Traffic - Flow
Traffic Simulation.

Investigation of Network-Level Traffic Flow Relationships: Some Simulation Results

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ABSTRACT

Results of an exploratory study of network-level relationships in an isolated network with a fixed number of vehicles circulating according to the microscopic rules embedded in the NETSIM traffic simulation model are presented. The primary concern was to assess the usefulness of such simulation-based approaches in the investigation of macroscopic network-level traffic relationships. Three specific objectives were addressed: (a) identification of network-level descriptors that are related in operationally useful and simple ways, (b) exploration of some aspects of the two-fluid theory of town traffic, and (c) examination of the traffic flow distribution over the network components. A number of simulations were conducted on the same network under two different sets of control schemes and traffic characteristics at widely varying vehicle concentrations. The results were analyzed with respect to the three objectives, yielding useful insights into network-level traffic phenomena and suggesting promising avenues for further research.

The characterization of traffic in city networks by a small number of network-level descriptors and the quantification of their interrelationships constitute an important problem that has not received sufficient attention to date in traffic research. This problem is important because there is a need (a) to evaluate and compare the overall resulting quality of service of traffic control strategies and designs at the network level, (b) to make comparisons among cities or of the same city over a number of time periods, and (c) to identify possible deficiencies in current operations that result in overall conditions that are below the norm.

A theory of town traffic, based on a two-fluid representation of traffic in a city network, was proposed by Herman and Prigogine (1). This theory leads to a relationship between average time stopped and average time running on a network. Empirical validation of the theory and related phenomena has since been undertaken (2-4). These efforts have relied primarily on data obtained using chase-car techniques, supplemented by aerial photography, and thus have required considerable time and other data collection and analysis resources.

A complementary approach to gaining further insights into the relationships between network-level descriptors and the effect of various network features and system controls is the use of computer simulation. For example, it seems plausible that microscopic traffic simulation models can yield potentially useful insights into a wide variety of situations and conditions that would otherwise require enormous resources to investigate. Computer simulation provides the capability of looking at a network under controlled conditions at relatively reasonable costs. Simulation experiments can guide further theoretical development as well as assist in the judicious selection and design of observational studies to validate key assumptions and results.

One such exploratory study, in which a set of simulation experiments was performed using the NETSIM traffic simulation package, is described. The primary objective of the study was to assess the usefulness of a simulation-based approach to the investigation of macroscopic network-level traffic relationships. More specific technical objectives included attempts (a) to identify relevant network-level descriptors that may be related in operationally useful and simple ways, including an initial determination of these relationships; (b) to explore some aspects of the two-fluid model of town traffic under controlled conditions, including the sensitivity of its parameters to network features and controls; and (c) to examine the distribution of flow on various components of a closed (i.e., isolated) network under a variety of operating conditions and the implication for overall traffic service quality.

The next section briefly introduces the essential conceptual background. The details of the experimental set-up, including the features and characteristics of the test network, are described in the third section. This is followed by a presentation and critical discussion of the principal results obtained in the effort to date. Concluding remarks include suggestions for further research in this highly promising area.

CONCEPTUAL BACKGROUND

The key concepts and theories underlying the research objectives addressed in these simulation experiments can be grouped in three categories: (a) network traffic flow theory, (b) the two-fluid theory of town traffic, and (c) flow distribution on network components. A complete theoretical presentation will not be given here because such presentations can be found in the literature. This introduction is limited to only those concepts necessary for an understanding of the new results presented.

Network Traffic Flow Theory

The concern here was with a macroscopic theory of traffic flow in a network, not with traffic flow on roadways and arterials or isolated intersections, which have been the subject of nearly three decades of traffic research. Three major tasks of this effort were (a) to identify appropriate fundamental macroscopic traffic flow variables, (b) to determine how these variables are interrelated, and (c) to understand how these relationships are affected by the characteristics of the network, including its topology and its control system.

In the first two tasks, it is natural to be guided by the extensive body of knowledge accumulated over years of studying traffic relationships for arterials. Three fundamental variables are thus of concern: speed, concentration, and flow. To the extent that networkwide averages of these quantities are of interest, the definition, measurement, and computation of the appropriate averages, particularly for the flow variable, may be problematic. For a given period of observation, τ, average speed, V, will be taken as the ratio of total vehicle-miles to total vehicle-hours over the network during period τ (yielding an average speed in miles per hour). This average is taken both over time and over all vehicles in the network.

The average concentration, K, for the same period, τ, is the time average of the number of vehicles per unit lane length. Letting N(t) denote the number of vehicles at time t, and L the lane-miles of roadway, the average concentration, K, can be expressed as

$$K = (1/\tau) \int_{t_o}^{t_o+\tau} [N(t)/L]\, dt$$

where t_o is the beginning of the observation period. Effectively, K can be obtained by dividing total vehicle-hours by the product τL. In these experiments, to avoid averaging over widely fluctuating traffic conditions, concentration has been maintained constant throughout a given observation period.

The definition of an average flow variable, Q, is somewhat less obvious; the one pursued here considers average network flow to be the average number of vehicles per unit time that passes through an "average" point of the network. Letting q_i and ℓ_i, respectively, denote the average flow over the observation period and the length of link i, i = 1, ..., M, where M denotes the total number of links,

$$Q = \left(\sum_{i=1}^{M} \ell_i q_i\right) / \left(\sum_{i=1}^{M} \ell_i\right)$$

Two principal relationships between these three variables will be investigated. The first concerns the joint variation of speed, V, and concentration, K, at the macroscopic networkwide level. A number of studies have addressed this question for arterials, and although several functional forms have been suggested, the underlying trend of a decreasing average speed as a function of increasing concentration is well accepted (5,6). At the network level, although this same general trend can be expected to hold, it cannot be analytically derived from the single roadway relationships because of the added complexity of the interconnections in a network. Furthermore, virtually no empirical evidence is available on this matter; this is undoubtedly due to the considerable resources required for gathering the needed data. The simulations described thus provide an opportunity to examine how K and V may be related at the network level.

The second relationship examined is one that is fundamental in traffic flow theory, namely that Q = KV. This relationship is well established for arterials, but its validity when Q, K, and V are defined for the whole network remains to be verified. Preliminary indications of its validity are offered. The importance of this type of investigation and its eminent relevance to engineering practice are perhaps best underscored by the significant role that traffic stream models for arterials have played in the development of the Highway Capacity Manual (7) and in everyday applications.

Two-Fluid Theory of Town Traffic

The principal concept underlying Herman and Prigogine's two-fluid theory of town traffic (1) initially appeared in their kinetic theory of multilane highway traffic (8) when the transition to the so-called collective flow regime was made at sufficiently high vehicular concentrations. Essentially, traffic in an urban network is viewed as consisting of two traffic "fluids": one composed of the moving vehicles and the other of vehicles that are stopped as a result of congestion, traffic control devices, and other obstructions. Parked vehicles are not considered part of the "stopped" fluid but as a part of the geometrics.

A 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 way:

$$V_r = V_m(1-f_s)^n \qquad (1)$$

where V_m is the average maximum running speed in the network and n is a parameter that was subsequently found to be a useful indicator of the quality of traffic service in a network (3,4).

That 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 time stopped, all per unit distance (note that $T = T_r + T_s$) of the following form (1):

$$T_s = T - T_m^{(1/n+1)}\, T^{(n/n+1)} \qquad (2)$$

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, which were found to be robust characteristics of a given network, for a particular network has to date been conducted using observations on stopped time and moving time gathered by one or more test vehicles circulating in the network and passively following randomly selected vehicles (chase-car technique). The details of the measurement procedures and subsequent data processing and analysis are extensively described elsewhere (3,4).

An important result used in the derivation of the two-fluid model is that the mean fraction of time stopped, $E(T_s/T)$, (taken over the population of vehicles circulating in the network) is equal to f_s, the average of the fraction of vehicles stopped taken over a given observation period. A proof of this result can be found elsewhere (3,4). This result is actually at the root of the measurement and calibration procedure, where it is assumed that the fraction of time stopped for one or more test vehicles sampling the network passively would provide estimates of $E(T_s/T)$ and thus of f_s.

Observational studies to validate the model have been quite successful (3,4) though limited in nature by the obvious difficulty of obtaining the required data on a whole population of vehicles at the network level. Aerial photography is currently being used to measure f_s, but it is rather costly and time consuming, especially at the interpretation and reduction stages, which are still in progress (4).

The results presented will be analyzed from the perspective of the two-fluid representation to illustrate the use of simulation to further explore some aspects of this theory. Moreover, insights into the sensitivity of the model parameters T_m and n to physical and operating features of the network could be gained under controlled conditions on a scale that generally precludes real-world experimentation.

In addition, the simulations will address a proposed extension (1) of the two-fluid model that postulates a relation between the fraction of time stopped, f_s, and the network concentration, K, of the form

$$f_s = (K/_m)^p \tag{3}$$

where K_m is the average maximum concentration level at which the network jams (in a sense, a network-level parallel to the jam concentration of an arterial) and p is a network-specific parameter reflecting the sensitivity of f_s to increasing levels of use. Combining their expression with the previous equations of the two-fluid model yields (1)

$$K = K_m[1-(V/V_m)^{(1/n+1)}]^{1/p} \tag{4}$$

The relationship between K and V ties the two-fluid concept to the earlier discussion of a network traffic flow theory.

Flow Distribution on Network Components

In addition to the network performance models discussed previously, the distribution of traffic on various components of the network will be examined. The importance of this question is primarily methodological in that it relates to the design of simulation experiments to examine the circulation of vehicles in a network under controlled conditions.

As will be seen in the next section, an attempt has been made to maintain a certain degree of homogeneity and uniformity within each experiment (at least in these early stages) to avoid unnecessary complications that would make insights more difficult to obtain. A question arises about whether there are long-term trends of traffic distributing itself in some parts of the network to the exclusion of others. For instance, for a given (closed) test network configuration and control system and a given set of parameters governing the movement of vehicles on that network (i.e., the inputs to the simulation model), particular circulatory patterns involving only those links that define the boundary of the study network might be observed. This issue will become clearer in the next section in the context of the description of the test network and of the other details of the simulation experiments.

EXPERIMENTAL DESIGN AND SETUP

In all simulations, interest was in the network-level properties of a fixed number of vehicles circulating in a closed system. Thereby a constant concentration of vehicles in the network throughout the simulation period was maintained. Although the same network configuration was used in all the experiments, the traffic characteristics (including usage patterns) as well as the control strategy were varied. Two groups of simulation runs were performed, each group corresponding to a different combination of traffic characteristics and control strategy. Within each of the two groups, two parameters were varied across runs: (a) the concentration level (ranging from 1 to 75 vehicles per lane-mile) and (b) the mean "desired" speed, specified as either 25 or 35 mph (the desired speed of a given driver is the speed at which he would travel in the absence of other vehicles and traffic controls) (9).

Further details on these elements of the simulation experiments are presented hereafter, following a brief overview of the NETSIM model, which, as was noted earlier, was used to perform all of these experiments.

The NETSIM Model

NETSIM is a fixed-step, microscopic, network traffic simulation model, which was developed primarily as a tool for the analysis of alternative urban street network control and traffic management strategies. It is generally accepted as a well-validated model and has been used extensively by traffic researchers and engineers.

Each vehicle in the system is treated separately during the simulation. Vehicle behavior is governed by a set of microscopic car-following, queue-discharge and lane-switching rules. An array of performance characteristics is stochastically assigned to each vehicle as it enters the network. All vehicles are processed once every second and their time-space trajectory recorded to a resolution of 0.1 sec. [Further details are given elsewhere (9,10).] The NETSIM model was selected primarily for its high level of detail in the representation of microscopic traffic phenomena, its sensitivity to the factors of interest in the investigation, and its rather well-developed user-related features such as types of output and summaries.

Network Configuration and Geometric Features

As noted in the previous section, a degree of regularity and uniformity in the test network used at this stage of the investigation was sought. 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-like grid. Because only directed links should 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 400 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

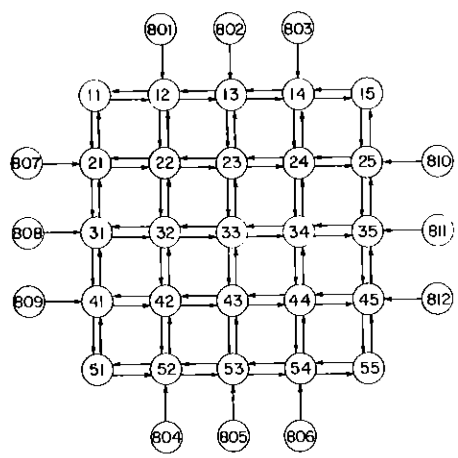

FIGURE 1 Network configuration (nodes 801-812 are source nodes and not part of the circulation network).

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 Strategies

As mentioned previously, the simulations reported here belong to one of two groups. In the first group, vehicle turning movements were uniform throughout; at the interior nodes, one-third of all incoming vehicles (on any of the approaches incident to a given node) turned left, one-third turned right, and one-third continued straight through. At the boundary nodes, incoming traffic split equally between the two available options. Fixed-time traffic signals were placed at all 25 nodes, each with a 50-sec cycle length and a 50/50 split (i.e., green time equally divided between the intersecting streets), with no protected turning movements. All 25 signals were operated simultaneously, so that all the north and south approaches were green together, followed by all the east and west approaches.

In the second group, vehicle movements at the interior nodes were changed to 10 percent left, 15 percent right, and 75 percent through; they were not changed (relative to group 1) at the boundary nodes. A phase was added to the signals along the boundary to provide a protected left turn for vehicles reentering the interior of the system. The 50-sec cycle length was apportioned equally among the three approaches (phases); however, splits at the interior intersections were not changed. The four signals at the corner nodes were removed, thus allowing traffic to move unhindered through the corner nodes. Signals were operated according to a single alternative system whereby offsets between adjacent signals were all 50 percent of the cycle length so that, at any given time, every other signal along a street was green and the intervening signals were red.

There were no pedestrians, and right-turn-on-red was allowed at all intersections in both groups. Additional details of individual runs are presented next.

Individual Runs

A 5-min start-up period was used in all runs during which vehicles were generated uniformly on the 12 entry links. The 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 simulation period (15 min for most of cases, although longer runs were made). Intermediate output was printed every minute, providing a "snapshot" of each link's condition at that time along with some cumulative information for each link. Network-level cumulative information as well as additional cumulative link data were printed every 3 min during the simulation period.

As mentioned earlier, two quantities were allowed to vary within each of the two groups. The mean desired speed in the network had an assumed value of either 25 or 35 mph in a given simulation. Vehicle concentration, which is a key quantity in these experiments, varied across a wide range of up to 75 vehicles per lane-mile. The results of these simulations are analyzed and critically discussed in the next section.

ANALYSIS OF SIMULATION RESULTS

The results of the simulation experiments conducted to date are analyzed with respect to those aspects of network traffic behavior identified earlier. The discussion is organized in the same three categories that were used in the conceptual background description, namely, flow distribution on network components, network traffic flow theory, and the two-fluid theory of town traffic.

Flow Distribution on Network Components

This aspect is discussed first because of its implications for the remainder of the analysis. In particular, the determination of the appropriate observation period, over which time averages of the network variables of interest were defined, was predicated on the results of the analysis of the long-run circulatory patterns developing in the test network. Two phenomena are investigated: the relative distribution of actual flow in the boundary links versus the interior links and the respective fractions of vehicles on boundary links and on interior links. In both cases, the chief concern is with the time-varying patterns of the quantities under consideration. Note that boundary links are defined as those one-way links, shown in Figure 1, with both end nodes belonging to the set of nodes {11, 12, 13, 14, 15, 21, 25, 31, 35, 41, 45, 51, 52, 53, 54, 55}. All other links, with the exception of the entry links, in the circulation network of Figure 1 are interior links.

To observe the dynamic behavior of the traffic measures pertaining to the relevant questions, a number of runs were conducted, each with 30 min of simulation beyond the initial 5 min required to load the network. The relative distribution of flow in boundary versus interior links is addressed first. Link flow can be calculated from the cumulative discharges given for each link in each intermediate output of the NETSIM model. The arithmetic averages of these minute-by-minute flows were taken separately over the boundary and interior links. These minute-by-minute boundary-average and interior-average flows are shown in Figure 2 for a representative simulation run. This run is from group 1 (groups 1 and 2 are used hereafter to denote the two combinations of traffic characteristics and control strategies described earlier).

As expected, average flows for both boundary and interior links start by increasing monotonically during and shortly after the network loading period. Subsequently, fluctuations can be observed, and there is a clear tendency for these fluctuations to occur around an apparently stable average value. The

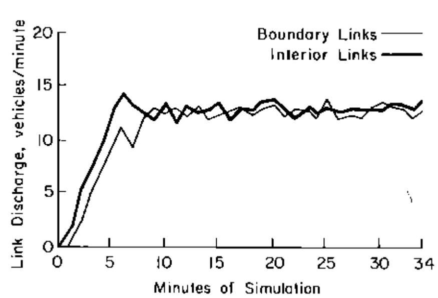

FIGURE 2 Link discharge for interior and boundary links.

system is considered stable when the link flows stabilize about an average value particular to each simulation. It can be seen in Figure 2 that this condition is achieved after approximately 8 min of total simulation time (i.e., 3 min after all the vehicles have been emitted at the source nodes). Furthermore, Figure 2 shows that the average flows for the boundary and interior links, respectively, have approximately the same value. The same conclusions could be reached for the other runs as well. Accordingly, it was decided to start the observation period, for the purpose of these analyses, at the 8th minute in all cases. In most runs analyzed, the observation period was ended at the 20th minute.

The second perspective from which to examine the general stability of the network is based on the respective fractions of vehicles on the boundary links and the interior links. In all cases, vehicles were injected directly into the interior of the network. Thereafter, given the rules governing turning movements at the intersections, vehicles eventually reached the boundary links, and, after some period of time, the fractions of vehicles on the boundary and interior links, respectively, seemed to stabilize about some constant value that was different for each of the two link classes. As is the case with average link flows, the network appears to be generally stable after about 8 min.

The time variation of the respective fractions of vehicles on the boundary and interior links for a representative 35-min run (also from group 1) are shown in Figure 3. These fractions were calculated on a minute-by-minute basis from tallies of link occupancies (separately for boundary and interior links) from the intermediate output of NETSIM. Figure 3 shows that, although the vehicle fractions undergo fluctuations, these appear to stabilize about a mean value of approximately 0.440 for boundary links and 0.560 for interior links for the simulation run under consideration. These values are actually extremely close to the arithmetic averages taken over all group 1 simulations. In this network, boundary links comprise 40 percent of the total network length, and the interior links comprise the remaining 60 percent. As the fractions here indicate, the boundary links have a higher average vehicle concentration than do the interior links. The results from the other group 1 runs are given in Table 1.

Vehicle fractions on the boundary and interior links for a simulation from group 2 are shown in Figure 4. Similar results were found for the other runs in group 2 and are given in Table 2. As in the previous cases, the network appears to stabilize after about 8 min of simulation, but the vehicle fractions on the links are different: 0.402 on the boundary links and 0.598 on the interior links. This is much closer to the ratio of total length of the

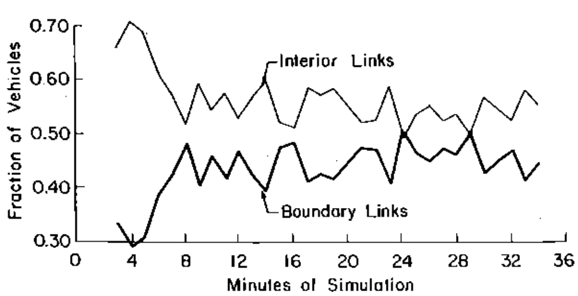

FIGURE 3 Fraction of vehicles on boundary and interior links, group 1.

TABLE 1 Average Fractions of Vehicles on Boundary and Interior Links (f_b and f_i), Group 1

	f_b	f_i
	0.440	0.560
	0.453	0.547
	0.460	0.540
	0.426	0.574
	0.424	0.576
Overall average	0.441	0.559

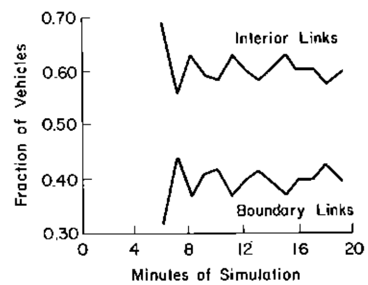

FIGURE 4 Fraction of vehicles on boundary and interior links, group 2.

TABLE 2 Average Fractions of Vehicles on Boundary and Interior Links (f_b and f_i), Group 2

	f_b	f_i
	0.395	0.605
	0.396	0.604
	0.394	0.606
	0.391	0.609
	0.400	0.600
	0.401	0.599
	0.416	0.584
	0.407	0.593
	0.398	0.602
	0.405	0.595
	0.425	0.575
	0.389	0.611
Overall average	0.402	0.598

boundary and interior links than is evident in the group 1 runs. The specified turning movements between groups 1 and 2 changed only for the interior intersections, and the primary cause of this change is probably the modified traffic signal phasing at the boundary nodes. The addition of a protected left-turn phase to allow traffic to more readily re-enter the network interior has apparently led to a reduction in vehicle concentrations on the boundary.

Network Traffic Flow Theory

As discussed previously, the relationship between network concentration, K, and average speed, V, (both taken over the same observation period) is of prime interest. This was explored by varying concentration levels, K, while keeping all other features of the network, including the control system and the traffic characteristics, constant. For each run, the average speed was found by dividing the total amount of time spent in the system by the vehicle-miles traveled. Both quantities were aggregated over the population of vehicles in the network between the 8th and 20th minutes of simulation, which defines the observation period for the reasons explained earlier in this section.

The average speeds thus obtained for a number of group 2 simulation runs (with a 35-mph mean desired speed) at different concentration levels of up to 75 vehicles per lane-mile are shown in Figure 5. Note here that each point corresponds to an individual simulation run at a given concentration level and not to an average over a number of replicated runs [i.e., using different seeds for the random number generator underlying the stochastic features of NETSIM (9,10)] at the same concentration. Replications were not needed for the exploratory study because of the very large number of vehicles and the long observation periods over which the average quantities of interest were calculated. This was confirmed by a number of replications that were performed using different seeds for a variety of conditions, all of which yielded practically identical results for the averages under investigation (greater sensitivity to this aspect could, however, be problematic at very low concentration levels where stochastic effects are more pronounced). It can be seen in Figure 5 that the average network speed clearly decreases as a function of increasing network concentration. This is not unlike the K-V relationship that prevails on arterials. Particular care must be exercised in interpreting the extreme values (low K and high K); at the lower end of the concentration spectrum, the aforementioned stochastic effects might be prevalent, whereas at the higher end instabilities, which may not be adequately captured in the simulation, might arise. The results shown are nevertheless insightful because they reveal a clear qualitative trend between K and V. Note also that the rate of decrease of V slowly decreases at the higher concentration values shown in Figure 5.

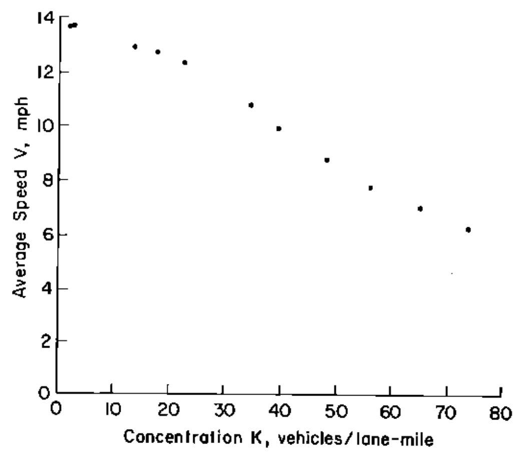

FIGURE 5 Average speed versus network concentration, group 2 runs (35 mph mean desired speed).

To highlight the effect of the operational control system and associated traffic characteristics on the relationship between V and K, Figure 6 shows the average speeds obtained for a wider selection of simulation conditions under varying concentration levels but over a more restricted range. Thus both groups 1 and 2 are represented in Figure 6 at both mean desired speeds (25 and 35 mph). For each desired speed within each group, a separate K-V trend can be distinguished over the range of speeds and concentrations under consideration. Although there is only one reading for a group 1 simulation at 35-mph mean desired speed, it is included in Figure 6 because it clearly lies off the other three lines. It is apparent in Figure 6 that, within a given group, simulations conducted with a 35-mph mean desired speed displayed a higher average speed, for the same concentration level, than a corresponding run with 25-mph mean desired speed. Furthermore, the group 1 combination of traffic controls and operating characteristics resulted in better performance, in terms of average speed at a given concentration level, than did the group 2 combination at both mean desired speed levels. The main conclusion is that although average speed in a network shows a clear decreasing trend as network concentration increases, the trend itself seems to vary as a function of the operational characteristics and controls governing the use of the network configuration. However, considerable further probing is required before more generalizable conclusions can be reached.

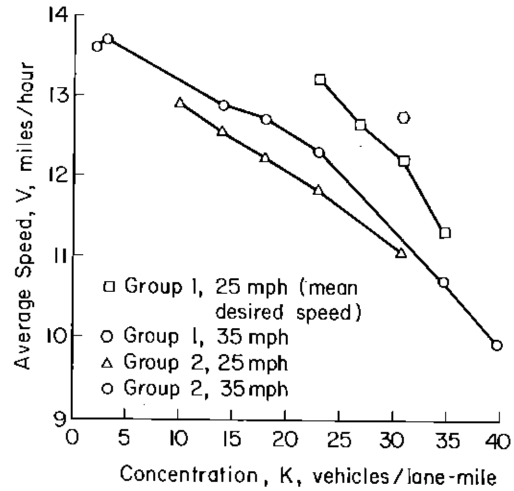

FIGURE 6 Comparison of average speed-network concentration relationship for various simulation groups.

Next the Q = KV relationship, discussed earlier, is investigated. The concentration, K, remains constant over the observation period during each simulation, and the speed is calculated as described previously. The average link flow, also defined earlier and used in determining network stability, is averaged over all links over the period between the 8th to 20th minutes of simulation. Because the link discharges represent the flow in each link and each link is identical (400 ft long, two-lane, and one-way), the average of the link discharges over the period of time in question represents the average flow seen by an average point of the network. The results for a selected number of simulations (corresponding to a variety of conditions) are given in Table 3. The value of the product of concentration and speed is quite close, in all cases, to the observed flow found directly from the link discharge information. The fact that the latter quantity was calculated by averaging over a series of network "snapshots" taken at 1-min intervals whereas the average speed was determined by parameters accumulated semicontinuously over the same period may account for some of the minor discrepancies apparent in this table.

TABLE 3 Comparison of Average Network Flow with Product of Average Speed and Concentration for Selected Runs

V^a	K^b	KV^c	Q^d	Difference[e] (%)
12.21	61.38	749	762	1.7
12.74	61.38	782	792	1.3
11.32	69.30	784	810	3.3
12.64	53.46	676	690	2.1
13.20	45.54	601	618	2.8
12.54	27.72	348	354	1.7
12.87	27.72	357	360	0.8
12.24	35.64	436	438	0.5
12.71	35.64	453	456	0.7
11.19	61.38	687	696	1.3
12.90	19.80	255	258	1.2
11.84	45.54	539	546	1.3
12.32	45.54	561	570	1.6
10.70	69.30	742	750	1.1
9.93	79.20	786	798	1.5
11.30	53.46	604	600	−0.7

[a] Average speed in mph, calculated by dividing total vehicle-miles traveled by total time spent in the system by all vehicles.
[b] Concentration in vehicles per link-mile calculated by dividing the constant number of vehicles on the network by total link-miles. Link-miles are used here instead of lane-miles because all links are identical (2 lanes).
[c] Product of V and K in vehicles per hour.
[d] Average flow in vehicles per hour found from the vehicle discharges for each link. (Compare with column 3.)
[e] Percentage difference between KV and Q.

Two-Fluid Theory of Town Traffic

The results of the simulations are analyzed here from the perspective of the two-fluid representation of traffic in a network. As described earlier, traffic is divided into moving vehicles and stopped vehicles. Thus, how various properties aggregated separately over stopped and moving vehicles vary as a function of increasing network concentration and with respect to each other is examined in the context of idealized simulations.

It should first be noted that the relation given by Equation 1 between the average speed of the moving fluid and the average fraction of vehicles running is predicated on the interactions that occur among moving vehicles. In particular, as the concentration in the network increases, and the average speed decreases (meaning that T, the average trip time per unit distance, increases), the average moving time, T_r (per unit distance), has been observed to increase in real urban street networks. This results from perturbations including short stops to pick up or drop off passengers or goods, pedestrian infringement on the right-of-way, illegal and double parking maneuvers, and other incidents that induce sudden braking or forced lane switching. These sources of turbulence occur primarily along the links rather than at the nodes where most controlled stopping takes place.

In the test network, these sources of intralink friction are virtually absent. For instance, no driveways, parking garages, unsignalized minor streets, buses, or pedestrians have been specified. Furthermore, it is not clear that adequate analytic models of the microscopic aspects of these interactions have been developed to date. This deficiency was acknowledged in earlier studies of NETSIM (11, pp.278-280) where intralink "rare events" were believed to be the primary cause of some discrepancy between simulated results and field observations for a few links in the Washington, D.C., central business district. (This led the model developers to introduce the short and long rare event and blockage features in NETSIM to increase its ability to represent realistic features of urban street networks.)

In view of the this, the effect of intralink interactions, which are essential in the description offered by the two-fluid theory, was anticipated to be insignificant in idealized simulations; this is reflected in the results presented later in this section.

A key identity invoked in the derivation of the relationship between T and T_s (Equation 2) in the two-fluid theory is that the mean fraction of time stopped is equal to f_s, the average fraction of vehicles stopped. This identity, which can be proved mathematically for a constant number of vehicles circulating in a closed network (3), could be verified. Over a given observation period (following the stabilization period discussed earlier), the mean fraction of time stopped can be readily obtained from the networkwide cumulative statistics generated by the simulation model. The estimation of f_s is not as straightforward; the arithmetic average of a number of snapshots of the network taken at 1-min intervals during the observation period was used. For each snapshot, vehicles stopped in queue were tallied over all links and divided by the total number of vehicles on the network. Twelve snapshots (between the 8th and 20th min of simulation) were thus taken for each run, with the exception of the longer runs where more snapshots could be taken, and averaged to yield an estimate $\hat{f}_s$ of f_s.

Table 4 gives $\hat{f}_s$ alongside the corresponding mean fraction of time stopped, $E(T/T_s)$, for a selected number of runs from both simulation groups (and mean desired speeds) and for varying concentration levels. The percent difference between $E(T/T_s)$ and $\hat{f}_s$, also shown for each run in Table 4, clearly indicates the close correspondence between the two values in nearly all cases. The observed discrepancy stems of course from the coarse discretization on which $\hat{f}_s$ is based. It is actually rather remarkable that as few as 12 snapshots yield such close estimates of f_s,

$$(1/\tau)\int_{t_0}^{t_0+\tau} f_s(t)dt$$

where $f_s(t)$ is the time-varying fraction of vehicles stopped, and τ the duration of the observation period. Insights into the dynamic behavior of $f_s(t)$ can be obtained by looking at successive

TABLE 4 Comparison of Fraction of Total Time Stopped with Average Fraction of Vehicles Stopped[a] for Selected Runs

Mean Fraction of Time Stopped	$\hat{f}_s^b$	Difference (%)
0.291	0.298	2.4
0.288	0.295	2.4
0.349	0.352	0.9
0.258	0.269	4.3
0.240	0.242	0.8
0.279	0.297	6.5
0.284	0.274	−3.5
0.292	0.298	2.1
0.295	0.307	4.1
0.351	0.357	1.7
0.353	0.362	2.5
0.260	0.261	0.4
0.313	0.310	−1.0
0.311	0.292	−6.1
0.394	0.405	2.7
0.437	0.443	1.4
0.341	0.350	2.6

[a] Estimated from discrete snapshots.
[b] Based on 1-min snapshots.

snapshots, obtained at 1-min intervals, for one or more runs. Figure 7 shows such snapshots for two selected runs. The bottom line corresponds to a group 1 run (35-mph mean desired speed) with a network concentration of 30.69, and the top line corresponds to a group 2 run (35-mph mean desired speed) and concentration of 39.60. For both runs, the variation is rather substantial, which is typical of all the simulations performed. Variation of average fraction of vehicles stopped as a fraction of network concentration is discussed later in this section.

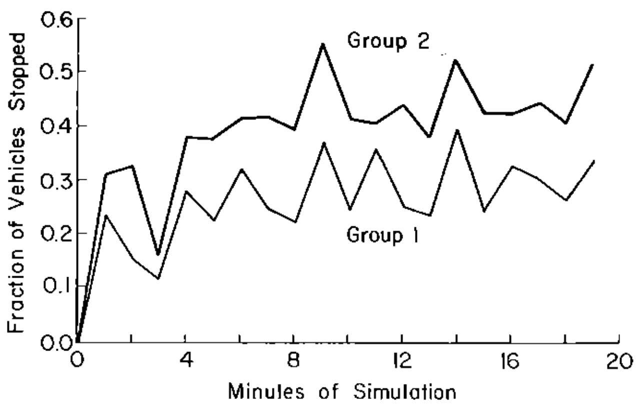

FIGURE 7 Instantaneous fraction of vehicles stopped evaluated at successive network snapshots for two selected runs.

The variation of T, T_s, and T_r as a function of network concentration, K, while network control features and traffic characteristics are kept fixed, is examined next. Group 2 simulation runs with mean desired speed of 35 mph are considered for this purpose. Table 5 gives a summary of the values of T, T_r, and T_s that correspond to concentrations of up to 75 vehicles per lane-mile; also given are the ratios T_r/T and T_s/T. As expected (and seen earlier in the discussion of the K-V relationship), the average trip time per unit distance, T, increases with increasing concentration. It can also be seen from the values of T_s that this increase in T is due overwhelmingly to increasing stopped time; the average running time (per unit distance), T_r, is seen to remain at approximately the same level throughout. This behavior, which does not correspond to that observed in real urban networks, confirms the concerns about the inadequate representation of perturbations and interactions that are an integral aspect of urban street traffic. The almost constant T_r obtained in these runs corresponds to a value of the parameter n (of the two-fluid model), which is not significantly different from zero, indicating the relative lack of sensitivity of T_r to changes in the fraction of vehicles running in the range of concentrations considered in the idealized system. It is, however, conceivable that greater realism could be achieved by specification of random "rare events" (allowed by NETSIM) or other sources of interference; an investigation of these possibilities was beyond the scope of the present exploratory study. Further thoughts on this matter are offered in the next section.

Table 5 also allows examination of the variation of f_s (which is identical to T_s/T) as a function of network concentration. An analytical relationship between f_s and K, proposed by Herman and Prigogine (1) as an extension of the two-fluid model, has been presented (Equation 3). The general trend predicted by Equation 3 is present in the results of the simulations whereby f_s increases nonlinearly with increasing concentration; this trend is shown in Figure 8. It can also be seen in Figure 8 that the fraction of vehicles stopped tends to level off and not fall below a minimum threshold at lower concentrations. A plausible explanation is that, over any meaningful observation period, it is inevitable that a number of stoppages will occur due to the nature of the traffic control system governing the network used in the simulations. In other words, it is virtually impossible to circulate in a network of this type for 12 min within some fraction of the vehicles stopping at some of the frequently encountered signals.

A least-squares estimation of the parameters p and K_m in Equation 3 yielded the values 0.589 and 156.0 vehicles per lane-mile, respectively. Note that these estimates are for K in the range of 15 to 75 vehicles per lane-mile. The corresponding R^2 was equal to 0.988. It is interesting to note here that the magnitude of K_m is consistent with its interpretation as the concentration at which the network "jams." A partial simulation run with an intended K of 150 vehicles per lane-mile showed extreme congestion levels with prevailing spillbacks at most intersections, which effectively delayed the complete loading of the vehicles onto the network by as much as 20 min after the last vehicle was emitted from the source nodes. (Computational cost considerations prevented the pursuit of the matter further at this stage with such unrealistically high concentration levels.)

TABLE 5 Average Trip Time, Stop Time, and Running Time Characteristics for Group 2 Runs[a] Under Varying Network Concentration Levels

Concentration (veh/lane-mile)	Trip Time[b] (T)	Running Time[b] (T_r)	Stop Time[b] (T_s)	T_r/T	T_s/T
1.98	4.41	3.34	1.07	0.758	0.242
2.97	4.38	3.30	1.08	0.754	0.246
13.86	4.66	3.34	1.33	0.716	0.284
17.82	4.72	3.33	1.39	0.705	0.295
22.77	4.87	3.35	1.52	0.689	0.311
34.65	5.61	3.40	2.21	0.606	0.394
39.60	6.04	3.40	2.64	0.563	0.437
48.51	6.86	3.41	3.44	0.498	0.502
56.43	7.80	3.41	4.39	0.437	0.563
65.34	8.62	3.39	5.24	0.393	0.607
74.25	9.68	3.37	6.31	0.349	0.651

[a] 35 mph mean desired speed.
[b] T, T_r, and T_s are averages (over time and over vehicles) expessed in minutes per mile.

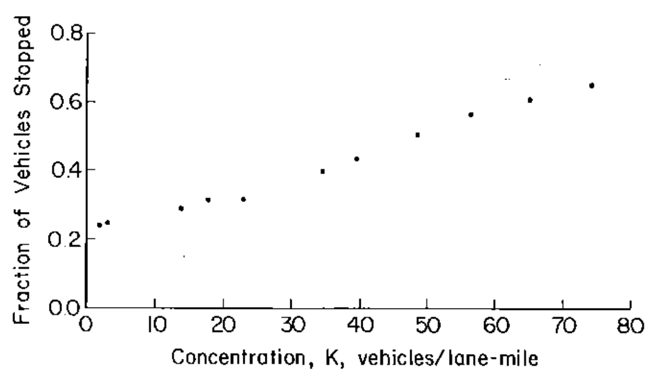

FIGURE 8 Average fraction of vehicles stopped versus network concentration, group 2 runs (35 mph mean desired speed).

SUMMARY AND ASSESSMENT

An exploratory study designed to assess the usefulness of a simulation-based approach to support the investigation of network-level macroscopic traffic flow relationships has been discussed. The NETSIM microscopic network traffic simulation model was used in conjunction with an idealized system consisting of an isolated CBD-like rectangular grid network operating under various combinations of traffic control schemes and characteristics. The results were analyzed with respect to (a) network traffic flow theory, (b) the two-fluid theory of town traffic, and (c) flow distribution on network components.

The analysis of flow distribution on network components was concerned primarily with the dynamic behavior of the relative concentrations and flows on boundary links and interior links, respectively. Useful insights were gained regarding the general stabilization of the respective fractions of vehicles and flows on boundary and interior links after an initial period. This provided the basis for defining an appropriate observation period over which average traffic descriptors, used in other parts of this study, were calculated.

Two principal network traffic flow theoretic relationships were addressed. Average network speed was found to decrease as a function of increasing network concentration, as anticipated, with an overall trend that is not unlike that observed for arterials. This trend was also explored under varying signal timing schemes and traffic characteristics. The second relationship addressed was $Q = KV$, which is fundamental for arterials but unverified at the network level. Simulations seemed to indicate that, for properly defined averages of the three quantities, $Q = KV$ could be expected to hold.

The analysis of the results from the perspective of the two-fluid theory of town traffic verified the identity between the average fraction of vehicles stopped and the mean fraction of time stopped for a fixed number of vehicles circulating in a closed network over the same observation period. The dynamic behavior of the instantaneous fraction of vehicles stopped was also examined. In addition, the variation of the average fraction of vehicles stopped as a function of network concentration was studied and seemed to indicate that a proposed extension of the two-fluid model (1) holds rather well over a middle range of concentrations. On the other hand, the idealized simulation conditions apparently did not generate the interactions among moving vehicles that constitute an essential feature of real urban traffic systems operations and that, as such, are critical to the description encapsulated by the two-fluid theory.

It is essential to re-emphasize here the exploratory nature of the research described. It is evident that a number of probably severe limitations are present in the preliminary results. The list of these limitations includes the highly idealized nature of the system and its operating conditions, the well-known fact that a simulation model is only an abstraction of the real world, and many others ranging from specifics of the execution to the restricted scope of the results and associated conclusions. It is nevertheless believed that such exploratory studies yield useful insights into the behavior of traffic systems under a variety of conditions that cannot be easily achieved in the real world. Such studies can provide a useful complement to observational studies of network-level traffic phenomena, which remain the cornerstone of a scientific approach to the development of a network traffic flow theory. By raising questions and probing some possible answers, simulation-based studies can suggest to the analyst important directions for both theoretical and observationally based advances.

A number of avenues exist for further effort in this general area of investigation. Some of the more immediate ones include the assessment of how NETSIM could be used to adequately describe the interactions among moving vehicles or intralink phenomena that are fundamental in real urban street systems. It was mentioned earlier that the introduction of short- and long-term rare events and blockages, in addition to heavy vehicles, pedestrian interference, driveways, and parking maneuvers, is likely to improve the realism of this representation. However, more fundamental modifications in the car-following and lane-switching procedures embedded in NETSIM may be required. A related possibility exists for using some of the recent empirical results obtained in conjunction with the two-fluid theory whereby one or two test vehicles circulating in a network can yield sufficient information for characterizing the quality of traffic service in an urban network (3,4). This relatively easily acquired information could provide the basis for calibrating a simulation model like NETSIM, particularly with respect to difficult-to-model intralink interactions.

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Banks and banking -- Lincoln (Neb.)

Another Look at Storage Requirements for Bank Drive-In Facilities

(University of Nebraska Lincoln) ... [et al.]

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ABSTRACT

Observations of the operation and performance of bank drive-in facilities in Lincoln, Nebraska, indicated that current storage requirements for these facilities were excessive. The objective of this research was to determine why these theoretically and empirically developed requirements were excessive and to develop more reasonable storage requirements. Arrival and service-time data collected at bank drive-in facilities were analyzed. It was determined that the arrivals were Poisson. But, contrary to the usually employed queuing theory assumptions of negative exponential serving times, which had been used to develop previous storage requirements, the service-time distributions were found to be gamma distributions with shape parameters between 2.75 and 5.00. Because of the intractability of using queuing theory with gamma service-time distributions, simulation models of single-queue and multiple-queue, multiple-channel queuing systems typical of bank drive-in facilities were developed and validated. The models were then used to determine more appropriate storage requirements.

Before April 1981 the storage requirements for bank drive-in facilities imposed by the city of Lincoln, Nebraska, were those given in Table 1. These requirements were developed from a review of the literature, primarily papers written by Woods and Messer (1) and Scifres (2), and the results of field studies conducted by the city in 1974, which in general confirmed the findings presented in the literature. These requirements were generally accepted as reasonable for several years. Beginning in 1980 they were challenged for requiring too much storage, and the need for updated studies became apparent.

TABLE 1 City of Lincoln, Nebraska, Drive-in Bank Storage Requirements Before April 1981

No. of Windows	Minimum Storage Required[a,b] (vehicles)
1	7
2	14
3	21
4	28
5	30
6	30

[a]In addition to the service position.
[b]22 ft per vehicle required in storage lanes.

The need for updated studies resulted primarily from major changes in the banking industry in Lincoln. Among these changes were

1. A sharp increase in the number of drive-in facilities available, spreading the business around and reducing peaking at any one facility.
2. The introduction of 24-hour electronic teller machines at sales points such as grocery stores provided a new convenience for customers. This raised the customers' expectations and reduced their tolerance of delay.
3. There was an increased trend toward staggered payrolls among major employers, which reduced peaking characteristics for deposits and withdrawals.

Consequently, in early 1981, the city conducted studies of traffic operations at drive-in banking facilities to determine the reasonableness of its storage requirements. A total of 1,142 transactions were observed during which the average traffic intensity was 0.89. However, the maximum queue length observed in any one storage lane was only five vehicles, and it existed for only 18 sec. Otherwise, the maximum queue length was four vehicles. The average transaction time observed was 2.12 min, which is considerably lower than the average service times often assumed in design guidelines (1,2). In addi-