the festibility of using measures of effectiveness oriented around travel time.

The data in this study demonstrate that capacity-type arguments (in this case, flow at the output boundary) do not always fully explain travel time. Traffic flow theories oriented around capacity will not, therefore, by themselves portray performance of freeway networks, and it is suggested here that they be supplemented by theories based on travel time. There, of course, has been work on what might be referred to as theoretical "travel time" models of traffic flow (3). But the results of this paper suggest that the "travel time" phenomenon is more complex than might have been suspected, and warrants even more detailed attention than theorists have given it to date.

In addition to the theoretical work per se, there also must be "real world" measurements to validate (or negate) proposed theories and even, possibly, to suggest new theoretical avenues. Travel time models of traffic flow accordingly require measurement of travel time; capacity-type models require the much simpler counting of vehicles. This latter fact alone might explain why there has been much theoretical and applied work on capacity-type arguments, but relatively little on travel time. From this it follows that more attention should be given to the problem of measuring and analyzing travel time.

The license matching method offers substantial promise of bringing travel time field work within reasonable economic bounds, particularly with high speed electronic computers accomplishing the actual matching, subtracting clock times, detailed cross tabulations, etc. Another significant economic justification is that while producing the travel time analyses, the matching method also can yield the travel pattern analyses at essentially no additional cost. The most difficult aspect of the technique is, and will continue to be, identifying the license of vehicles moving at high speeds. Significant improvements are possible in the photographic techniques. But the full potential of the method will probably not be realized until the license plates themselves have been designed specifically to facilitate the numbers being transduced automatically into form suitable for computer input.

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