

Traffic Flow Simulation for an Urban Freeway Corridor

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The objective of this paper is to develop a realistic and operational macroscopic traffic flow simulation model which requires relatively less data collection efforts. Such a model should be capable of delineating the dynamics of traffic flow created by the merging and diverging activities and complex geometric conditions. In addition, it should have the capability of describing shock wave phenomena and movements along the freeway corridor. A modification of the existing equilibrium speed-density function was made. The modified equilibrium speed-density model provided a greater degree of accuracy in describing the nonlinear speed-density relationship. A modified macroscopic traffic flow simulation model was developed in conjunction with the modified speed-density model. The resulting simulation model showed considerable success in simulating actual freeway conditions, and more importantly, provided accurate solutions of ramp metering requirements for the study section. Key words: traffic flow simulation, speed-density relationship, ITS/ATMS application.

INTRODUCTION

The approaches to traffic flow theory may be microscopic or macroscopic. The microscopic approach has resulted in car-following theories which study the behavior of one vehicle following another. The macroscopic approach is analogous to theories of fluid dynamics or continuum theories. Macroscopic traffic flow models are characterized by representations of traffic flow in terms of aggregate measures such as volume, space mean speed, and density. Unlike microscopic models which represent individual vehicle movements, macroscopic models sacrifice a great deal of detail but gain by way of efficiency an ability to deal with problems of much larger scope. An important feature of these latter theories is the conservation of vehicles. It is particularly useful in describing the generation of waves in a traffic stream, their speed, and the behavior of vehicles passing through the waves.

Many older urban freeway corridors are characterized with heavy traffic flow, numerous on- and off-ramps and multiple weaving areas, and poor geometric conditions. Existing macroscopic models generally failed to simulate the traffic operations of such freeway corridors due to their unique characteristics. Therefore, modifications of existing macroscopic traffic flow simulation techniques are necessary to adequate study such fully saturated freeway corridors.

In addition, the data requirements for existing simulation packages are rather sophisticated. Data usually are collected in an interval between 5 to 30 seconds. Recently developed models usually require information gathered in a five-second interval. Certainly, applying more detailed data may result in relatively superior models. Although today's technology supports such data collection needs, buying such expensive sophisticated data collection equipment is still a major budget concern for many cities and states. The development of a less expensive simulation model in terms of data collection is necessary for cities and states that have budget constraints. Such model development certainly will provide a better opportunity to implement advanced traffic management techniques in these organizations.

The objective of this paper is to develop a realistic and operational macroscopic traffic flow simulation model which requires relatively less data collection efforts. Such a model should be capable of delineating the dynamics of traffic flow created by the merging and diverging activities and complex geometric conditions. In addition, it should have the capability of describing shock wave phenomena and movements along the freeway corridor.

BACKGROUND

A variety of macroscopic models of traffic flow on freeways have been developed during the past two decades. Among those models, Payne's FREFLO is the most well known freeway simulation package. Payne (1,2) formulated a variant of the equilibrium speed-density hypothesis that overcomes the spontaneous lockup problem by adding a "look-ahead" term to the speed equation. In Payne's formulation, the equilibrium speed is the speed appropriate for the local density plus a term appropriate for the next downstream section. Although the anticipation term eliminates the spontaneous lockup problem, several studies pointed out that there are other problems with equilibrium speed-density formulations that make them untenable, especially under congested flow conditions (3,4,5).

A major extension of Payne's is due to Papageorgiou et al. (6,7,8,9). Applying a similar space-time discretization of the conservation equation, Papageorgiou further assumed that traffic volume between two freeway sections might be expressed as a weighted sum of the traffic volumes corresponding to the densities of the sections. Papageorgiou's model is well validated and is capable of describing complicated traffic phenomena with considerable accuracy. However, it consists of a number of nonlinear equations, and required computation time and cost is considerably higher.

Michalopoulos et al. (10,11) proposed a simulation model which used the simple continuum modeling based on the conservation

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equation and an equilibrium speed-density relationship. He argued that the hypothesis of an equilibrium speed-density relationship proposed by Payne (1) may not hold, especially at congested and interrupted flows. As such, he developed a model for simulating congested and interrupted flows which does not contain an equilibrium speed-density relationship.

The most noticeable inaccuracy in the above models was the instability in simulating severe congestion with extremely high density. The instability occurred when the traffic entering the freeway from an on-ramp was relatively higher than its normal load, and the densities in the study section as well as adjacent sections tended to be unstable. The potential "lockup" of density was also a major problem of such instability. As such, modifications of the flow conservation equation as well as other components are necessary (12,13,14,15).

SIMULATION MODEL FORMULATION

Finite difference methods are the most common approaches to develop macroscopic traffic simulation models. The time and space continuum of traffic flow is divided into discrete intervals to form a difference mesh, and the continuous equation is numerically approximated at the lattice points of the mesh. A criterion $\Delta x/\Delta t > u_f$ has to be met in the discretization process, where Δx is the distance increment of the mesh, Δt is the time increment, and u_f is the free-flow speed. This criterion was included to ensure that the law of traffic flow conservation was not violated, and further, to improve model convergence and numerical stability (16).

Four simulation models were developed by employing finite difference methods with the above criterion. The structures of these models are presented below.

Model A

Applying the forward difference method, a discretized conservation equation identical to the FREFLO formula was obtained.

Equation (1):

$$k_j(n+1) = k_j(n) + \frac{\Delta t}{l_j \Delta x_j} [q_{j-1}(n) - q_j(n) + q_j^{on}(n) - q_j^{off}(n)]$$

where $k_j(n)$, $u_j(n)$ = traffic density and speed, respectively in section j at time n ;

$q_j(n)$ = flow rate at the downstream boundary of section j at time n ;

$q_j^{on}(n)$ = number of vehicles entering freeway via on-ramps in section j at time n ;

$q_j^{off}(n)$ = number of vehicles leaving freeway via off-ramps in section j at time n ,

$q_j^{off}(n) = \beta_{1j} \times k_j(n) \times u_j(n)$, and β_{1j} is the proportion of mainline traffic leaving the freeway via off-ramps in section j .

Δt = time interval, 1 minute;

Δx_j = section length (miles)

l_j = number of lanes;

A necessary boundary condition for Equation (1) is

$$k_{j+1}(n) = k_j(n) \text{ if there is no downstream section.}$$

Equation (2) represents the dynamic speed-density relationship:

$$u_j(n+1) = u_e[k_j(n+1)] + K_T \left[\frac{u_j(n) - u_e[k_j(n)]}{\Delta x_j} \right] + K_V \left[\frac{k_{j+1}(n) - k_j(n)}{\Delta x_j} \right]$$

where $u_e[k_j(n)]$ = equilibrium speed-density relationship;

K_T, K_V = constants.

The first term of the right hand side of Equation (2) is the equilibrium speed function. The second term of the right hand side is an adjustment to speed by relating to the equilibrium speed. The third term provides an adjustment to speed by relating to the changing density in the downstream section. This third term takes into account the effect of drivers' reaction to the changes of traffic condition ahead, as they will either increase or reduce the speed according to the changing densities in the adjacent downstream section.

Equation (3) is the relation to flow-speed-density. The quantity $q_j(n+1)$ in Equation (3) is defined as the flow rate passing through the downstream boundary of section j during time $n+1$.

$$q_j(n+1) = (1 - \beta_{2j}) \cdot l_j \cdot k_j(n+1) \cdot u_j(n+1)$$

where β_{2j} is the proportion of mainline traffic leaving the freeway via the off-ramps downstream to the critical location of section j . Both the values of β_{1j} and β_{2j} were obtained from the collected data. It was found that the ratios of off-ramp volumes to mainline volumes were nearly constant.

Model B

The first Equation (4) of Model B is a modified conservation equation which was obtained also by applying the forward difference method. The first term of the right hand side in Equation (1), $k_j(n)$, was replaced by a linear combination of $k_j(n)$ and $k_{j+1}(n)$. The first two terms on the right hand side of Equation (4), $\alpha_j \times k_j(n)$ and $(1 - \alpha_j) \times k_{j+1}(n)$, represent adjustments in changing density with respect to the density measures in the subject and downstream sections, respectively. That is, Equation (4) describes the change in section density by taking into account a "look-ahead" factor—the impact of density in the downstream section. The least squares method was used to calibrate the constant α_j . The speed-density Equation (5) was simplified by using the steady-state equilibrium function. The complete set of Model B is presented as the following: Equation (4):

$$k_j(n+1) = \alpha_j \cdot k_j(n) + (1 - \alpha_j) k_{j+1}(n) + \frac{\Delta t}{l_j \Delta x_j} [q_{j-1}(n) - q_j(n) + q_j^{on}(n) - q_j^{off}(n)]$$

Equation (5):

$$u_j(n+1) = u_e[k_j(n+1)]$$

Equation (6):

$$q_j(n+1) = (1 - \beta_{2j}) \cdot l_j \cdot k_j(n+1) \cdot u_j(n+1)$$

where $q_j^{off}(n) = \beta_{1j} \times k_j(n) \times u_j(n)$

$\alpha_j = \text{constant}$

The objective of this modification was to examine and evaluate the choice of α_j in conjunction with the simplified speed–density equation to eliminate the tendency of density “lockup” and instability.

Model C

The flow conservation equations in both Model A and Model B were discretized using the forward difference method. The central difference method was employed to develop the third model. Using the central difference method with a minor modification, the conservation equation can be discretized in terms of space and time in the following form:

Equation (7):

$$k_j(n+1) = \frac{k_{j-1}(n) + k_{j+1}(n)}{2} + \frac{\Delta t}{l_j \Delta x_j} \left[\frac{q_{j-1}(n) - q_{j+1}(n)}{2} + q_j^{on}(n) - q_j^{off}(n) \right]$$

$$\text{where } q_j^{off}(n) = \beta_{1j} \times q_j(n)$$

Equation (7) describes traffic density in progression quite realistically, as a future example will illustrate. However, a minor adjustment has to be made to increase the accuracy of the model. A boundary condition of Equation (7) is same as the one in the previous models, that is, $k_{j+1}(n) = k_j(n)$ if there is no downstream section. In addition, a necessary boundary condition to this model is that, $k_{j-1}(n) = k_j(n)$ if there is no upstream section. The model does not work well at the first and the last sections due to the above boundary condition. Thus, Equation (7) was modified as the following:

Equation (8):

$$k_j(n+1) = \alpha_j \cdot k_{j-1}(n) + (1 - \alpha_j) k_{j+1}(n) + \frac{\Delta t}{l_j \Delta x_j} \left[\frac{q_{j-1}(n) - q_{j+1}(n)}{2} + q_j^{on}(n) - q_j^{off}(n) \right]$$

The equilibrium speed-density equation is applied directly to obtain the simulated section mean speed. That is,

Equation (9):

$$u_j(n+1) = u_e[k_j(n+1)]$$

The flow-speed-density equation is Equation (10):

$$q_j(n+1) = l_j \cdot k_j(n+1) \cdot u_j(n+1)$$

Model D

Model D is the most complicated model developed in this paper. The conservation equation obtained from the central difference method, Equation (7), was further modified by adding another term

$\theta_j \times q_j^w(n)$.

Equation (11):

$$k_j(n+1) = \alpha_j \cdot k_{j-1}(n) + (1 - \alpha_j) k_{j+1}(n) + \frac{\Delta t}{l_j \Delta x_j} \left[\frac{q_{j-1}(n) - q_{j+1}(n)}{2} + q_j^{on}(n) - q_j^{off}(n) + \theta_j \times q_j^w(n) \right]$$

where $q_j^w(n)$ = effective weaving volume in section j at time n

θ_j = weaving constant of section j

$$\alpha_j = \begin{cases} 0.67 & \text{when } j = 1 \\ 0.33 & \text{when } j = J \\ 0.50 & \text{otherwise} \end{cases} \quad j = 1, 2, \dots, J$$

$q_j^w(n)$ is computed by summing the volumes of on- and off-ramps within the weaving area. The addition of this new term takes into account the weaving conflict in traffic flow simulation. The speed-density equation of Model A, Equation (2), was applied to this model. The flow-speed-density equation of this model is identical to the one in Model C, that is, Equation (10).

SPEED-DENSITY RELATIONSHIP

Another major modification is the interpretation and construction of the speed-density relationship. The first steady-state speed-density model is introduced by Greenshields (17), who proposed a linear relationship between speed and density. Various models were developed following Greenshields’ direction, including a logarithmic model (18), generalized single-regimes models (19,20,21), and multiregime models (22). These models in fact can be summarized in a fairly general form as Equation (12):

$$u_e = u_f \left[1 - \left(\frac{k}{k_{jam}} \right)^l \right]^m$$

where u_f = free flow speed

k_{jam} = jam density

The above formula can be transformed into Equation (13):

$$u_e = u_f \cdot \exp \left[a \left(\frac{k_j}{k_{cr}} \right)^b \right]$$

where k_{cr} = critical density

a, b = constants

From speed-density curves as shown in Figure 1, it was found that the speed-density relationships can be viewed as two different curves separated by the corresponding critical density. Therefore, Equation (13) can be rewritten as Equation (14):

$$u_e = u_f \times \exp \left[a_j \times \left(\frac{k_j}{k_{cr}} \right)^{b_j} \right] \quad \begin{cases} b_j = b_{1j}, & \text{if } k_j \leq k_{cr} \\ b_j = b_{2j}, & \text{if } k_j > k_{cr} \end{cases}$$

The method of least squares was applied to the curve fitting process. As shown in Figure 1, the resulting model generally describes the relationship between speed and density with greater accuracy.

MODEL APPLICATION AND RESULT EVALUATION

The above models were calibrated and applied to simulate a 5.4-mile section of the I-64-40 corridor in the St. Louis metropolitan area. The study area is comprised of the eastbound and westbound sections between Kingshighway Boulevard on the east and McKnight Road on the west, as illustrated in Figure 2.

The simulation results showed that Model A, shared a similar structure to FREFLO, had a high tendency of “lockup” phenomenon. That is, the density tended to increase very fast and exceeded

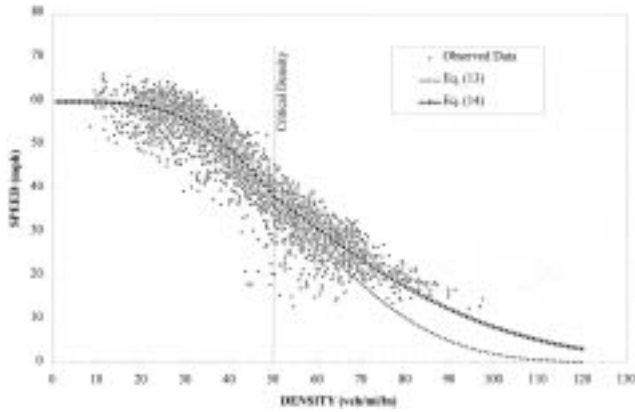


FIGURE 1 Equilibrium speed-density relationship.

the reasonable values. Model B, on the other hand, performed much better than Model A. However, Model B did not simulate well in sections 3 and 4, although it did capture the dramatic increase in density in section 3. The simulation for section 4 generally underestimated the density, and the instability was again a problem of this model.

The results of Model C showed the improvement of the simulation in section 4 as well as the overall model stability. However, it underestimated the impact of the weaving traffic in sections 3 and 4 and failed to capture the dynamics accurately.

The results of Model D showed great improvement in simulation accuracy and stability, especially in sections 2, 3, and 4. The

addition of the weaving term in Model D captures the traffic dynamics amplified by the weaving operation in sections 3 and 4. The results of Model D are illustrated in Figures 3 to 5. These graphics vividly show the propagation of congestion along the freeway corridor and the description of the shock wave phenomenon with respect to time and space.

CONCLUSIONS

Modification of existing macroscopic traffic flow simulation techniques is necessary to adequately study fully saturated freeways with multiple ramps in short distance, multiple weaving areas, poor geometric design, and short sight distances, such as the I-64-40 corridor. A successful modification of the modeling approaches has been successfully developed. The modified simulation model takes into account the impacts of merging and diverging activities and weaving operations, resulting in significant improvement in accuracy in simulating the dynamics of traffic operations.

In addition, the data requirements of the developed traffic flow simulation model are less complicated. The simulation model results in high accuracy in simulating the traffic dynamics in real time, and it is sufficient for the development of advanced traffic management programs. Thus, it provides significant cost savings in data collection and model implementation.

The simulation model presented herein is useful to simulate the changes of traffic conditions with the employment of control strategies. Various Advanced Traffic Management Systems (ATMS) control strategies can be developed in conjunction with the simulation model. The freeway simulation model provides an essential requirement for the successful development of a comprehensive

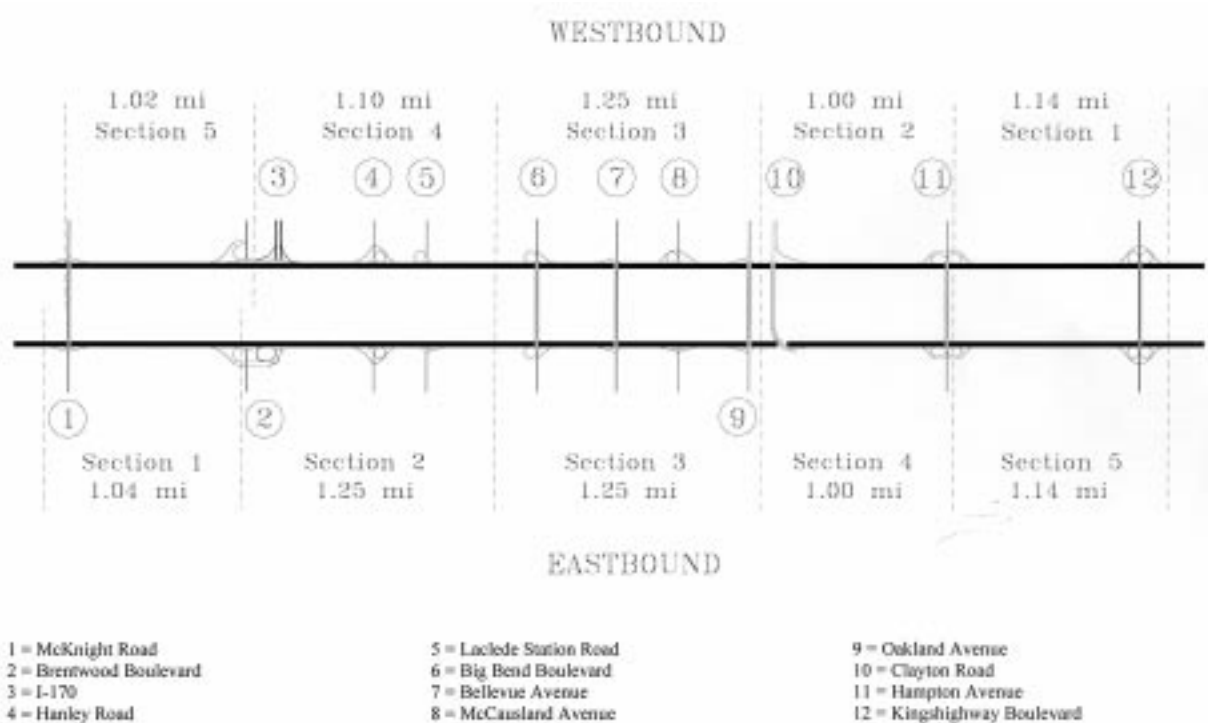


FIGURE 2 Schematic diagram of study site.

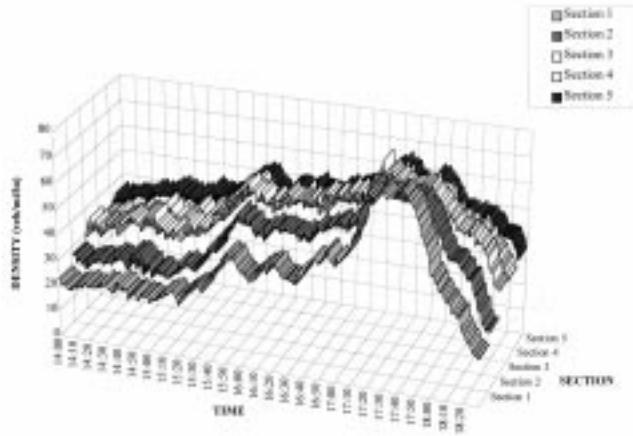


FIGURE 3 Simulation result, Model D, density.

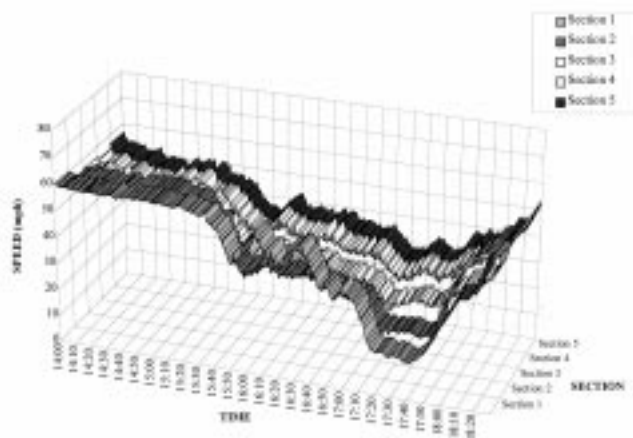


FIGURE 4 Simulation result, Model D, speed.

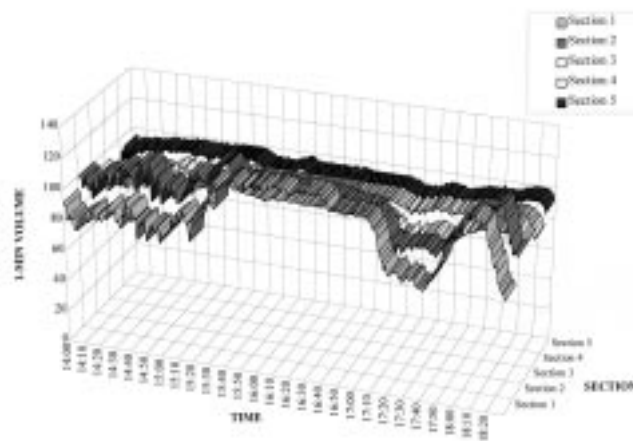


FIGURE 5 Simulation result, Model D, volume.

Intelligent Transportation System (ITS) program. Continued research and implementation of the model refinement will result in improved freeway efficiency and quality of life for many metropolitan areas.

ACKNOWLEDGMENT

Funding for this study was provided by the Missouri Highway and Transportation Department and its District 6 Metro Office in St. Louis through the Transportation and Urban Systems Engineering Program, Department of Civil Engineering, Washington University.

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