CARSIM: Car-Following Model for Simulation of Traffic in Normal and Stop-and-Go Conditions

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A CAR-following SIMulation model, CARSIM, with more realistic features to simulate not only normal traffic flow but also stop-and-go conditions on freeways, has been developed. The features of CARSIM are: (1) marginally safe spacings are provided for all vehicles, (2) start-up delays of vehicles are taken into account, (3) reaction times of drivers are randomly generated, (4) shorter reaction times are assigned at higher densities, and (5) dual behavior of traffic in congested and non-congested conditions is taken into consideration in developing the car-following logic of this model. The validation of CARSIM has been performed at microscopic and macroscopic levels. At the microscopic level, the speed change patterns and trajectories from CARSIM were compared with those from field data; whereas at the macroscopic level, average speed, density, and volume computed in CARSIM were compared with the values from real world traffic conditions. The regression analysis of simulation results versus field data yielded R^2 values of 0.98 and higher, indicating that the results from CARSIM are very close to the values obtained from field data. One example of the application of CARSIM to study traffic-wave propagation is presented.

Since the beginning of traffic simulation in the mid-1950s, more realistic features have been added to newly developed models. In the more recent models, the emphasis has shifted from machine-processing efficiency to human efficiency in using the models (*2, 3*). A comprehensive review of car-following studies is provided (*1*), as are a comparison of car following models (*4, 5, 9*) and a review of traffic simulation models (*6, 7, 8*). The feasibility of developing an integrated simulation system to improve the human and computational efficiency has been investigated by Federal Highway Administration since 1975. As a result, an integrated traffic simulation model, called TRAF, has been developed and can be used for the evaluation and development of traffic control and traffic management policies (*2*). The creation of TRAF was not involved with new model development, but with the enhancement of the best existing traffic simulation models.

The most complete and updated microscopic freeway simulation model is INTRAS (*9*), which was included in phase I of TRAF. INTRAS is a highly complex stochastic model and is capable of simulating a variety of traffic/flow conditions. However, the INTRAS model is not capable of realistically simulating the behavior of traffic in stop-and-go situations on freeways. This is mainly due to the following assumptions made in developing its car-following algorithm:

(1) INTRAS uses a constant value of 0.3 seconds to represent the reaction time of drivers (a lag).
(2) INTRAS does not take into account the start-up delay of the stopped vehicles.
(3) In INTRAS, the dual behavior of traffic in congested and non-congested conditions has not been taken into consideration.

Therefore, a new car-following model or a substantial improvement in the car-following algorithm of INTRAS is needed, if the model to be is used for simulation of stop-and-go conditions on freeways.

The CAR-following SIMulation model, CARSIM, was developed to take into consideration the aforementioned shortcomings of the INTRAS car-following algorithm and to offer additional realistic features and capabilities for simulation of stop-and-go conditions on freeways. In its present form, CARSIM simulates only the car-following behavior of freeway traffic. CARSIM has been validated at microscopic and macroscopic levels using field data. At the microscopic level, the speed change patterns and the trajectories of vehicles obtained from CARSIM were compared with those from field data. At the macroscopic level, however, the average speed, density, and volume computed in CARSIM were compared with the values calculated from the field data. The development and validation of CARSIM as well as its features and capabilities are briefly discussed in the following sections.

FEATURES OF CARSIM

The following features were included in the development of car-following logic of CARSIM:

1. The vehicles' acceleration and deceleration rates were kept within the reasonable values observed in actual traffic conditions, and yet marginally safe spacings were provided for all vehicles.
2. The delay in response of the following driver to the lead car's deceleration was taken into consideration. The delay is equal to the reaction time of the driver.
3. The start-up delay of a stopped vehicle was taken into consideration. The start-up delay is, on the average, less than 2 seconds.

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4. The dual behavior of traffic in congested and non-congested conditions was taken into consideration. For non-congested flow condition (density less than 60 vpm), the following and lead vehicle both have the same maximum deceleration rate. However, a maximum deceleration rate of 13 ft/sec/sec is used for the following vehicle when density exceeds 60 vpm, while the maximum deceleration rate for the lead car is 16 ft/sec/sec. The use of different maximum deceleration rates for congested flow condition is merely for computational purposes.

5. CARSIM uses varying reaction times for an individual driver and different reaction times for different drivers. The reaction time of a driver in congested flow conditions is less than his reaction time in free flow conditions. A driver's reaction time is randomly selected from a category of twelve different reaction times.

6. CARSIM has the capability to simulate stop-and-go conditions, a feature that is extremely important in studying the effects of kinematic disturbances on traffic.

DESCRIPTION OF CARSIM

The car-following and the acceleration algorithms are the two most critical routines in CARSIM. A detailed discussion of these algorithms will be given in the following sections. A brief discussion of the inter-arrival time of vehicles, vehicle generation, reaction time of drivers, and speed distribution will be also presented. For programming of CARSIM, SIMSCRIPT II.5, a simulation language, is used (*10*).

Car-Following Algorithm

The car-following algorithm is basically a vehicle-advancing mechanism that facilitates the movement of vehicles from one point to another along the road. In conjunction with the acceleration routine, it determines the proper acceleration or deceleration rate a vehicle should maintain in a given time interval. Once the acceleration or deceleration rate is determined, it is used to compute the speed and the location of the vehicle at the end of that time interval. In CARSIM, the following vehicle will be advanced to a position that provides it enough space headway to decelerate to a safe speed or a complete stop when the lead car reduces its speed.

The very important parameter in advancing a vehicle throughout the system is finding the proper acceleration or deceleration rate (*AXL*). *AXL* is determined in the acceleration routine. Once this rate is known, the speed and the location of the vehicle, at the end of updating time interval, is calculated using the following equations:

$$V_F = V_F + (AXL)(DT) \qquad (1)$$

$$X_F = X_F + V_F\,(DT) + 0.5\,(AXL)(DT)^2 \qquad (2)$$

where:

AXL = proper acceleration or deceleration rate for that time interval;
DT = scanning time interval (1 second);
V_F = velocity of the following vehicle at the beginning or end of the scanning time interval;
X_F = position of the following vehicle at the beginning or the end of the scanning time interval.

The car-following algorithm checks whether or not the vehicle is the first unit in the system (leader). If the vehicle is the first unit in the system and is traveling at its desired speed or at the speed limit, an acceleration rate of zero is used to update the speed and location of this vehicle. However, for a vehicle traveling slower than the desired speed or the speed limit, the rate (*AXL*) is computed from the acceleration routine. When the first vehicle in the system is traveling faster than the desired speed or speed limit, either an acceleration of zero or a comfortable deceleration rate is used to update the speed and location of this vehicle.

For the following vehicles in the system, the acceleration routine is called to determine the acceleration or deceleration rate. The following section describes how the acceleration or deceleration rates are determined in the acceleration routine.

Acceleration Algorithm

The acceleration routine determines the acceleration or deceleration rate a following vehicle should have while satisfying all safety and operational constraints. Several acceleration or deceleration rates are computed for different situations, and the most suitable one is selected for each vehicle in every time interval.

The acceleration or deceleration rates are computed for every vehicle in 1-second time intervals for the following situations:

1. The following vehicle is moving but has not reached its speed limit or desired speed: *A1*.
2. The following vehicle has reached its speed limit or desired speed: *A2*.
3. The following car was stopped and has to start from a standing still position: *A3*.
4. The following vehicle's performance is governed by the car-following algorithm while space headway constraint is satisfied: *A4*.
5. The following vehicle is advanced according to the car-following algorithm with non-collision constraint: *A5*.

In addition to these, comfortable deceleration rates and maximum allowable deceleration rates of the following and the lead vehicles are taken into consideration in order to limit the computed values within a reasonable boundary.

The discussion of the procedures for the computation of the acceleration or deceleration rates are given in the following sections.

Computation of A1

A1 is acceleration rate of a moving vehicle or a vehicle ready to move, constrained only by the mechanical ability of the vehicle. *A1* is taken from Table 1 for a given vehicle type and speed. This table is constructed based on maximum acceleration-rate information given in the *Transportation and Traffic Engineering Handbook* (T&TEH) (*11*).

The normal acceleration and deceleration rates for a pas-

TABLE 1 TYPICAL ACCELERATION RATES (ft/sec/sec) FROM STANDING START TO 15 mph AND 30 mph, AND AT VARIOUS RUNNING SPEEDS THEREAFTER, ON A LEVEL ROAD

vehicle type	speed (mph)					
	0-15	15-30	30-40	40-50	50-60	>60
passenger car	8.80	5.50	5.17	4.17	3.08	2.09
tractor semi-trailer	2.20	1.10	0.88	0.44	0.44	0.44

TABLE 2 NORMAL ACCELERATION AND DECELERATION RATES (ft/sec/sec) FOR PASSENGER CARS WHEN THE DRIVERS ARE NOT INFLUENCED TO REACT RAPIDLY

speed change (mph)		acceleration	deceleration
from	0-15	4.84	7.77
	15-30	4.84	6.74
	30-40	4.84	4.84
	40-50	3.81	4.84
	50-60	2.93	4.84
	60-70	1.91	4.84

senger car are given in Table 2 (*11*). These values were observed where the drivers were not influenced to react rapidly. For trucks, 75% of the values in Table 2 are used.

Computation of A2

A2 is the acceleration or deceleration rate a vehicle needs to reach the desired speed ($DS \cdot V_F$) or the speed limit. A driver will try to reach his desired speed or the speed limit as fast as possible while satisfying all safety and operational constraints.

The desired speed will be equal to the speed limit when a driver does not want to drive above the speed limit. In CARSIM, a courtesy factor which shows what percentages of the drivers will obey the speed limit or the suggested speed is assigned by the user.

Computation of A3

A3 is the acceleration rate of a stopped vehicle when it starts moving after a start-up delay. When a platoon of vehicles is subjected to a kinematic disturbance, the speed of the vehicles will decrease gradually and finally they may come to a complete stop. After the lead car moves, the follower will move after a few seconds of delay: "start-up delay." The investigation of Ohio State University trajectory data (*12*) revealed that the start-up delay for the cars in a platoon is about 1 to 3 seconds.

It is assumed that the drivers with shorter reaction times will wait less than the drivers with longer reaction times. In CARSIM, less than 20% of the drivers have a reaction time of 0.68 seconds in a surprise situation. These drivers will wait 1 second, but the rest of the drivers will wait a maximum of 2 seconds, before moving again. Comparison of the trajectory plots generated by CARSIM for four stop-and-go conditions indicated that the assumed start-up delays are very reasonable. Less satisfactory results were obtained when a 2-second start-up delay was used for all drivers. The propagation speed of the starting wave would be about 14 ft/sec when the assumed start-up delays are used.

A vehicle will not be allowed to move, regardless of how long it has been stopped, as long as the non-collision constraint is not satisfied. For a vehicle starting from a stand-still position, the acceleration rate is 2 ft/sec/sec for passenger cars and 1 ft/sec/sec for trucks for the first second of the movement. Thereafter, the acceleration is determined according to the car-following algorithm.

Computation of A4

A4 is the acceleration computed from the following equation (using equality):

$$X_L - (X_F + V_F (DT) + 0.5 (A4) (DT)^2) \geq L_L + K \qquad (3)$$

where:

X_L = position of the lead vehicle;
L_L = length of the lead vehicle;
K = buffer space between vehicles; K = 10 ft when density is not very high.

The other terms have been defined previously.

A4 is the acceleration rate when a space headway of greater than or equal to the sum of the length of the lead car and a buffer space of *K* feet is provided. A buffer space of 10 feet, as suggested by the INTRAS model, provided satisfactory trajectory plots when density was not very high. However, study of the Ohio State University trajectory data (*12*) indicated that the use of a 10-foot buffer space cannot be justified at high densities. For example, for platoon 123 with fifteen cars, minimum space headway which occurred near jam density was in the range of 18.41 to 30.99 feet, and the average of the minimum distances was 22.44 feet. The minimum spacing would be different depending on the density of traffic: for near-jam density conditions, a 5- to 7-foot buffer space was used.

Computation of *A5*

A5 is the acceleration or deceleration rate of a vehicle when the non-collision constraint is satisfied. The following equation is used to assure that enough spacing is provided:

$$X_L - (X_F + V_F(DT) + 0.5\,(A5)\,(DT)^2) - L_L - K \geq$$

$$\text{maximum of} \left| \begin{array}{l} [V_F + (A5)\,(DT)]\,(BRT), \text{ or} \\ [V_F + (A5)\,(DT)]\,(BRT) \\ \quad + \dfrac{[V_F + (A5)\,(DT)]^2}{2(MX.F)} - \dfrac{V_L{}^2}{2(MX.L)} \end{array} \right. \qquad (4)$$

where:

BRT = brake-reaction time of a driver;
V_L = velocity of the lead car at the end of time interval;
$MX.F$ = maximum deceleration rate of the following car;
$MX.L$ = maximum deceleration rate of the lead car.

It can be seen that the non-collision constraint built in the logic of CARSIM is:

$$[V_F + (A5)\,(DT)]\,(BRT) + \frac{[V_F + (A5)\,(DT)]^2}{2(MX.F)} - \frac{V_L{}^2}{2(MX.L)} \geq 0 \qquad (5)$$

The value of *A5* is determined such that after moving a following vehicle to its new position there will be enough space headway for this vehicle to react to a decelerating lead vehicle, and stop or reach a safe driving speed. Assuming the non-collision constraint is satisfied, solve equation 4 for *A5* and simplify it to obtain equation 6:

$$(DT)^2\,(A5)^2 + B(A5) + C <= 0 \qquad (6)$$

where

$$B = 2\,(V_F)(DT) + 2\,(MX.F)(DT)(BRT) + (MX.F)(DT)^2$$

$$C = -2\,(MX.F)(X_L - X_F - V_F\,(DT) - L_L - K - V_F)\,(BRT) + \frac{V_L^2}{2(MX.L)} + V_F^2$$

Solve equation 6 for *A5*.

$$A5 = [-B + (B^2 - 4\,(DT)^2\,(C)]^{1/2} / [2(DT)^2] \qquad (7)$$

A5 computed from equation 7 may be for acceleration or deceleration depending on the values of *B* and *C*.

Since *A5* is computed using the non-collision constraint, equation 4 is evaluated using *A5*. By substituting *A5* in equation 4, determine whether or not the left-hand side of equation 4 is greater than or equal to the maximum of the two expressions on the right-hand side. If this condition is not satisfied, use the first expression on the right-hand side of equation 4 to compute *A5*.

To use CARSIM as a dual-regime model, computations are performed with different *MX.F* and *MX.L* values. When the density is greater than 60 vpm, an *MX.F* of 13 ft/sec/sec, instead of 16 ft/sec/sec, is used in computations of *A5*. When the density is less than 60 vpm, a maximum deceleration rate of 16 ft/sec/sec is used for both the following and the lead vehicles.

Proper Acceleration or Deceleration Rate

Once *A1*, *A2*, *A3*, *A4*, and *A5* have been computed, a comfortable deceleration rate (*AC*) is also determined for each speed group from Table 2. The comfortable deceleration rate will be used when a driver slows down just to reach the posted speed limit. Using a comfortable deceleration rate would prevent a sudden decrease of speed which might cause another kinematic disturbance.

To choose the proper acceleration value, the program finds the minimum of *A1*, *A2*, *A3*, *A4*, and *A5* and uses this positive number as the acceleration rate. The proper deceleration value is either comfortable deceleration (*AC*), or *A2*, or *A5*. It is always less than the maximum deceleration rate of 16 ft/sec/sec. If $A2 < AC$ and $AC <$ minimum of (*A4*,*A5*), then *AC* is used. If $AC < A2$ and $A2 <$ minimum of (*A4*,*A5*), then *A2* should be used; otherwise, *A5* is used.

After determining the proper acceleration or deceleration rate, the speed and the position of a vehicle are computed using equations 1 and 2. This vehicle is advanced to a new position and the rest of the vehicles are moved in a similar fashion. This process is repeated in 1-second time intervals for all vehicles in the system. For each driver-vehicle unit in CARSIM, a set of attributes is assigned before it is allowed to enter the model. These attributes are discussed in the following section.

Driver-Vehicle Characteristics

Vehicles are generated one at a time, and a set of attributes is assigned to each vehicle upon generation. The driver-vehicle characteristics such as type and length of vehicle, emergency deceleration, complying index, location, identification number, desired speed, brake reaction time, and arrival time are assigned to every unit. The traffic mix is a user-specified input variable.

In developing the model, several decisions are made with regard to the inter-arrival time, brake reaction time, and speed distribution of the vehicles. These topics will be discussed in the following sections.

For light traffic, where there is less vehicle interaction, the inter-arrival time constitutes an exponential function. As traffic volume increases, the interaction between vehicles becomes more frequent. Considering the behavior of drivers in the car-following situations, one may expect the headway distribution to have an exponential tail. Therefore, the headways can be generated from functions such as log normal, truncated normal, or shifted exponential. For this model, the time headway between successive vehicles is generated from a negative shifted exponential distribution.

Another characteristic assigned to each vehicle is the desired speed. One important factor influencing the shape of the speed distribution plot is the density of traffic. In high density traffic the variation in speed is not as much as in free-flow traffic conditions, thus more uniformity is expected. Duncan (*14*), Breiman et al. (*13*), and Pahl (*15*) suggested normal distribution, while Ashworth (*16*) proposed an Erlang distribution instead of a normal distribution for speed. In CARSIM, the desired speed of vehicles is generated from a truncated normal distribution with a mean of 55 mph and a standard deviation of 5 mph.

A full description of the other attributes used in CARSIM is described elsewhere (*1*). In the following section, the discussion about brake reaction time is presented.

Brake Reaction Time

The response of a driver jointly varies with that driver's stimulus and sensitivity. Thus, the brake-reaction time not only varies among the drivers but also changes for a given driver under different conditions. Johansson and Rumer (*17*) reported that the median brake-reaction time was 0.66 seconds and the range was between 0.3 to 2.0 seconds in alerted situations. A recent study by Olson et al. (*18*) used two groups of drivers: a younger group, age 40 or younger; and an older group, 60 or more years old.

For surprise conditions, the 5th and 95th percentile range was 0.85 to 1.6 seconds for young drivers and very close to these values for older drivers. For young drivers, the 5th and 95th percentiles for alerted conditions were 0.57 and 1.37. For older drivers, the values were a little longer.

The reaction times used in CARSIM were obtained from a cumulative distribution plot based on Johansson and Rumer's data. The reaction time varies from 0.4 to 1.5 seconds for alerted (congested) conditions, in increments of 0.1 seconds. There are twelve different reaction times, and one of them is assigned randomly to each driver. The probability of assigning each one of the twelve values is not the same. The percentage of drivers having reaction times of less than or equal to the specified value are given in Table 3 for alerted and surprise situations. The reaction times used in CARSIM are very close to the young drivers' reaction times in Olson's study.

The use of varying reaction times is more realistic than using a constant value for all densities and more reasonable than using a constant value for all drivers. When a driver is in a platoon or in unexpected traffic congestion on the freeway, he would be driving with more attention to the situation than when he sees only a few cars on the freeway. Due to this fact, CARSIM uses shorter reaction times when density is greater than 60 vpm.

However, adjustments are made for trucks such that no truck with a reaction time of less than 1 second is allowed to enter the system.

DATA BASE

The data used for validation of CARSIM are the Ohio State University trajectories data collected by Treiterer (*12*) using aerial photogrammetric techniques. The photographs were taken in 1-second time intervals. The location of a vehicle is estimated to be accurate within ± 0.50 feet and the speed is determined with an error of ± 1.0 mph. The data was collected from I-70 in Columbus, Ohio, a 3.5-mile-long section with three on- and three off-ramps. The data provides spacings, headways, longitudinal positions, and speeds for all vehicles.

From the data, the following four platoons which experi-

TABLE 3 REACTION TIME OF DRIVERS (IN SECONDS) IN LIMITED ANTICIPATION (ALERTED) AND SURPRISE CONDITIONS

% of drivers	alerted situation	surprised situation
100	1.50	2.03
98	1.40	1.89
96	1.30	1.76
94	1.20	1.62
90	1.10	1.49
88	1.00	1.35
81	0.90	1.22
72	0.80	1.08
64	0.70	0.95
48	0.60	0.81
20	0.50	0.68
4	0.40	0.54

enced a stop-and-go condition are used in the validation of CARSIM:

(1) Platoon 123: A group of fifteen vehicles which has no vehicles entering or leaving the platoon.

(2) Platoon 126: The platoon started with fifteen vehicles, and after several seconds two cars left the platoon and one car joined to it. This group of fourteen vehicles went through a kinematic disturbance and lost another car before recovering and one more car after recovering from the disturbance.

(3) Platoon 127: This platoon reached a very high density. It started with ten vehicles and remained a ten-vehicle platoon.

(4) Platoon L123X: A group of five vehicles following each other for 202 seconds. The vehicles in this platoon are also in Platoon 123.

VALIDATION OF CARSIM

Validation of CARSIM was performed at microscopic and macroscopic levels. At the microscopic level, the location and the speed of each vehicle from the field data were compared with those computed from CARSIM; whereas at the macroscopic level, the average speed, density, and volume from the field data were compared with the values calculated by CARSIM. The discussion of different aspects of the procedures used for validation of this simulation model are provided elsewhere (*19–26*).

Four different platoons of vehicles covering a wide range of traffic operations were used for the comparison of field data with CARSIM's results. Here, only the results for platoon 126 are presented. (The other platoons' results were very similar.)

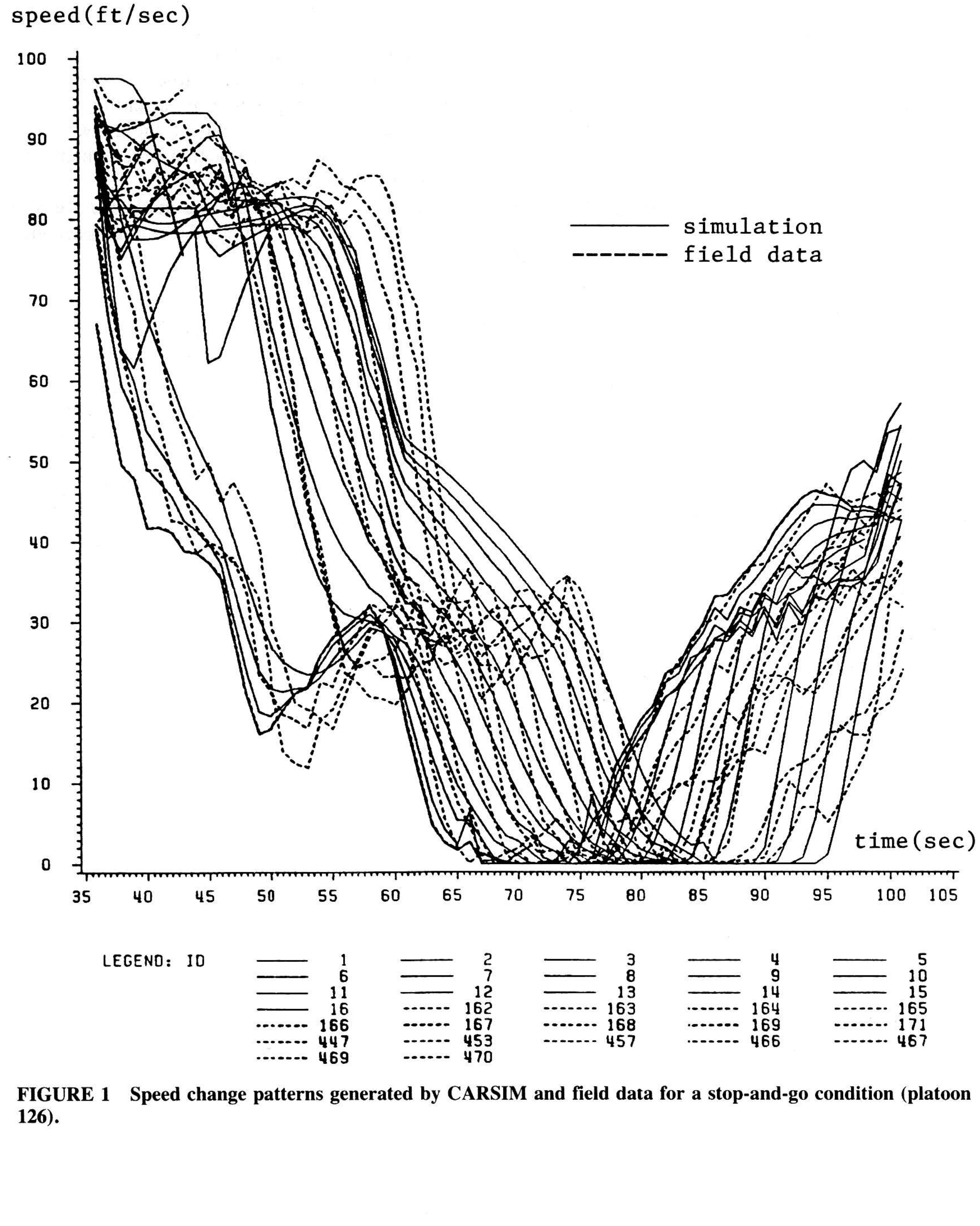

FIGURE 1 Speed change patterns generated by CARSIM and field data for a stop-and-go condition (platoon 126).

Five independent replications of CARSIM were made for each real-world condition. In the replications, the characteristics of vehicles and drivers were generated randomly and assigned to them. However, the speed and location of the first vehicles in CARSIM and the real-world platoon were the same.

Validation at Microscopic Level

The average speed and location of each vehicle were computed at time intervals of 1 second and were compared to the values obtained from the field data for that vehicle. For platoon 126, the plot of the average speeds computed by CARSIM versus the values obtained from the field data are shown in Figure 1. As can be seen, the speed change patterns generated by CARSIM were very close to those from the field data. It should be noted that the last three vehicles of the real-world platoon were not closely following the other cars in the platoon, while the last cars in the simulated platoon were keeping up with the lead cars.

For the trajectory comparison, the average location of each vehicle computed from the replications was compared with the location determined from the field data, as shown in Figure 2. This figure shows that all of the vehicles in platoon 126 were forced to stop for awhile and then move. CARSIM is

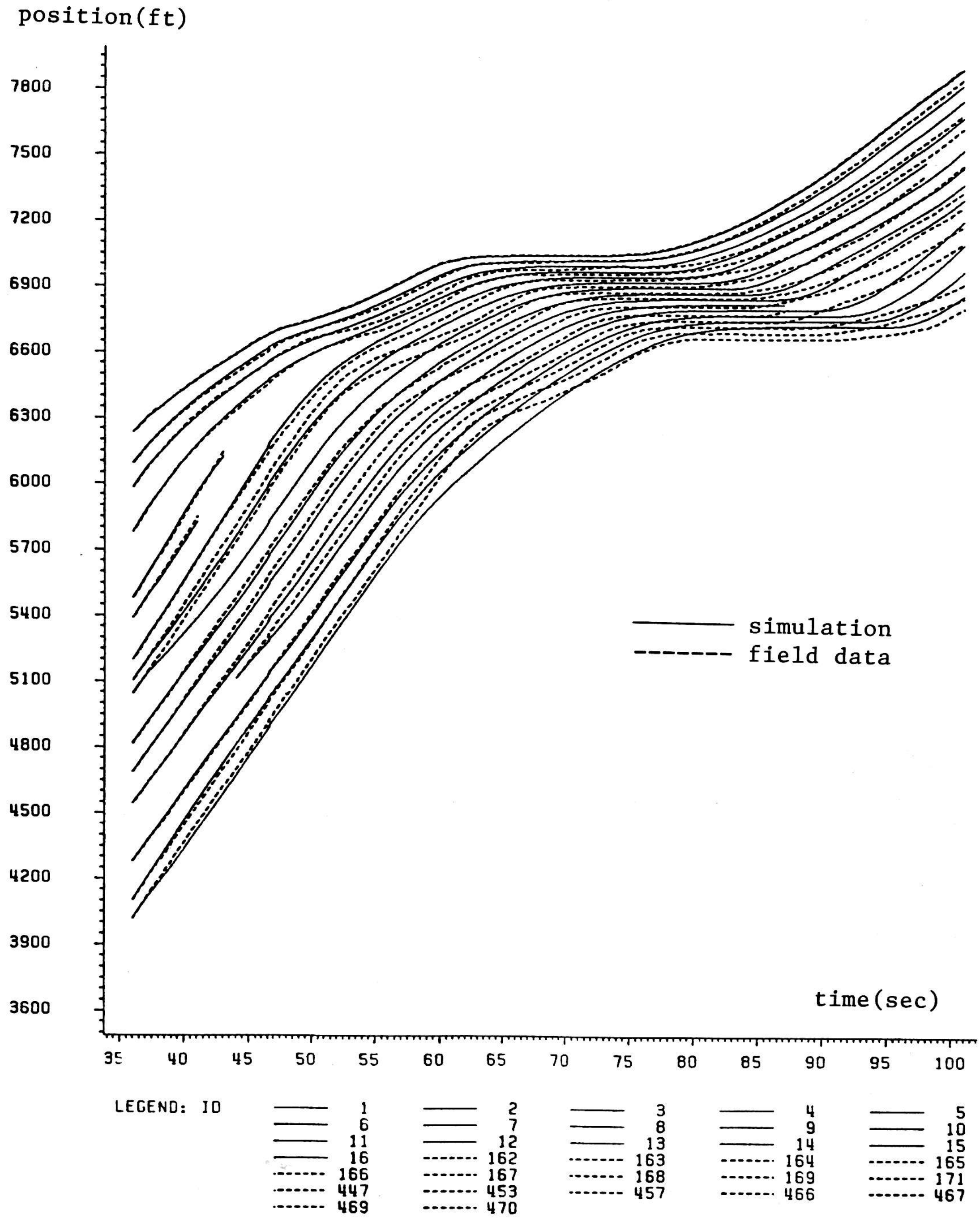

FIGURE 2 Trajectories generated by CARSIM and field data for a stop-and-go condition (platoon 126).

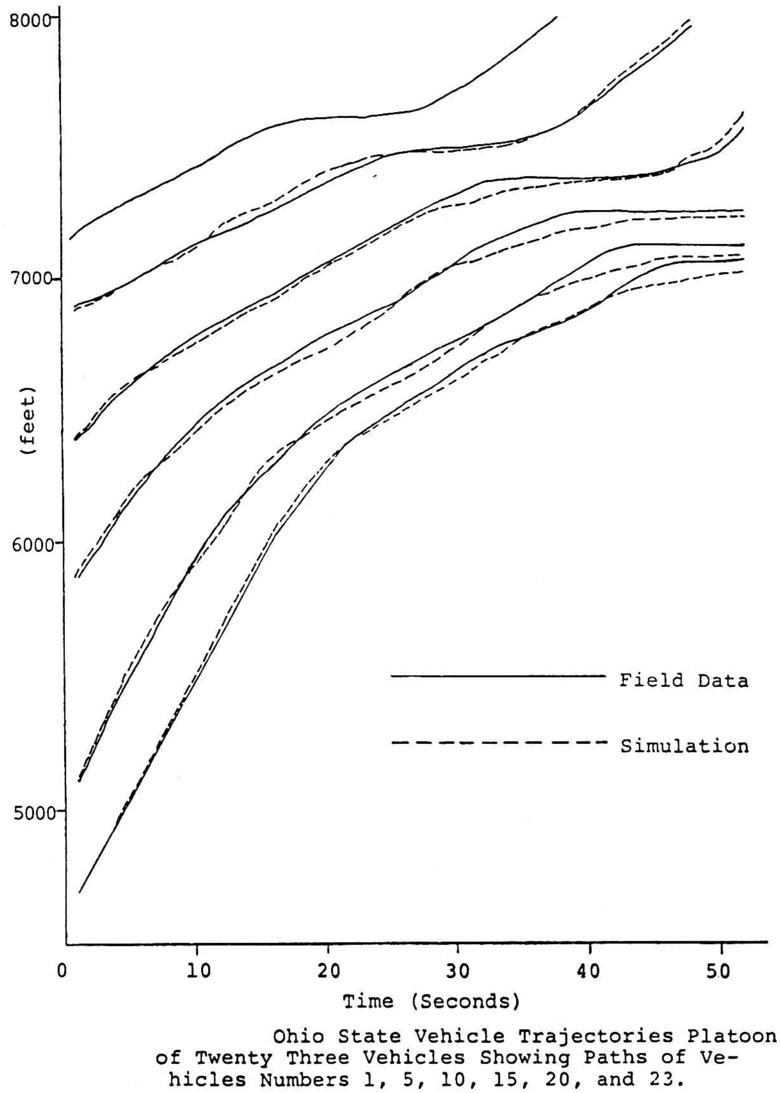

FIGURE 3 INTRAS trajectory validation graph, showing every fifth car in the platoon (*9*).

capable of simulating such stop-and-go operations in a realistic manner. No statistical tests were run; only visual comparisons were made at the microscopic level.

When the traffic flow is not in a steady state condition, it is quite challenging to generate trajectory plots from simulation models that would replicate the actual trajectory plots. It is not clear how the existing car-following models would perform when subjected to this challenge. For example, the INTRAS model (*9*) used only one phase of going through a kinematic disturbance, namely the deceleration phase, and did not use the second phase (Figure 3). For comparison of the trajectories generated by INTRAS and CARSIM, see Figures 2 and 3. The results from CARSIM show the deceleration and the acceleration phase (stop-and-go), but the results from INTRAS show only the deceleration phase.

Validation at Macroscopic Level

At the macroscopic level, the overall performance of a platoon of vehicles, rather than the performance of an individual vehicle, was evaluated.

For each platoon, the following comparisons were made between CARSIM's results and field data:

1. Comparison of flow parameters over time,
2. Comparison of fundamental relations of traffic flow, and
3. Regression of similar results versus the field data.

Comparison of Flow Parameters

The flow parameters used for comparisons are: speed, density, and volume. These parameters are computed from CARSIM and the field data at 1-second time intervals for every platoon. For platoon 126, the plot of the average speeds from CARSIM versus the speeds from the field data is shown in Figure 4. As can be seen, the speed computed by CARSIM was very close to the actual speed of the platoon. It is important to note that platoon 126, from its initial speed of about 80 fps, reached a speed of near zero in less than 1 minute; and that CARSIM simulated such a rapid speed reduction. The simulation curve shows less fluctuation than the curve for the field data, as expected.

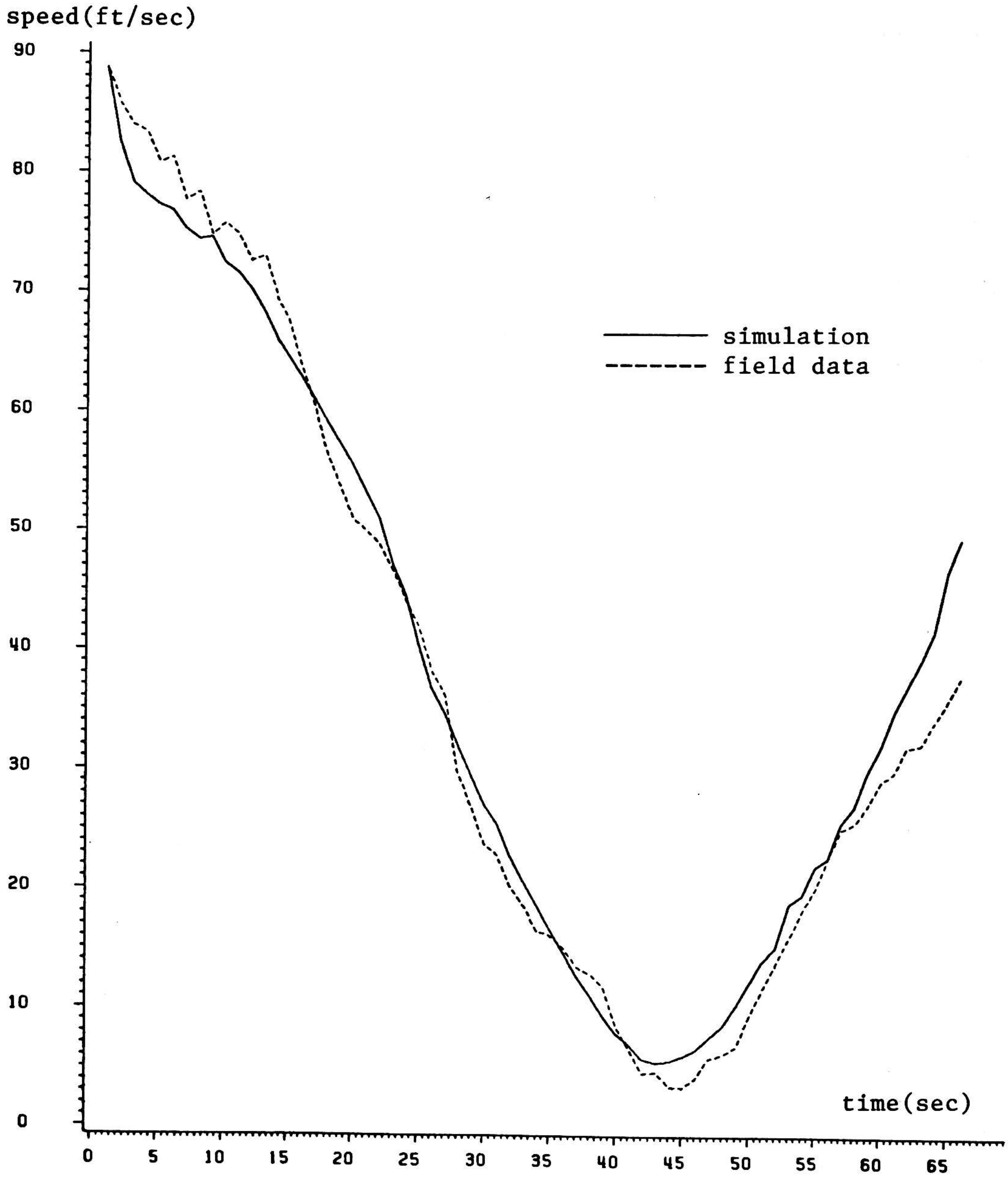

FIGURE 4 A platoon speeds computed from CARSIM and field for a stop-and-go condition (platoon 126).

The plot of densities computed from CARSIM and the field data are shown in Figure 5. This graph shows very similar density fluctuation curves for the simulated platoon and for the actual platoon. It should be noted that the time in which the simulated platoon reached the jam density was very close to that of the actual platoon. One should be very careful in using the density of platoon when comparing simulation results with field data, because the density of a platoon is computed from the position difference of the first and the last car in the platoon and is very dependent on the spacing between these vehicles.

Comparison of Speed-Density Plots

The relationship between speed, density, and volume computed from the field data and CARSIM was compared for all platoons (*1*). For platoon 126, the speed-density curves from CARSIM and field data are shown in Figure 6. A nonlinear relationship and a loop between the values obtained before and after the disturbance is produced by the field data and by CARSIM. The loop was more distinct when the results from each replication of CARSIM were plotted against the field data. The loop is an indication of the dual behavior of traffic before and after a disturbance.

In addition to the graphical presentation of the results, regression analysis of the simulation results versus the field data was also carried out. The results will be discussed in the following section.

Regression of Simulation Results vs. Field Data

Regression of the speed, density, and volume computed from CARSIM versus the values obtained from the field data were

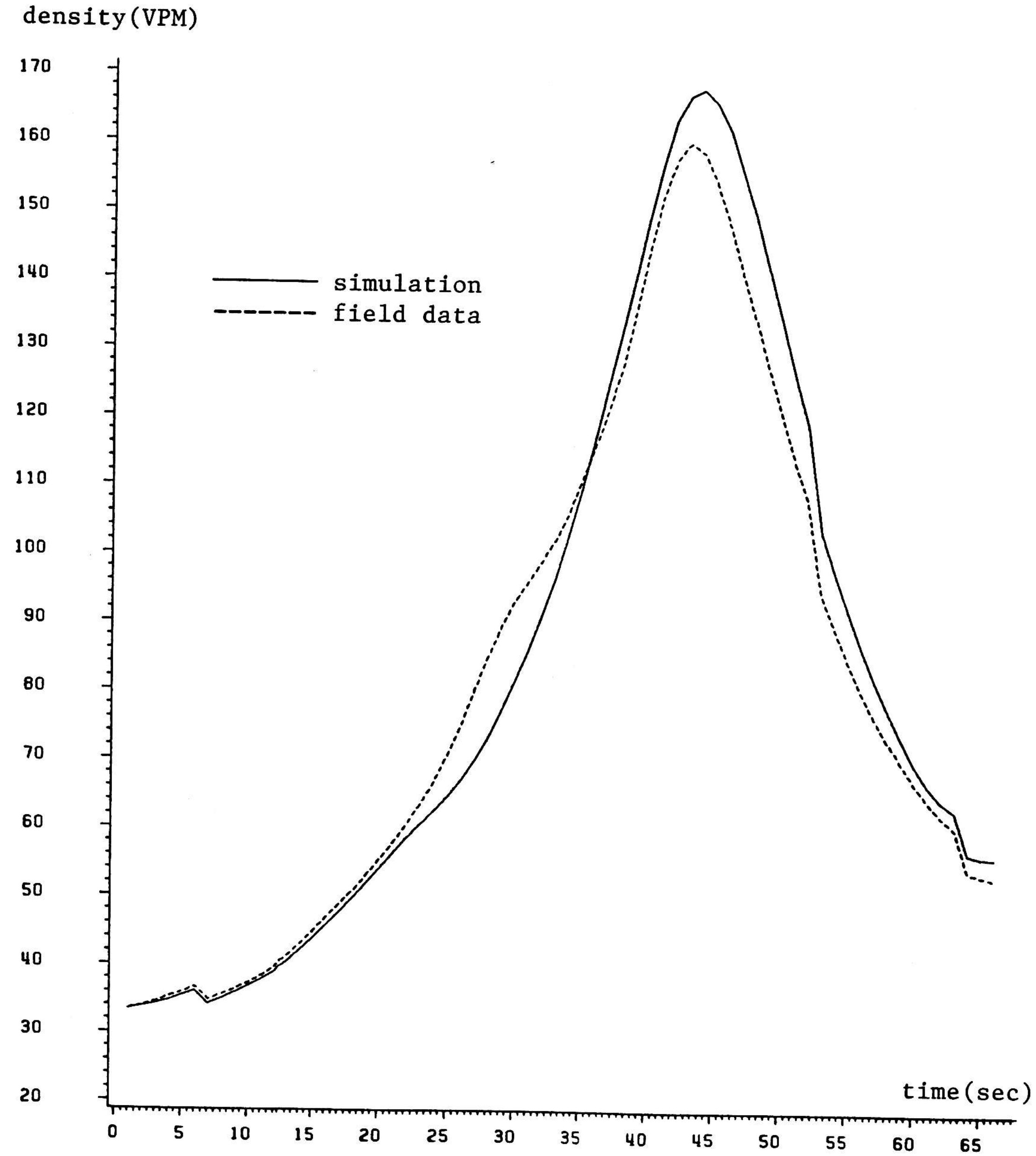

FIGURE 5 A platoon densities computed from CARSIM and field data in a stop-and-go condition (platoon 126).

carried out for all platoons. The average values of speed, density, and volume were computed from the replications in 1-second time intervals for all platoons and used for comparison. Table 4 gives the summary of the regression analysis. It can be seen that the slopes of the regression lines (*b1*) are very close to 1, and the *y*-intercepts (*b0*) are almost zero. This combination of slope and *y* intercept indicates that the plot of CARSIM's results versus the field data are scattered around a line going through the origin with a 45-degree angle. This means CARSIM's results are very close to the value from the field data.

The regression analysis indicates that there is a strong agreement between the simulation and the real-world results. The *R*-squared values for the regression of speed and density from CARSIM versus the values from the field data are 0.98 or higher. Such high *R*-squared values and low variability on the slopes of the regression lines indicate that the results obtained from CARSIM are very close to the values computed from the field data.

The graphical comparison and the regression analysis of the results from CARSIM and the field data indicate that CARSIM realistically reproduces normal and stop-and-go traffic flow conditions on freeways. From this comparison, the result seems reliable. For further validation, more field data from stop-and-go conditions on freeways is needed. In the following section, one application of CARSIM is demonstrated.

APPLICATION

This example is to demonstrate how CARSIM handles a road blockage and how the traffic waves propagate and dissipate.

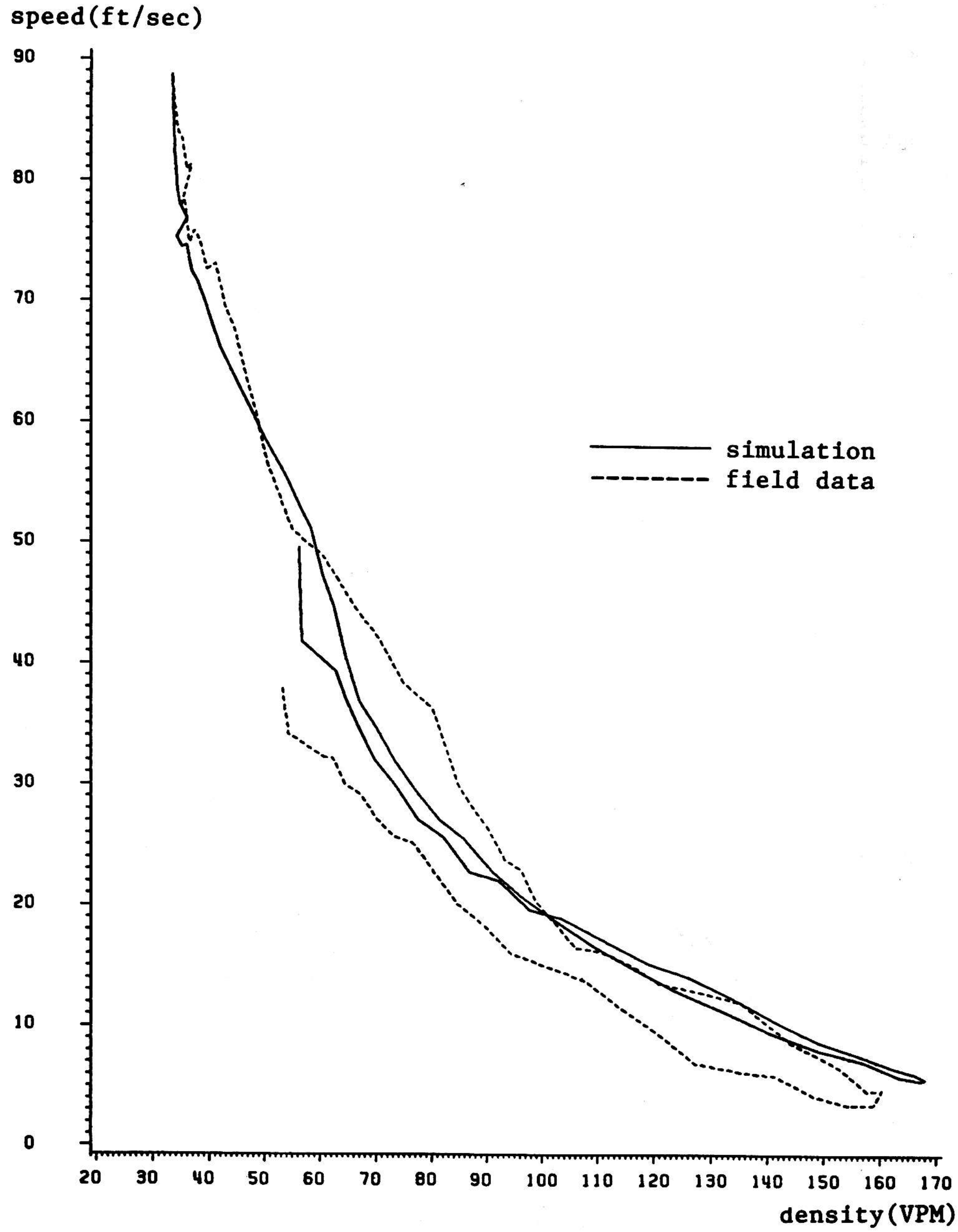

FIGURE 6 A speed-density relationship computed from CARSIM and field data for a stop-and-go condition (platoon 126).

TABLE 4 RESULTS OF REGRESSION OF CARSIM'S VALUES VS. FIELD DATA

type of data	platoon number	b0	b1	R**2	s(b0)	s(b1)
	123	1.70554	0.94705	0.98383	0.49177	0.01220
Speed	126	3.26491	0.93782	0.98621	0.63354	0.01386
	127	-1.14070	1.02664	0.98708	0.52923	0.01105
	123	1.43827	0.98432	0.98922	0.88620	0.01033
Density	126	-5.12594	1.08229	0.98183	1.65879	0.01841
	127	2.46060	0.93949	0.97765	1.22708	0.01336

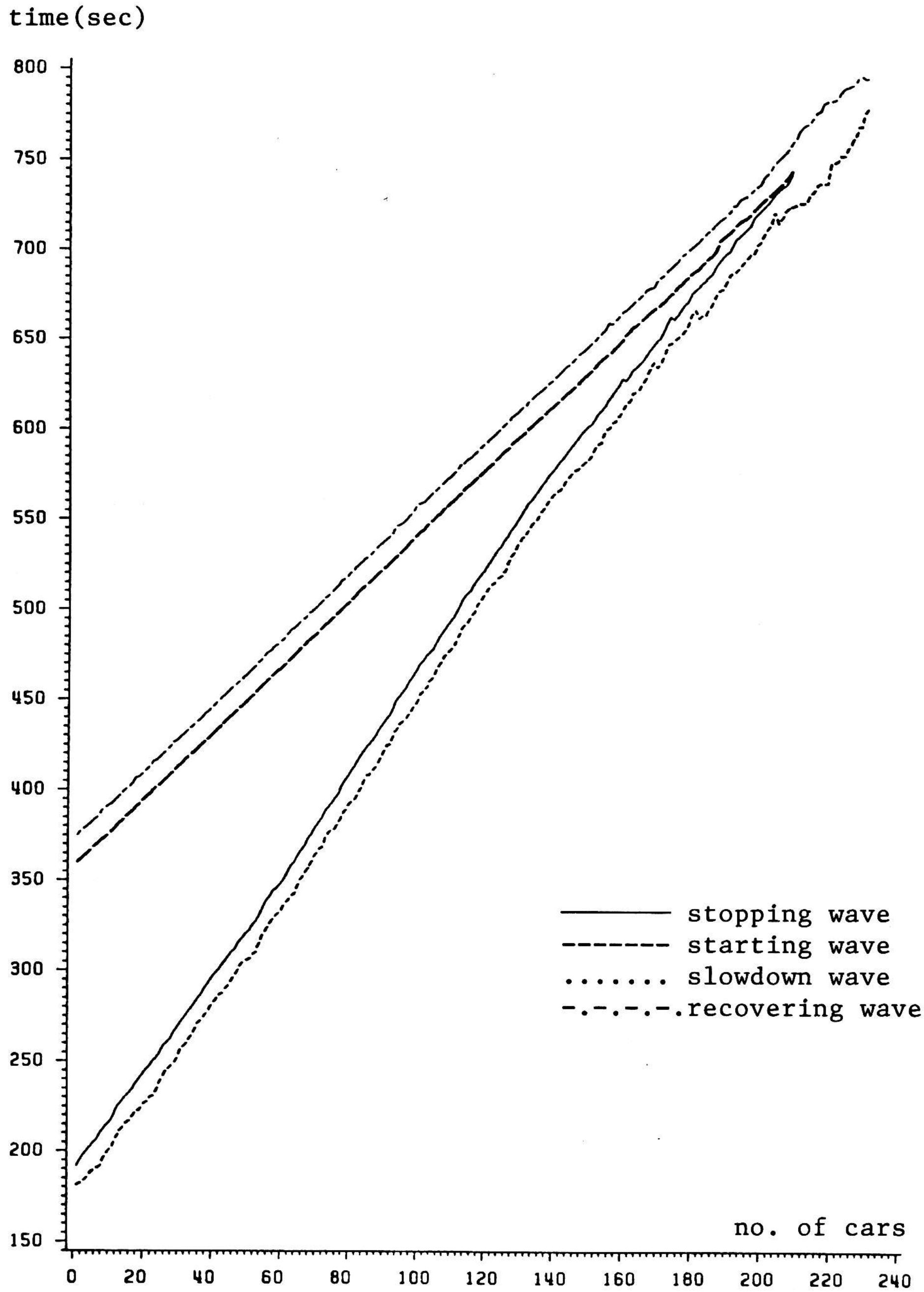

FIGURE 7 Simulation of effect of a 3 minute road blockage on propagation and dissipation of traffic waves (volume is 1,200 VPH).

Due to an incident, a roadway is blocked for 3 minutes and the arriving vehicles form a very long queue. The closed section is a single-lane road with no exit, such as a long bridge or a construction zone. The vehicles are allowed to accelerate to a desired speed of 55 mph when the incident is removed. While the cars in the front of the queue accelerate to reach the desired speed, the arriving cars join the rear of the queue. Through this process, the location of the bottleneck moves to upstream traffic. The traffic volume is 1200 vph and the desired speed is 55 mph (80.67 fps). The incident happens 180 seconds after the lead car enters the system and forces the cars to decelerate to a complete stop. There are enough cars in the system (about 240 cars) that the effect of 3 minutes' road blockage does not reach the last vehicle in the system. After 3 minutes, the lead car is allowed to move and accelerate to the desired speed. The time a vehicle slows down, stops, starts moving again, and reaches the desired speed is determined by CARSIM for all vehicles affected by the road blockage.

Four different kinematic traffic waves are identified as: (1) slow-down wave, (2) stopping wave, (3) starting wave, and (4) recovering wave. The waves are evidenced by the effect imposed on the following car due to the road blockage. Figure 7 shows the time each wave is reached by a given vehicle.

At the point a starting wave reaches a stopping wave, the queue of stopped cars is eliminated. Similarly, at the point the recovering wave reaches the last affected vehicle, the effect of road blockage is completely eliminated. The relationships between these waves can easily be used to study characteristics of traffic congestions. As it can be seen in Figure 7, the slope of the starting wave is less than the slope of stopping wave. This indicates that more vehicles will move, rather than stop, in a certain period of time. When the slope of the moving wave is equal to or greater than that of the slope of the stopping wave, there will always be a queue of stopped vehicles. Application of CARSIM for traffic wave studies is discussed elsewhere (*1*).

CONCLUSIONS

A car-following model, CARSIM, is developed to simulate not only normal but also stop-and-go traffic flow conditions on freeways. More realistic features to reflect the behavior of traffic in stop-and-go conditions are included in the car-following algorithm of this model. For validation of CARSIM, graphical and statistical techniques were used and the results from CARSIM were compared to the field data. The comparison of the trajectory and the speed-change plots yielded satisfactory results. The regression analysis of speeds and densities computed from CARSIM versus those from the field data resulted in R-squared values of 0.98 or higher, indicating a strong agreement between the simulation results and real-world traffic data.

REFERENCES

1. R. F. Benekohal. *Development and Validation of a Car Following Model for Simulation of Traffic Flow and Traffic Wave Studies at Bottlenecks.* Ph.D. Dissertation. The Ohio State University, Columbus, Ohio, 1986.
2. E. B. Lieberman. *Integrated Traffic Simulation Model Phase 1,* Vol. 1, Executive Summary. Report FHWA-RD-80-086. FHWA, U.S. Department of Transportation, Sept. 1980.
3. G. Radelat. Simulation Developments in Progress. In *Special Report 194,*, TRB, National Research Council, Washington, D.C., 1981.
4. D. N. Goodwin. *Examination of Nine Freeway Simulation Models.* System Development Corporation TM-4638/014/01, Santa Monica, Calif., July 1972.
5. Y. S. Hsu and P. K. Munjal. Freeway Digital Simulation Models. In *Transportation Research Record 508*, TRB, National Research Council, Washington, D.C., 1974, pp. 29–41.
6. A. D. May. Models for Freeway Corridor Analysis. In *Special Report 194: Application of Traffic Simulation Models*, TRB, National Research Council, Washington, D.C., 1981, pp. 23–32.
7. D. R. P. Gibson. Available Computer Models for Traffic Operations Analysis. In *Special Report 194: Application of Traffic Simulation Models*, TRB, National Research Council, Washington, D.C., 1981, pp. 12–22.
8. A. S. Byrne, et al. *Handbook of Computer Models for Traffic Operations Analysis.* Report FHWA-TS-82-213. FHWA, U.S. Department of Transportation, 1982.
9. D. Wicks, et al. *Development and Testing of INTRAS, A Microscopic Freeway Simulation Model,* Vols. I-IV. Final Reports. FHWA, U.S. Department of Transportation, 1980.
10. E. C. Russell. *Building Simulation Models With SIMSCRIPT II.5.* C.A.C.I., Inc., Los Angeles, Calif., 1982.
11. *Transportation and Traffic Engineering Handbook,* 2nd ed. Institute of Transportation and Traffic Engineering, Washington, D.C., 1982.
12. J. Treiterer. *Investigation of Traffic Dynamics by Aerial Photogrammetry Techniques.* Transportation Research Center, Department of Civil Engineering, Ohio State University, Final Report EES 278, Feb. 1975.
13. L. Breiman, R. Lawrence, D. Goodwin, and B. Bailey. The Statistical Properties of Freeway Traffic. *Transportation Research,* Vol. 11, 1977, pp. 221–228.
14. N. C. Duncan. *A Method of Estimating the Distribution of Speeds of Cars on a Motorway.* Transport and Road Research Laboratory, Report 598, 1973.
15. J. Pahl. The Effect of Discrete Time Measurement on Speed Data. In *Highway Research Record 349*, HRB, National Research Council, Washington, D.C., 1971.
16. R. Ashworth. An Alternative Procedure for Estimating Speed Distribution Parameters on Motorways and Similar Roads. *Transportation Research,* Vol. 10, 1976, pp. 25–29.
17. G. Johansson and K. Rumer. Drivers' Brake Reaction Times. *Human Factors,* Vol. 13, No. 1, Feb. 1971, p. 23.
18. D. L. Olson, et al. *NCHRP Report 270: Parameters Affecting Stopping Sight Distance.* TRB, National Research Council, Washington, D.C., 1984.
19. R. S. Sargent. Verification and Validation of Simulation Models. In *Progress in Modeling and Simulation* (F. E. Cellier, ed.), Academic Press, 1982.
20. G. S. Fishman. Problems in the Statistical Analysis of Simulation Experiments: The Comparison of Means and the Length of Sample Records. *Communications of the ACM,* Vol. 10, No. 2, 1967, pp. 94–99.
21. J. F. Torres, A. Halati, and A. Gafarian. *Statistical Guidelines for Simulation Experiments.* Executive Summary, Prepared for FHWA by JFT Associates, Culver City, Calif., 1983.
22. J. P. C. Kleijnen. Design and Analysis of Simulations: Practical Statistical Techniques. *SCI Simulation,* Vol. 28, No. 3, March 1977.
23. J. P. C. Kleijnen. Experimentation with Models: Statistical Design and Analysis Techniques. In *Progress in Modeling and Simulation* (F.E. Cellier, ed.), Academic Press, 1982.
24. J. R. Wilson and A. B. Pritsker. A Survey of Research on the Simulation Startup Problem. *Simulation,* Vol. 31, No. 2, Aug. 1978.
25. J. R. Wilson and A. B. Pritsker. Evaluation of Startup Policies in Simulation Experiments. *Simulation,* Vol. 31, No. 3, Sept. 1978.
26. J. P. C. Kleijnen. Antithetic Variates, Common Random Numbers and Optimal Computer Time Allocation in Simulation. *Management Science,* Vol. 21, No. 10, 1975.

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