tests to examine the run time efficiency of the enhanced PASSER II-84 versus the existing PASSER II-80 on different computer systems are recommended. Developing possibly more efficient program architecture for PASSER II-84 to optimize calculation and eliminate duplicated FORTRAN coding is also recommended.

ACKNOWLEDGMENTS

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Analysis of Traffic Network Flow Relations and Two-Fluid Model Parameter Sensitivity

JAMES C. WILLIAMS, HANI S. MAHMASSANI, and ROBERT HERMAN

ABSTRACT

Presented in this paper is a systematic exploration, using microscopic simulation, of the sensitivity of network-level traffic flow descriptors and relationships, particularly those of the two-fluid theory of town traffic, to network features, traffic control, and traffic-interfering urban activity levels. Moving traffic interference, which is represented by stochastic short-term lane blockages of varying duration and frequency, is shown to be a key determinant of the traffic character of an urban street network and of the behavior described by the two-fluid theory and verified operationally. In addition, the sensitivity of the two-fluid model parameters to a change in traffic control strategy, in this case the coordination of signals to achieve progression, is demonstrated. Furthermore, keeping the same network configuration, the effect of network topology on traffic flow is examined by changing the identical length of the links.

The importance of characterizing traffic in a city network stems from the need to evaluate and compare control strategies in terms of their overall network impact, to assess the quality of operations and identify deficiencies in a given network, and to monitor the level of traffic service over time in a designated area. The complex interactions taking place in a traffic network effectively preclude the analytic derivation of network-level macroscopic relationships from the basic principles governing microscopic traffic behavior or from link-level macroscopic models. In addition, field validation of postulated theories requires considerable and often elaborate data-gathering efforts.

In a previous paper (1), Williams et al. established the feasibility of using microscopic simulation to study network-level traffic flow relationships. Computer simulation offers the opportunity to conduct systematic analyses of network traffic performance under controlled experimental conditions. In the previous effort, the NETSIM model was employed to examine the variation of mean speed with concentration in a closed test network, as well as to establish and verify relationships among certain fundamental network-level traffic flow descriptors. In addition, the sensitivity of network performance to various control and operational features was demonstrated. Furthermore, a preliminary investigation of certain aspects of Herman and Prigogine's two-fluid theory of town traffic (2) was conducted, particularly with regard to the dependence of the fraction of vehicles stopped in a network on the concentration in that network (1).

The two-fluid theory of town traffic provides a useful framework within which to attempt to characterize with a small number of parameters for traffic flow in a network. The two "fluids" consist of vehicles moving in the system and of stopped vehicles (still in the traffic stream, such as at traffic signals, as opposed to parked vehicles). The theory leads to a relatively simple relationship between the average running time and the average stopped time in a network (2). Validation studies, relying on chase-car techniques and, more recently, aerial photographs, have been ongoing for the past 5 years and have firmly established the basic underlying premises of the theory under operating conditions found in actual city networks (3-6).

In addition to the description of traffic flow in a given network under a particular traffic control scheme and usage pattern, it would be of considerable interest and practical importance to understand the mechanisms and factors affecting network-level performance characteristics such as those proposed by the two-fluid theory. Conducting this type of investigation with exclusive reliance on the observation of actual systems is clearly prohibitive and unpractical, given the need for extensive data from a large cross section of actual networks and operating conditions. As noted earlier, microscopic simulation has already yielded useful insights into these phenomena (1).

Presented here is a systematic exploration, using NETSIM, of the sensitivity of network traffic descriptors and relationships, particularly those of the two-fluid theory, to network topology, traffic control, and an urban area's "activity level" (events that interfere with the flow of traffic). The results presented contribute to two interrelated fundamental research objectives. The first is to determine how to capture, in a microscopic simulation model such as NETSIM, the fundamental character of an urban network, including the often intense levels of interfering activities. The second objective is the identification and ultimate representation of the effect of key traffic mechanisms and of a network's physical and operating features on network-level macroscopic descriptors and relations.

The relevant conceptual background is briefly presented in the next section, with particular emphasis on the key traffic flow descriptors used in the analysis as well as in the two-fluid model parameters. The basic structure of the simulation experiments is presented in the third section, along with a description of the features of the test network common to all the simulations performed in this study. The fourth section is a description of how interference with flow, which is an inherent characteristic of traffic in city networks, is captured using the "short-term events" capability in NETSIM. A systematic analysis of the effect of this mechanism for representing interfering urban activity levels on the two-fluid model parameters and their descriptors is presented in the fourth section. Further investigation of the sensitivity of network-level traffic flow relationships to network topology (block length) and traffic signal coordination is discussed in the fifth section. Concluding comments, including some implications for city traffic network operations and future research, are presented in the final section.

REVIEW OF RELATED CONCEPTS

The principal network-level traffic flow descriptors and their interrelation are described elsewhere (1). A brief review of concepts relevant to the present paper is presented in this section. These include the definition of average speed and concentration at the network level, the principal variables addressed in the two-fluid theory and the interpretation of its parameters, and the related variation of the average fraction of vehicles stopped in a network as a function of concentration.

Speed-Concentration Relation

The three fundamental traffic variables speed, concentration, and flow, extensively studied in the context of flow along arterials or through intersections, have been generalized to the network level elsewhere (1). Of interest here is the variation of average network speed (V) with average concentration (K). These averages are taken both over time and over all vehicles in the network. Average speed, in miles per hour, is thus taken as the ratio of total vehicle-miles traveled to total vehicle-hours on the network during a given observation period. The average concentration, for the same time period, consists of the time average of the number of vehicles per unit lane-length in the system. One element of control exercised in these experiments is to maintain concentration constant throughout any given observation period in order to avoid confounding effects due to varying concentrations with those under investigation.

Previous simulations (1) clearly indicated that V is a decreasing function of K at the network level also, as would be expected from the well-known speed-concentration behavior on arterials. Furthermore, the sensitivity of the K-V relationship to traffic control and usage patterns in the network was also observed in earlier simulations (1), suggesting that this relationship can provide a good indicator of a network's performance under varying network physical and operating characteristics. However, the way in which this relationship is affected by the various factors of interest remains to be established. The present computer experiments provide important insights into this relationship.

Two-Fluid Theory of Town Traffic

In their kinetic theory of multilane highway traffic, Prigogine and Herman (7) recognized the existence of two distinct traffic flow regimes: the individual and the collective flow regimes, which are a function of vehicle concentration. When concentration rises so that traffic is in the collective flow regime, the flow pattern becomes largely independent of the will of individual drivers. The two-fluid model (2) views traffic in this latter regime, in an urban network, as two "fluids": one consisting of moving vehicles and another of stopped vehicles, which remain in the traffic stream.

The basic postulate of the two-fluid theory states that V_r, the average speed of the moving vehicles, is related to f_s, the fraction of vehicles stopped, in the following manner:

$$V_r = V_m(1 - f_s)^n \tag{1}$$

where V_m is the average maximum running speed in the network and n is a parameter that has been found to be a useful indicator of the quality of traffic service in a network (4,5).

This postulate leads to a relationship between three principal variables, T, T_r, and T_s, respectively, average travel time, average running (or moving) time, and average stopped time, all per unit distance, of the following form (2):

$$T_s = T - T_m^{[1/(n + 1)]}T^{[n/(n + 1)]} \tag{2}$$

where T_m is a parameter of the model equal to V_m^{-1} and thus reflecting the minimum travel time per unit distance in the network under free-flow conditions.

The calibration of the model parameters T_m and n (both of which were found to be robust characteristics of a given network) to a particular city has been performed empirically using trip time and stop time information obtained by one or more circulating vehicles "sampling" the network according to the chase-car technique (4,5). From Equation 2, T_r is given by

$$T_r = T_m^{[1/(n + 1)]}T^{[n/(n + 1)]} \tag{3}$$

In simulation experiments, T_r and T can be calculated over any desired observation period and obtained from the output of the simulation package (1). The two parameters T_m and n can then be found by simple linear regression using a log transformation of Equation 3:

$$\ln T_r = [1/(n + 1)] \ln T_m + [n/(n + 1)] \ln T \tag{4}$$

The network parameter n can be viewed as an approximate measure of the slope of the T-versus-T_s relation (2). If n = 0, $T_r = T_m$ (see Equation 3), and trip time would increase at the same rate as stop time. If n > 0, trip time increases at a faster rate than stop time, meaning that running time (T_r) is also increasing. Intuitively, n would be expected to be greater than zero because the usual cause for increased stop time is heavier congestion, which generally results in vehicles moving at lower speeds, which implies higher average running time per unit distance.

The two parameters T_m and n, as well as the interrelation between T_r, T_s, and T and their dependence on network concentration, are important performance indicators of the effect of the various network and traffic control features of interest.

Another important quantity in the two-fluid conceptualization of traffic is f_s, the average fraction of vehicles stopped in the network, taken over a given observation period. This quantity was postulated to be an increasing function of network concentration (2), a result that was later verified (1). The variation of f_s with K and the factors that affect this variation are given particular consideration in these simulation experiments. Note in this regard that the mean fraction of time stopped (T_s/T) is used here in lieu of f_s because it is more readily calculated from the simulation output. The equality of f_s and T_s/T in a closed network has been shown theoretically (3) and verified by simulation (1).

EXPERIMENTAL DESIGN AND DESCRIPTION OF BASE CASE

In this section, the structure of the simulation experiments, as well as the characteristics of the network and traffic control scheme specified for the base condition used in this paper, is described. Although the same basic network configuration was used in all simulations, three different factors were varied in accordance with the experimental design. These factors are (a) level of traffic-interfering urban activity, (b) network topology, and (c) traffic control scheme. For each combination of factor levels, a set of five runs was performed, each run corresponding to a different network concentration level. The approximate concentration levels used within each set were 8, 15, 30, 45, and 60 vehicles per lane-mile. Note that, in a given simulation run, the interest is in the network-level properties of a fixed number of vehicles circulating in the specified closed system, thereby maintaining a constant concentration in the network throughout the simulation period.

A series of sets of simulation runs was first conducted to analyze the effect of the first factor, namely the level of interfering activity. Next, a representative activity level was selected for use in the reference base case and a second series of sets of runs was performed with each set corresponding to a change in one of the other two experimental factors of interest.

The NETSIM model, which was used to perform these experiments, is a fixed-step, microscopic, network traffic simulation model. Each vehicle in the system is treated separately during the simulation; its behavior is governed by a set of microscopic car-following, queue-discharge, and lane-switching rules (8,9). The feasibility of using the NETSIM model in this type of study was established previously (1).

Further details on the simulation experiments are presented hereafter; particulars concerning changes in activity levels and other network and traffic factors are presented in the next two sections, along with the results of these changes.

Network Configuration and Geometric Features

As noted in the previous section, a degree of regularity and uniformity was sought in the test network. This network consists of 25 nodes, arranged in a 5-node by 5-node square, connected by two-way, four-lane streets forming a regular, central business district (CBD)-like grid. Because only directed links can be used in representing the network in NETSIM (i.e., all links are one way), there are 80 one-way, two-lane links, as shown in Figure 1. Each link (block) is 1,000 ft long, with no right- or left-turn bays, and all grades are zero.

Vehicles are injected onto the network via 12 entry links placed around the perimeter, three to a side, with each entry link connecting a source node (source nodes are labeled 801 to 812 in Figure 1) to

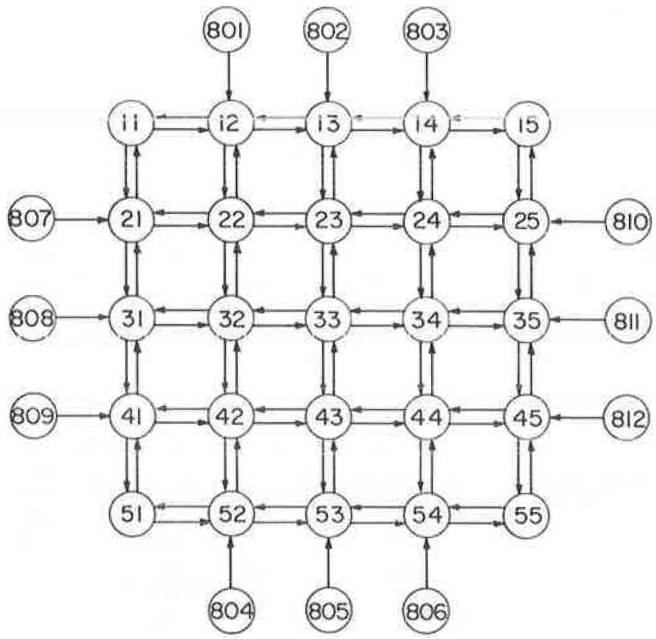

FIGURE 1 Network configuration.

a noncorner boundary node. No sink nodes have been designated because a closed system, where vehicles remain in the network once they have entered it, is under consideration.

Traffic Characteristics and Control Strategy

The mean desired speed for all the simulations was 35 mph, the desired speed of a given driver being the speed at which he would travel in the absence of other vehicles and of traffic controls. The model assigns desired speeds to vehicles as they enter the system according to a distribution about the specified desired speed. Likewise, the same vehicle-turning movements were used throughout the simulation runs: 10 percent of the vehicles turned left, 15 percent turned right, and 75 percent continued straight through at each interior intersection, whereas at the boundary nodes traffic split equally between the two available options. Fixed-time traffic signals were placed at all but the four corner nodes. At the interior nodes, two-phase timing with a 50-50 split and no protected turning movements was used. Three-phase signals were used at the boundary intersections, providing a protected left turn for vehicles reentering the interior of the system. The time was nearly equally allocated between the vehicles leaving the interior of the network and those reentering it from the boundary. Two-way progression at the mean desired speed was provided along the interior arterials by using a 40-sec cycle length with single alternate operation (offsets between adjacent signals were all 50 percent of the cycle length). Application of Webster's equation (10,p.57) indicated that this cycle length was adequate to handle the traffic volumes encountered in the various simulation runs.

There were no pedestrians and right turn on red was allowed at all intersections in all simulations. Additional details of the conduct of individual runs are presented next.

Individual Runs

A start-up period ranging from 5 to 15 min was used in all runs, during which vehicles were generated uniformly on the 12 entry links. The length of the start-up period depended on the number of vehicles necessary to achieve the desired concentration level in the network. Vehicles were injected directly into the network interior by not allowing turns onto the boundary from the entry links. The vehicles were then allowed to circulate in the network for the desired observation period of 15 min. Intermediate output was printed every minute, providing a "snapshot" of each link's condition (at that time) along with some cumulative information about each link. Network-level information, as well as additional cumulative link data, was printed every 3 min during the simulation period.

As mentioned earlier in this section, the vehicle concentration ranged from 8 to 60 vehicles per lane-mile within each set of runs. Specific changes from the base case and the results of these changes are analyzed in the next two sections, starting with the traffic-interfering activity factor.

ACTIVITY LEVEL EFFECTS

Considered here is the effect of differing levels of traffic-interfering activity in the test network on the quality of traffic service, as described by the network-level quantities and relations presented in the second section. "Activity level" refers to the degree of interference experienced by moving vehicles. Such interference may be due to intralink perturbations such as vehicles stopping to pick up or drop off passengers or goods, illegal parking and related maneuvers, pedestrian activity (other than that at intersections), and many other similar activities that are an inherent feature of a city street network. The NETSIM model provides for activities of this type with a "short-term events" option, whereby the user may specify, by link, the mean duration and the frequency of the events. In the model these are introduced stochastically and independently as blockages in the right lane in the center of the link. In the experiments described herein, short-term events were identically specified for all 80 links in the test network at the six levels given in Table 1. The first column gives the level designation; the second, the mean duration of each event; the third, the mean time interval between the beginning of successive events on a link; and the fourth, the fraction of time the right lane of a link is blocked by an event, which is the duration (in column 2) divided by the time between events (in column 3). Note that Level B is the one specified in the base case mentioned in the previous section. For each of these six activity levels, a set of five runs at varying concentrations was performed with all other factors remaining the same.

TABLE 1 Activity Levels

Activity Level	Mean Event Duration (sec)	Time Between Events (sec)	Fraction of Time Lane is Blocked
0	0		0.000
A	30	240	0.125
B	45	120	0.375
C	14	36	0.389
D	30	36	0.833
E	30	120	0.250

Single values of T and T_r were calculated from the final 12 min of each simulation run, resulting in five pairs of data for each set of runs. The values of the two-fluid parameters T_m and n were then obtained as described in the second section. The results are given in Table 2 along with the corresponding r^2, using only the lowest four of the five concentration levels. The omission of the highest concentration level in the estimation of T_m and n is based on a comparison of estimates with and without this highest point, which revealed substantial discrepancies in the magnitudes of the parameter estimates. Further examination of the variation of T_r with concentration, shown in Figure 2, revealed clearly that, at extremely high concentrations, T_r exhibits as substantially lower rate of increase than at lesser, and more practically meaningful, concentration levels. This may mean that these are limiting cases of the two-fluid theory in that they go to concentration levels that are clearly beyond the range encountered in previous supporting empirical work.

The effects of these activity levels on the network performance parameters can be analyzed in three ways: (a) as a function of the mean event duration for a given mean interevent time, (b) as a function of the interevent time for a given mean duration, and (c) as a function of the fraction of time that the right lane of each link is blocked, thus allowing both the mean event duration and interevent time to vary.

TABLE 2 Estimates of the Two-Fluid Parameters T_m and n

Activity Level	n	T_m	r^2
0	0.076	2.238	0.947
A	0.338	2.196	0.964
B	0.845	2.135	0.973
C	0.784	2.123	0.982
D	1.738	1.997	0.993
E	0.573	2.173	0.966

Effect of Mean Event Duration

Two groups of runs can be distinguished: Activity Levels 0, C, and D (with a mean interevent time of 36 sec) and 0, E, and B (with a mean interevent time of 120 sec). Average speed is plotted against concentration in Figure 3(a) and fraction of vehicles stopped (f_s or T_s/T) is plotted against concentration in Figure 3(b) for Activity Levels 0, C, and D. As the mean event duration increases from 0 to 14 to 30 sec, both the average speed and the fraction of vehicles stopped decrease. Figure 3(a) also reveals that, at the lowest concentration considered, the average speeds are nearly identical for the three duration levels because of the ability of vehicles to get around the right lane blockages in the absence of significant competing traffic. As concentration increases, this ability is substantially hampered, resulting in a decrease of the average speed with increasing mean event duration. It can also be noted that, at higher concentrations, the speed differentials across mean event durations tend to decrease, as typified by the speed values for $K \approx 60$ vehicles per lane-mile in Figure 3(a). This is because, at higher concentrations, the fraction of time vehicles are stopped or slowed due to short-term events becomes smaller relative to the fraction of time they are stopped or slowed for other reasons, namely queueing at traffic signals and overall congestion.

Figure 3(b) reveals that, as expected, f_s increases with concentration, though at a slower rate with increasing mean event duration. At the lowest concentration, f_s is nearly identical for all

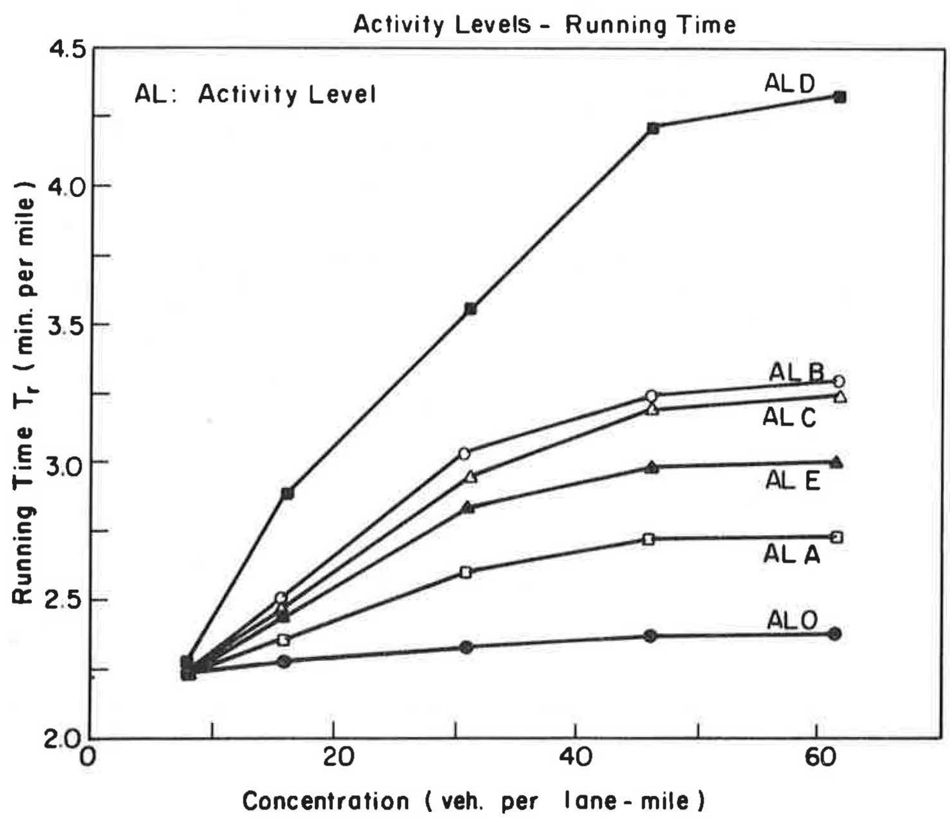

FIGURE 2 Running time versus concentration: activity levels.

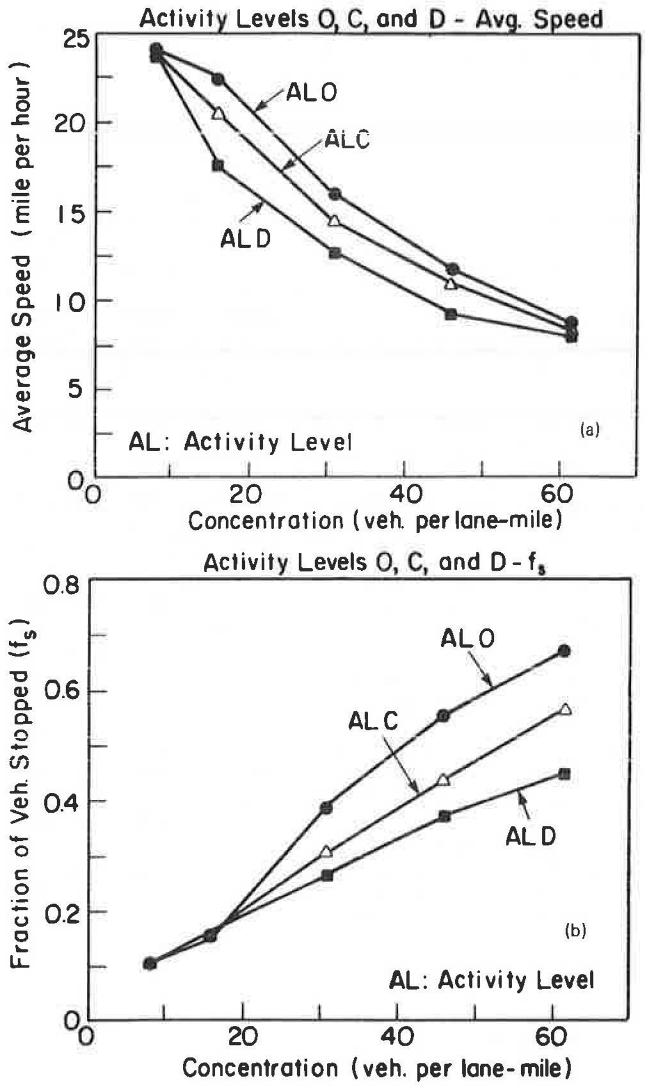

FIGURE 3 Effect of mean event duration for a mean interevent time of 36 sec (Activity Levels 0, C, and D): (a) average speed versus concentration and (b) fraction of vehicles stopped versus concentration.

three durations considered for the same reason that speeds are almost equal: vehicles in this nearly empty network encounter little impedance in getting around temporary obstructions. However, at each higher concentration level, and somewhat counter-intuitively, f_s is consistently smaller for longer event durations. This phenomenon can best be explained be realizing the identity, mentioned in the second section, of f_s and T_s/T. Essentially, as seen in Figure 2, increasing event duration results in a faster rate of increase of the average running time (T_r) with respect to concentration. Therefore, because $T = T_s + T_r$, the relative contribution of T_r to total trip time increases with increasing event duration, resulting in the observed decrease in f_s, particularly because T_s decreases with increasing mean event duration for a given concentration, as discussed hereafter.

Table 3 gives the average speed (V), trip time (T) and its two components T_r and T_s, along with the fractions T_r/T and T_s/T, corresponding to the three activity levels (0, C, and D) under three levels of concentration (approximately 8, 30, and 60 vehicles per lane-mile). The data in this table reveal that, at low concentrations ($K \approx 8$), there is essentially no difference in the descriptors across activity levels because of the ability of vehicles to get around the obstructions with minimal running or stopped delay. However, at higher concentrations, average (total) trip time (T) increases with activity level, as shown in Figure 4(a). This increase is due exclusively to the increase in running time (T_r), which even compensates for a decrease in average stop time (T_s). This somewhat counter-intuitive decrease in T_s is more evident at the highest concentration considered ($K \approx 60$). This probably arises because (stopped and moving) delays at the obstructions reduce the otherwise dominant stopped delays at the intersections.

Similar results were found for Activity Levels 0, B, and E, where the mean duration time varied from 0 to 30 to 45 sec for a mean interevent time of 120 sec. However, the effects were present to a lesser extent because the essentially similar durations took place within a much longer interevent time and therefore had a lesser impact on traffic. The effect of interevent time is further discussed hereafter. Finally, the two-fluid parameter n is plotted in Figure 4(b) as a function of mean event duration for the two levels of mean interevent time considered, indicating that n appears to increase linearly with duration time (for a given event frequency).

Effect of Mean Interevent Time

Activity levels at a 30-sec mean duration can be arranged in the order of least frequent (i.e., never occurring) events to most frequent events as follows: Level 0 (no events), Level A (240 sec between events), Level E (120 sec between events), and Level D (36 sec between events). Speed and fraction of stopped vehicles are plotted against concentration in Figures 5(a) and 5(b), respectively, for the four levels. The effect of decreasing interevent time (or increasing frequency) is essentially similar to that

TABLE 3 Effect of Activity Level on Average Speed and Trip Time Components Under Varying Concentrations

Concentration K (veh/ln-mile)	Activity Level	Average Speed V (mph)	Trip Time T (min/mile)	Stop Time T_s (min/mile)	Running Time T_r (min/mile)	T_r/T	T_s/T
7.92	0	24.03	2.50	0.26	2.24	0.897	0.103
	C	23.84	2.52	0.27	2.25	0.895	0.105
	D	23.64	2.54	0.26	2.28	0.896	0.104
30.89	0	15.84	3.79	1.45	2.33	0.616	0.384
	C	14.27	4.20	1.26	2.94	0.700	0.300
	D	12.52	4.79	1.25	3.54	0.738	0.262
61.38	0	8.53	7.03	4.65	2.38	0.339	0.661
	C	8.18	7.33	4.10	3.24	0.441	0.559
	D	7.73	7.76	3.44	4.32	0.557	0.443

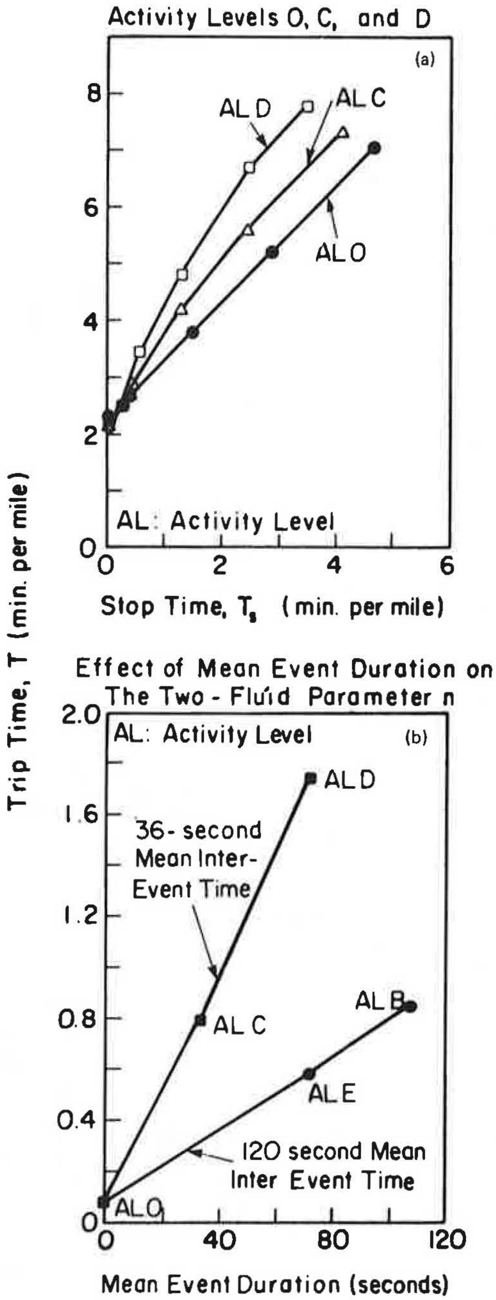

FIGURE 4 Effect of mean event duration for mean interevent times of 36 and 120 sec: (a) trip time versus stop time, 36-sec mean interevent time only (Activity Levels 0, C, and D) and (b) n versus mean event duration for two levels of mean interevent time (36 and 120 sec).

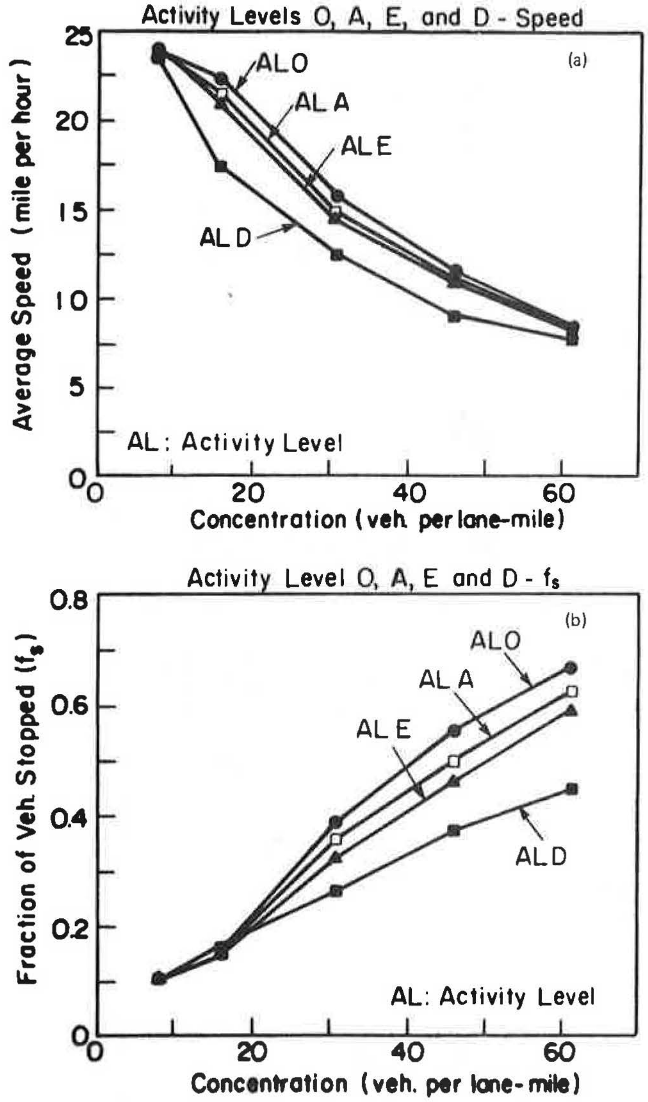

FIGURE 5 Effect of mean interevent time for a mean duration of 30 sec (Activity Levels 0, A, E, and D): (a) average speed versus concentration and (b) fraction of vehicles stopped versus concentration.

of increasing event duration, discussed earlier, and for the same reasons: as either mean duration increases or the interevent time decreases, the fraction of time a lane is blocked increases. The change between Levels E and D in Figures 5(a) and 5(b) is appreciably larger than the change between Levels E and A because events occur twice as frequently in Level E as they do in Level A but more than three times more frequently in Level D than in Level E.

Figure 2 shows that T_r increases with concentration at a faster rate for decreasing interevent times (Levels 0, A, E, and D, respectively), indicating that the parameter n increases correspondingly. The T-versus-T_s plot for these four levels is shown in Figure 6(a), revealing an increasing slope with decreasing interevent time. Figure 6(b) shows n as a function of the frequency of events, holding mean duration constant at 30 sec. As in Figure 4(b), this relationship appears to be linear.

Effect of Fraction of Time Lane Is Blocked

Next the effect of the fraction of time that the right lane is obstructed, without regard to the actual durations and interevent times, is considered. Activity Levels B and C were selected to have nearly equal values of this fraction (the slight difference is due to the necessity of specifying integers in the NETSIM model). The data in Table 2 indicate that n and T_m are extremely close (though not identical) for both levels, and only Level B will be used in the following comparisons. The remaining levels can be arranged in order of increasing fraction of time of lane blockage: Level 0 (no events), Level A (0.125), Level E (0.250), Level B (0.375), and Level D (0.833).

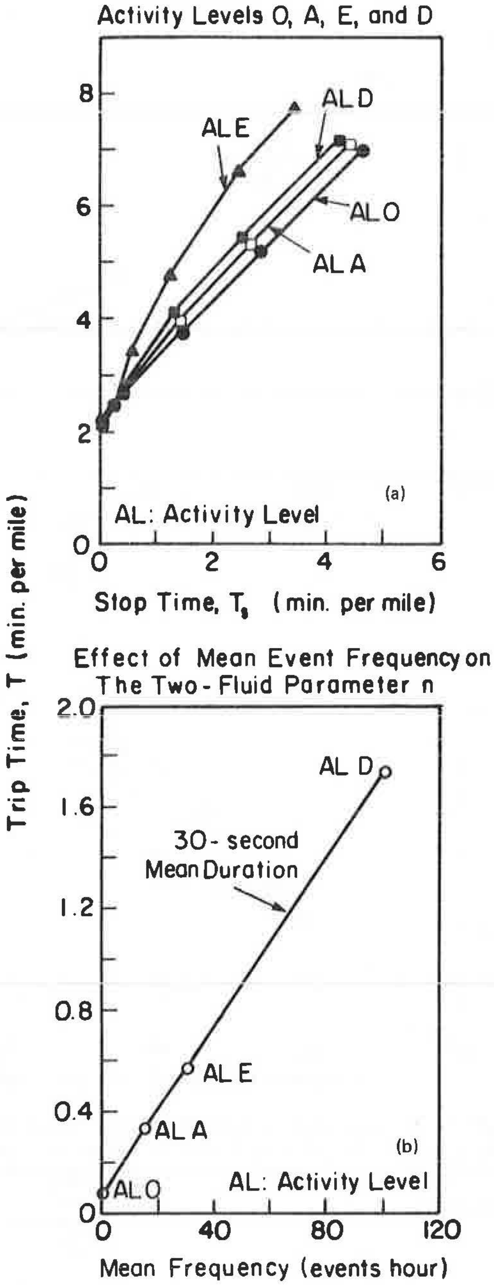

FIGURE 6 Effect of mean interevent time for a mean duration of 30 sec (Activity Levels 0, A, E, and D): (a) trip time versus stop time and (b) n versus event frequency.

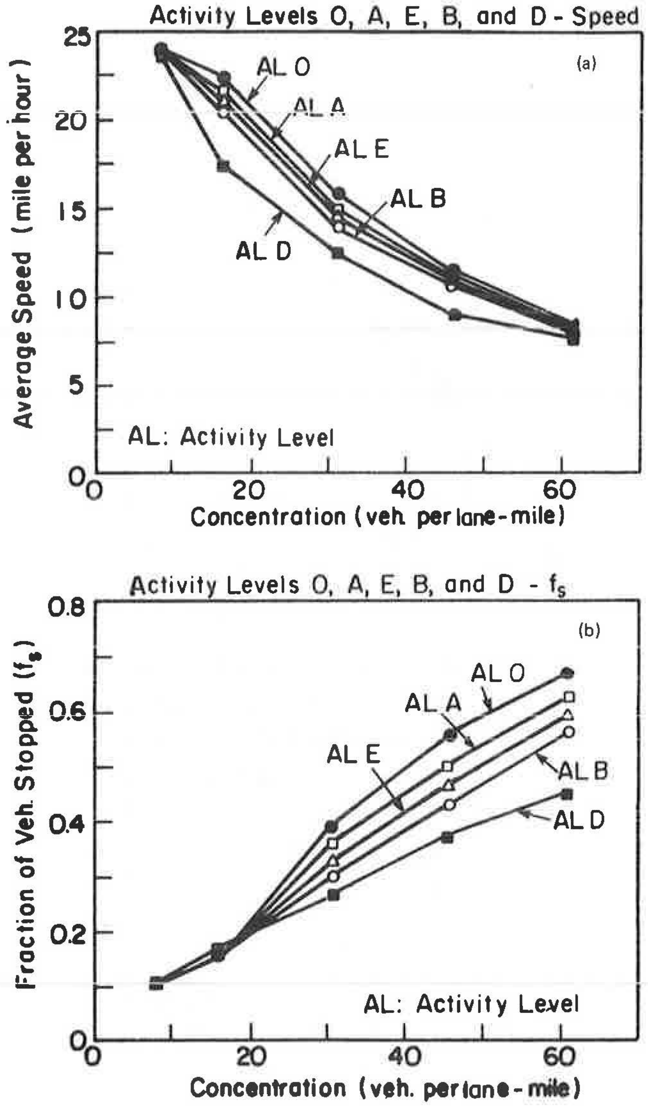

FIGURE 7 Effect of fraction of time lane is blocked (Activity Levels 0, A, E, B, and D): (a) average speed versus concentration and (b) fraction of vehicles stopped versus concentration.

Speed and fraction of stopped vehicles are shown plotted against concentration in Figures 7(a) and 7(b), respectively, and, as expected, bear a marked resemblance to the previous figures corresponding to duration and interevent time individually. Similarly, n increases with the fraction of time that the lane is blocked, as seen in Table 2 and reflected in the T-versus-T_s plot in Figure 8(a). In addition, n appears to be a linearly increasing function of this fraction, as shown in Figure 8(b).

Remarks

As was pointed out in the second section, an increasing T_r with respect to concentration is a result of congestion and perturbations in the moving traffic. When no short-term events are specified, n is nearly zero, intersection effects dominate intralink effects, and traffic-interfering activities normally observed in city streets at all but the lowest concentration levels are not represented in the simulations. As short-term events are introduced, T_r is allowed to increase with increasing concentration, resulting in non-zero values of n. When n is related to the specific components of the short-term events, as well as to a single measure of the event intensity, a linear relationship develops. Of course, other factors also affect the value of n, some of which will be discussed in the next section and others of which will be mentioned in the final section. In investigating these other factors, a moderate level of short-term events (Activity Level B) was used because the resulting higher values of n (as opposed to a case with a zero activity level) are more representative of traffic conditions in cities, thus allowing this parameter to better respond to changes in the network and traffic factors under consideration, as described in the next section.

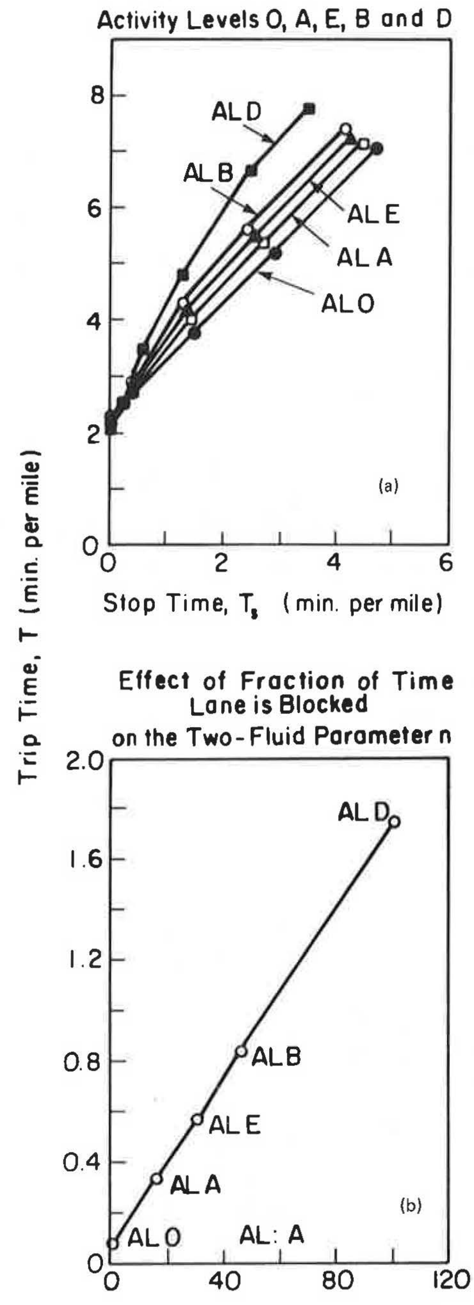

FIGURE 8 Effect of fraction of time lane is blocked (Activity Levels 0, A, E, B, and D): (a) trip time versus stop time and (b) n versus fraction of time lane is blocked.

NETWORK FEATURES AND TRAFFIC CONTROL

The sensitivity of the selected network parameters and traffic flow relationships to changes in traffic control strategy and network topology (block length) is addressed in this section. The base conditions described in the third section and used in the fourth section are also employed here, except to examine the effect of block length as indicated in the appropriate subsection. As mentioned in the previous section, Activity Level B was specified in order to provide a suitable degree of intralink friction in all runs.

Values of T_m and n used in this section were estimated in the manner described earlier and are given in Table 4, where the base case consists of Activity Level B applied to the base conditions described previously. Again, values obtained by regressing T and T_r from the four lower concentration levels only will be used, as discussed in the previous section. The results are presented hereafter for each of the two factors.

TABLE 4 Estimates of the Two-Fluid Parameters T_m and n

Case	n	T_m	r^2
Base case[a]	0.845	2.135	0.973
Traffic control strategy, no progression	0.490	2.196	0.921
Network topology, 400-ft links[b]	0.394	2.580	0.994

[a] 1,000-ft links, progression.
[b] This case should be compared with the no-progression case not the base case.

Traffic Control Strategy

A question of considerable practical importance is that of the effect of a major change in the traffic control scheme of a city network on the two-fluid parameters and on n in particular. To address this question, the base case, where signals were timed for progression (see the third section), was compared with a situation in which signal timing did not explicitly provide for such progression. Under the latter scheme, the cycle length of all the traffic signals in the test network was 50 sec (versus 40 sec in the base case). The percentage of signal splits and offsets remained unchanged.

The average speed and the fraction of vehicles stopped are plotted against concentration in Figures 9(a) and 9(b), respectively. Over all concentration levels, average speed dropped and the fraction of vehicles stopped rose. Because signal progression is implemented to reduce stopping, these results are not surprising. The drop in average speed results from vehicles being stopped a greater fraction of time while holding the desired speed constant.

After beginning at nearly the same value, average running time (T_r) increases with concentration at a faster rate under progression (see Figure 10), meaning that while they are moving vehicles are traveling at a slower speed than when there is no progression. But the higher average overall speed under progression along with the reduced fraction of vehicles stopped (and therefore fraction of time stopped for any one vehicle, averaged over all vehicles) indicate a system that is operating more smoothly with progression.

The slower increase of stopped time (T_s) with an increasing T when the signals are timed for progression is shown in Figure 11(a). This difference in slopes is also reflected in the values of n: 0.490 for no progression, 0.845 for progression. The values of T_m are nearly identical (see Table 4) with that for progression being slightly lower indicating a slightly higher V_m, the average minimum running speed in the network. The change in cycle length may be responsible for part of the difference between progression and no progression; however, such cycle changes are often necessary when implementing progression schemes in urban areas. The main result from the perspective of the present paper is that n can be quite sensitive to major changes in a network traffic control scheme. Such sensitivity had not been established previously and is quite important for practical engineering use of the two-fluid model.

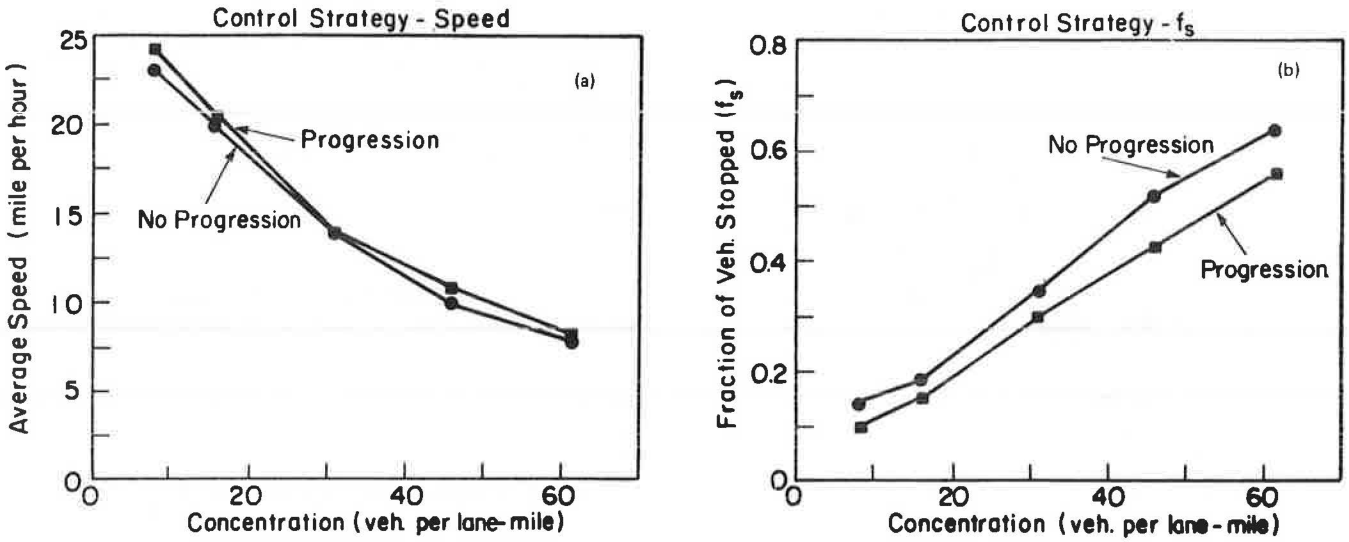

FIGURE 9 Traffic control strategy—progression versus no progression: (a) average speed versus concentration and (b) fraction of vehicles stopped versus concentration.

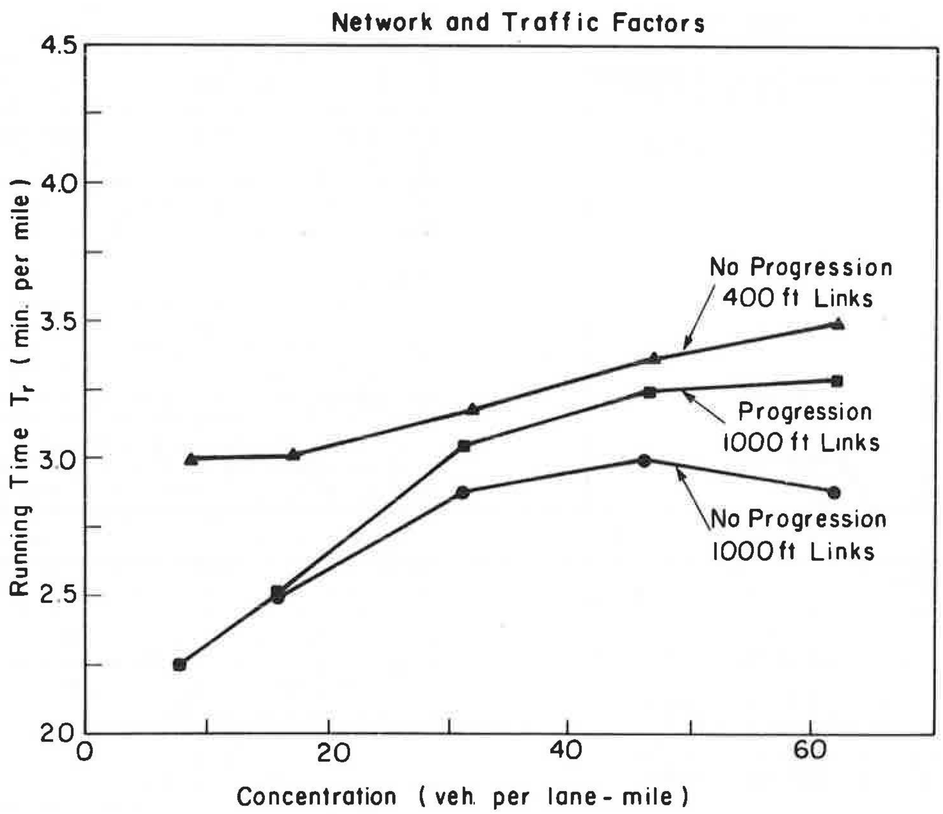

FIGURE 10 Running time versus concentration: network and traffic factors.

Network Topology--Block Length

The block length used to study network topology was reduced from 1,000 to 400 ft. A 50-sec cycle length was used so that these runs could be compared with the no-progression case, because a 40-sec cycle length no longer provided progression with the reduced block length. Average speed and f_s are plotted against concentration in Figures 12(a) and 12(b), respectively, and both indicate that the effect of block length is substantial. At low concentrations average speed for 400-ft links is reduced by almost half of that for the longer links. The more frequent intersections (associated with the shorter links) require vehicles to stop much more often (particularly because there is no progression in either case), and many are unable to ever reach their desired speed. However, at higher concentration, intense congestion does not allow vehicles to build up much speed in either case.

The fraction of vehicles stopped at the low concentrations is much higher for the shorter blocks,

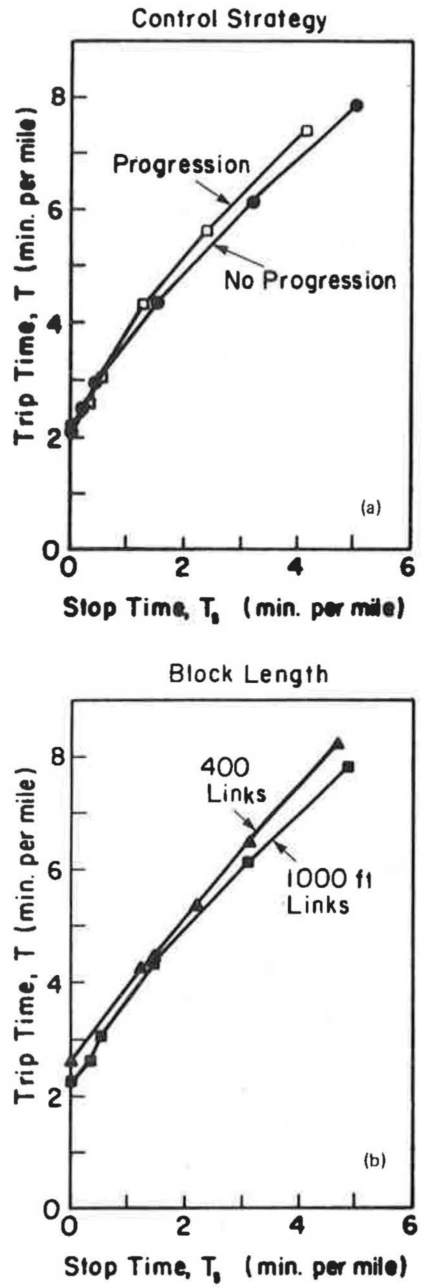

FIGURE 11 Trip time versus stop time for network and traffic factors: (a) progression versus no progression and (b) 1,000-ft versus 400-ft block lengths.

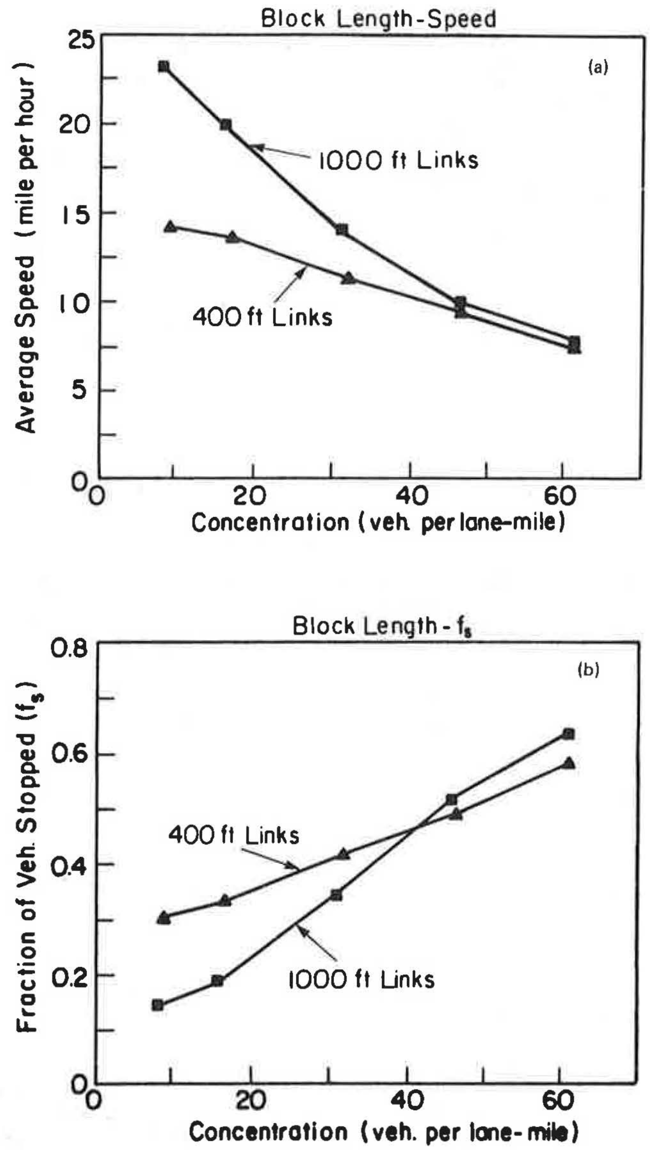

FIGURE 12 Network topology—1,000-ft versus 400-ft block lengths: (a) average speed versus concentration and (b) fraction of vehicles stopped versus concentration.

as expected. However, as concentration increases, Figure 12(b) reveals that the f_s-versus-K lines corresponding to the two lengths cross, and f_s for short block lengths becomes less than that for the longer block length.

The running time (T_r) for the short blocks is consistently higher than that for the longer blocks (see Figure 10), but the slope for the 1,000-ft blocks is somewhat steeper. The effect of this difference in slope on the value of n is somewhat offset by the fact that the slope of T (travel time, the inverse of the average speed) as a function of concentration K is steeper for the long links. The resulting values of n are 0.394 and 0.490 for the 400- and 1,000-ft links, respectively (Table 4). The difference in the values of T_m is substantial as well (see Table 4), with T_m for short links (2.580 min per mile) being larger than that for the long links (2.196 min per mile). The difference between the values of n and T_m are reflected in the T-versus-T_s plot in Figure 11(b).

CONCLUDING REMARKS

The analysis of network-level traffic flow relationships presented in this paper has addressed two aspects of this problem. First, although the feasibility of using the NETSIM microscopic traffic simulation model was established in previous work (1), serious limitations were present due to the highly idealized nature of traffic operations in the test network. In particular, the values of the two-fluid model parameters indicated that insufficient moving traffic interference was encountered by the vehicles circulating in the test network under the specified conditions. Therefore, as trip time increased with concentration, running time remained virtually unchanged (1). By use of the short-term events feature of NETSIM, this interference, or intralink friction, could be introduced into the traffic stream at specified levels. The model proved quite sensitive to these traffic-interfering urban activity levels, as was shown by the two-fluid parameter values. Essentially, it is such perturbations that give a city street network its inherent traffic character and the kind of behavior described by the two-fluid theory and verified by observation.

Second, although the two-fluid theory has been extremely successful at capturing relationships between macroscopic traffic flow descriptors, it does not explicitly address the key underlying mechanisms or how the model parameters may be affected by the physical and operational features of a given network. Analyses such as the present one can contribute greatly to those aspects that are outside the scope of the theory. For instance, this work has helped confirm the previously mentioned role of traffic-interfering activities in determining the behavior of a system. In addition, the effect of two major factors, namely block length and the traffic control scheme, were ascertained. Changes in both of these factors resulted in significant changes in the two-fluid model parameters as well as in other network traffic flow descriptors and relationships. It was thus seen that a major change in traffic control strategy, in this case retiming of all signals to achieve flow progression, could be detected by the two-fluid model parameters.

The two-fluid parameter n can be viewed as an indicator of overall network intralink friction, the effect of which becomes more apparent with increasing concentration. Specifically, n is a measure of how quickly average running time increases with average (total) trip time: the higher n is, the greater is the rate of increase of running time with respect to trip time.

Although one of the modeling objectives of this study was to achieve relatively high values of n that were comparable to values that have been observed in related field work in order to provide a realistic system representation, high values of n are not desirable from a traffic engineering design perspective. Indeed, all else being equal, a small n value would indicate less intralink friction (i.e., smoother flow) and a shorter running time for a given stop time. This clearly indicates that this parameter must not be used in isolation as an indicator of traffic service quality. A case in point is the introduction of progression in the timing of signals, whereby the value of n actually increased, though other indicators, such as average speed (or trip time) and fraction of vehicles stopped, clearly supported the desirability of the new timing scheme. Thus, although T_r for a given concentration level was lower under progressive timing, the corresponding increase in average speed (or, conversely, decrease in T) offset the effect of the variation of T_r, resulting in the observed higher n value.

Field studies indicate that running time continues to increase with trip time and rising concentration. However, field studies can only observe existing conditions, and the highest observed concentrations have been around 40 vehicles per lane-mile. The simulation experiments discussed here have gone as high as 60 vehicles per lane-mile and appear to indicate that the rate of increase of T_r may decrease at exceptionally high concentrations, with T_r perhaps approaching an upper limit. After all, there is a limit below which drivers will just stop instead of creeping along.

Finally, it has already been noted that the activity level was the one factor that allowed the greatest control over the selected network parameters. However, it is likely that there may be an upper limit to the extent to which the activity level (at least as defined here) can affect these parameters. The other network and traffic factors, discussed in the previous section, were also shown to have an effect on these parameters. The test network used herein, however, is still rather idealized, with uniform streets and intersections. Field studies conducted in reference to the two-fluid model have shown that relatively regular street systems (e.g., the Houston CBD) result in lower values of n than do the more irregular street networks of other cities (5). Thus, one of the next steps in these simulation experiments is to introduce network topological irregularities, such as boulevards, missing links, one-way streets, and so on. Naturally, numerous other avenues for additional research exist in the development of a macroscopic network-level theory of traffic flow.

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