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MACROSCOPIC SIMULATION MODEL INCORPORATING DRIVERS'LANE-CHANGING BEHAVIOR

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ABSTRACT

This research proposes a macroscopic simulation model for traffic flow on freeways which incorporates drivers' lane changing behavior. The model is formulated as a set of equations such as basic relationship, basic continuity equation and momentum equation, and is expected to describe traffic dynamics in the whole range of possible traffic densities. The model has a set of parameters, which are estimated using real vehicle trajectory data of NGSIM 2006. Numerical method and genetic algorithm are adopted to solve the nonlinear equation and the complicated minimization problem, respectively.

***Keywords**:* Macroscopic Simulation Model, Lane-Changing Behavior, Traffic Density, Genetic Algorithm

I. INTRODUCTION

Many researchers have developed a lot of models of traffic flow on highway and freeway during the past several decades. Their approaches are either microscopic or macroscopic. Microscopic models are at the level of individual vehicle movements, i.e., they describe the behavior of individual vehicles as a function of traffic conditions in their environment (Herman et al., 1959; May and Keller, 1967; Gazis 1974). Macroscopic models are characterized by representations of traffic flow in terms of aggregate measures such as volume (or flow rate), space-mean speed, and traffic density. They sacrifice a great deal of detail but gain by way of efficiency an ability to deal with problems of much larger scope (Payne, 1979).

As microscopic models are well known from nonlinear system theory, microscopic details have a way of affecting the macroscopic world unpredictably (Daganzo, 1993). Moreover, since microscopic models represent each vehicle separately, the simulation is time consuming and the results are burdened with random bias (Tarko, 1998). Thus, this research focuses on macroscopic models.

This research proposes a macroscopic simulation model for traffic flow on freeways which incorporates drivers' lane changing behavior. The model is formulated as a set of equations such as basic relationship, basic continuity equation and momentum equation, and is expected to describe traffic dynamics in the whole range of possible traffic densities. The model has a set of parameters, which are estimated using real vehicle trajectory data of NGSIM 2006. Numerical method and genetic algorithm are adopted to solve the nonlinear equation and the complicated minimization problem, respectively.

II. LITERATURE REVIEW

In macroscopic models, traffic is represented as a stream (Tarko et al, 1998). The traffic flow can be explained by using flow rate, density and speed, and also expressed as one dimensional compressible flow.

Two assumptions are required to constitute continuum flow models. The first assumption is "conservation of traffic flow," which explains that the number of vehicles in a stretch is equal to the difference between the number of vehicles entered to the stretch and exited from the stretch. The second assumption is that there exists the one-to-one relationship between speed, density and flow. Though it is intuitively plausible that certain density associates to only one speed, it is controversial because a lot of the observed traffic data prove that more than one speed are observed in the same density. Especially, the assumption that the speed is the function of density is meaningful in the equilibrium, but the steady-state is hardly observed in the real world.

III. SIMPLE AND HIGHER ORDER CONTINUUM MODELS

Simple continuum models consist of three equations such as 1) fundamental relationship, 2) basic continuity equation and 3) equilibrium speed-density relationship. The fundamental relationship between the three traffic characteristics such as traffic flow rate, density and speed is as follows: $q = ku$. Basic continuity equation ensures the conservation of traffic mass:

$$\frac{\partial q}{\partial x} + \frac{\partial k}{\partial t} = g(x,t),$$

where g(x,t) is the generation/dissipation rate in vehicle per unit time per unit length.
The equilibrium speed-density relationship is as follows:

$$U = U_f \times \left(1 - \left(\frac{k}{k_j}\right)^{\alpha}\right)^{\beta}$$

where
Uf = free flow speed,
kj = jam density, and
α, β = positive constants

For instance, for α = β = 1, the above equation becomes Greenshields equation of state. The relationship above can be obtained from empirical data or sometimes theoretically inferred. In reality, there is no agreement as to the specific form of the equilibrium speed-density relationship, partly because it is tedious to obtain and traffic equilibrium rarely exists (Tarko et al, 1998).

The simple continuum model has a problem that it can not explain the inertia effects in the traffic flow as well as acceleration/deceleration effects. The higher order continuum model was proposed to overcome this disadvantage of the simple continuum model by adding the speed equation showing the change of speed over space and time. In other words, the higher order models take into account acceleration/deceleration and inertia characteristics of traffic mass by replacing the equilibrium speed-density relationship with a momentum equation (Whitham, 1974; Payne, 1979).

One of the famous higher order continuum models is Payne's model.

$$\frac{\partial u}{\partial t} = -u \times \frac{\partial u}{\partial x} - \frac{(u - U_e)}{T} - \frac{v}{Tk}\left(\frac{\partial k}{\partial x}\right)$$

where
Ue = equilibrium speed,
T = relaxation time
v = anticipation coefficient

The model consists of thee groups of terms expressing three physical process. The firs of these, $-u \times \frac{\partial u}{\partial x}$, is convection, i.e., the fact that vehicles traveling at certain speed in the upstream section will tend to continue to travel at that speed as there enter the next section. The second, $-\frac{(u-U_e)}{T}$, represents the tendency of drivers to adjust their speeds to the equilibrium speed-density relationship. The third, $-\frac{v}{Tk}\left(\frac{\partial k}{\partial x}\right)$, is a model of anticipation of changing travel conditions ahead; i.e., drivers tend to slow down if the density is seen to be increasing (Payne, 1979).

Many previous works on macroscopic models deal with a freeway as a single pipe. Some works have been done in the context of multi-lane flows (Dressler, 1949; Gazis et al 1962). This has been done by applying a simple continuum model for describing flow along two or more one-directional lane. Changing between lanes is represented by the generation or loss of vehicles in the lane under consideration. The generation/loss term was obtained from the assumption that the exchange of vehicles between two neighboring lanes is proportional to the difference in their densities (Gazis et al 1962).

IV. EXTENSIONS OF THE CONTINUUM MODEL

The complete mathematical formulation of model applied to the higher order continuum model consists of 1) basic relationship, 2) basic continuity equation, 3) momentum equation and 4) lane change rate.

The fundamental relationship is as follows:

$$q_i = k_i u_i$$

where

qi = flow in lane i
ki = density in lane i
ui = speed in lane i

The continuity equation represents the law of conservation of traffic stream. Lanes are considered as separate pipes with an interaction between the adjacent pipes (Tarko, 1998). If the traffic sinks and sources exist within the section of the freeway lane i, the continuity equation takes the following form:

$$\frac{\partial q_i}{\partial x} + \frac{\partial k_i}{\partial t} = S_{i+1,i} + S_{i-1,i} - S_{i,i+1} - S_{i,i-1} + g_i$$

where

gi = generation/dissipation rate of vehicles at traffic sources or sinks
Si+1,i = the number of drivers who change lanes from lane i+1 to lane i per unit length per unit time

The momentum equation explains the acceleration / deceleration and inertia effects of traffic stream, and is applicable to non-equilibrium flows (Tarko, 1998). Payne's model is adopted for the momentum equation.

$$\frac{\partial u_i}{\partial t} = -u_i \times \frac{\partial u_i}{\partial x} - \frac{(u_i - U_{ei})}{T} - \frac{v}{Tk_i}\left(\frac{\partial k_i}{\partial x}\right)$$

where

Uei = equilibrium speed,
T = relaxation time
v = anticipation coefficient

Although the value of Uei is typically calculated using an empirical speed-density relationship developed from field data, the average speed of changing lane, 30.56 (mph) is used in this research. Relaxation time T represents the characteristic times for acceleration / deceleration time to adjust the speed from ui to Uei, and anticipation coefficient v/T shows the square of congestion velocity (Tarko, 1998).

Drivers change lane under the condition which they perceive in the other lane better than in the current lane. The lane change maneuver cannot be performed immediately since a driver has to find a sufficiently long gap in the adjacent lane and then perform the maneuver (Tarko, 1998). The lane change rate from lane i to lane i+1 is as follows:

$$S_{i,i+1} = \frac{k_i \times P_{i,i+1}}{T_{i,i+1}}$$

where

Pi,i+1 = likelihood that a given driver decides to change lanes during a short interval

ki = density in lane i

T i,i+1 = time required for the lane change maneuver

Likelihood Pi,i+1 reflects drivers' willingness to change lanes in response to the perceived geometry conditions, traffic conditions, and other factors. It is assumed that the driver choose a lane for further travel based on the traffic condition such as speed in both lanes. A logit model is adopted to estimate this likelihood:

$$P_{ij} = \frac{e^{\beta(u_j-\delta)}}{e^{\beta u_i} + e^{\beta(u_j-\delta)}}$$

where

ui = speed in lane i

β = parameter representing the driver's perception of speed

δ = parameter representing the risk associated with the lane change

Time, T i,i+1, is measured between the time when the decision to change lanes is made and the time when the maneuver is completed. T i,i+1 has two components: Td and Tf. The first component, Td, is the time drivers need to find a sufficiently long gap in the adjacent stream. The second, Tf, is a fixed time required to complete the maneuver after the sufficient gap is found (Tarko, 1998). Tf is assumed 3.5 sec in the research. The modified pedestrian delay model is adopted to estimate Td (TRB, Special Report 1975).

$$T_d = \frac{1}{\Delta q_{i+1} \times \exp(-\Delta q_{i+1} \times \tau)} - \frac{1}{\Delta q_{i+1}} - \tau$$

where

Δqi+1 = ki+1 ×Δvi,i+1

τ = critical time gap

V. DATA PREPARATION

Data used in the research were obtained from 2006 NGSIM (Next Generation SIMulation, http://www.ngsim.fhwa.dot.gov/). They are collected during the afternoon peak period on a segment of Interstate 80 in Emeryville (San Francisco), California. Three separate 15 minute periods of data are available: 1) 4:00 p.m. to 4:15 p.m.; 2) 5:00 p.m. to 5:15 p.m.; and 3) 5:15 p.m. to 5:30 p.m. All were collected on April 13th, 2005. The data for the 4:00 p.m. to 4:15 p.m. period primarily represent transitional traffic conditions during the build-up to congestion. The remaining two periods represent congested traffic conditions. Among them, the first one (4:00 p.m. to 4:15 p.m.) is used in the research.The description of the trajectory data is as follows:

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Table 1.Trajectory Data Summary

No	Content	Value
1	data collecting period	April 13th, 2005 4:00 p.m. to 4:15 p.m. (15 min.)
2	length of the site	1,650 ft.
3	total number of records	1,260,280
4	time step between records	0.1 sec
5	total number of time steps	9000

In order to convert the microscopic data such as vehicle trajectory into the macroscopic data such as volume (or flow rate), density and speed, the site is divided into 11 segments with 150 ft. in length each, and the ten time steps with 0.1 sec. are aggregated into one time step with 1 sec.

VI. MODEL DISCRETIZATION

The higher order continuum model can be solved numerically by discretizing both time and space.The model consists of three equations, two of which are partial differential equations involving time and space. It is very difficult to obtain a closed-form solution to compute flow, speed and density at any point of time and space for realistic boundary conditions. The practical way of solving these equations is the numerical method (Tarko, 1998).

Each lane of the freeway segment is divided into a number of segments. Density and speed are attributed to the entire segment, while flow is attributed to the end of the segement. An outflow from one segment section is the inflow to the following segment (Tarko, 1998).

The basic relationship in a discretized form for lane i, and segment j, and for time interval t is as follows:

$$q_{i,j}^{t} = k_{i,j}^{t} u_{i,j}^{t}$$

Lax method (Kwon & Michalopoulos, 1995) is adopted to represent the basic continuity equation.

$$k_{i,j}^{t+1} = \frac{1}{2} \times \left(k_{i,j+1}^{t} + k_{i,j-1}^{t}\right) - \frac{\Delta t}{2\Delta x}\left(q_{i,j+1}^{t} - q_{i,j-1}^{t}\right) - \frac{\Delta t}{2}\left(S_{j-1,i}^{t} + S_{j+1,i}^{t} - S_{i,j-1}^{t} - S_{i,j+1}^{t}\right)$$

Payne's model is adopted to represent the momentum equation.

$$u_{i,j}^{t+1} = u_{i,j}^{t} - \Delta t \times \left[u_{i,j}^{t} \times \frac{\left(u_{i,j}^{t} - u_{i,j-1}^{t}\right)}{\Delta x} + \frac{\left(u_{i,j}^{t} - U_{e}\right)}{T} + \frac{\nu}{T k_{i,j}^{t}} \left(k_{i,j+1}^{t} - k_{i,j}^{t}\right) \right]$$

The observed data are used for boundary conditions on segment 0 and 11, and also the observed data are used for initial condition.

VII. ESTIMATION AND SOLUTION PROCEDURE

The objective of estimation is to find the parameters minimizing the summation of mean square error(MSE) between the estimated speed ($\tilde{u}$) and density ($\tilde{k}$) and the observed speed ($\hat{u}$) and density ($\hat{k}$).

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$$\min(MSE) = \sum_{i,j,t}\left[\left(\hat{u}_{i,j}^{t} - \tilde{u}_{i,j}^{t}\right)^2 + \lambda\left(\hat{k}_{i,j}^{t} - \tilde{k}_{i,j}^{t}\right)^2\right]$$

For convenience, we let the weight parameter λ = 1 in this study.There are five parameters to estimate. They are 1) relaxation factor, 2) anticipation factor, 3) critical gap time, 4) driver's perception factor and 5) lane changing risk factor.

Genetic Algorithm

The popular heuristic "genetic algorithm" is employed to solve the minimizationproblem. In this research, the simple genetic algorithm (SGA) described by Goldberg (1988) is used containing following steps: (Henry et al, 2006)

Table 2.Genetic Algorithm

No	Step	Contents
1	Population Representation	A number of chromosomes, which are uniformly distributed in a given searchrange, are generated to search the optimal solution of objective. Each gene represents each parameter.
2	Evaluation	Evaluating the chromosome performances by calculating the objective function.
3	Selection	A procedure determining the number of times that a particular chromosome is chosen for generatingits offspring. The probability of selecting a chromosome is determined by its performance or correspondingfitness function value.
4	Crossover	The basic procedure reproducing new chromosomes in SGA. Crossover produces offspring bycombining different parts of both parents'genetic materials, such that their offspring has parts of their parents' features.
5	Mutation	As in natural evolution, a random process by which genes alter or change. This process guaranteesthat GA has the possibility of finding out a global optimum in given feasible region. In SGA, mutationoccurs with low probability.
6	Reinsertion	A procedure maintaining the population size in each generation. If fewer new chromosomes aregenerated after crossover and mutation than the size of the original population, new chromosomes must bereinserted.
7	Termination	Stopping iteration. Since the SGA is a probabilistic method, it cannot use the convergence criteriaas traditional methods. I terminate SGA after a predetermined number of generations.

VIII. ESTIMATION RESULT AND ANALYSIS

The parameters for genetic algorithm are as follows:

Table 3. Genetic Algorithm Parameters

Population Size	100
Maximal Number of Generations	1000
Selection Probability	0.3
Crossover Probability	0.3
Mutation Probability	0.2
Reinsertion Probability	0.2

Five parameters to be estimated, and their meaning, lower and upper bound are as follows:

Table 4.Lower and Upper Bound of Parameters

Parameter	Meaning	Lower Bound	Upper Bound
T	Relaxation time	0	15
N	Anticipation coefficient	0	999
T	Critical gap time	3	15
Β	Driver's perception factor	0	999
Δ	Risk factor	0	30

Relaxation time T expresses the acceleration and deceleration time to change the speed to the equilibrium speed, which should be less than 15 sec. Anticipation coefficient showing the square of congestion velocity divided by relaxation time should be less than 999. Critical gap time assumed to be greater than 3 and less than 15 sec. Driver's perception factor assumed to be less than 9999, and the risk factor, meaning the risk associated with the lane change, should be less than 30 mph.

The estimated values of the parameters are as follows:

Table 5.Estimated Parameters

Parameter	Meaning	Estimated Value
T	Relaxation time	14.9887
ν	Anticipation coefficient	6.2457
τ	Critical gap time	3.0000
β	Driver's perception factor	910.1529
δ	Risk factor	11.3848

As the table 5 shows, the relaxation time and critical gap time is almost equal to upper and lower bound, respectively, which means that the estimated optimal values of them are not reasonable. If the boundary values are changed, they should also be changed. While genetic algorithm ran, the driver's perception factor was fluctuating, but the objective values kept constant. This means that the factor does not affect the results at all. The reason that the estimated parameters are not reasonable is that the length of the road where the observed data were collected is too short. The short duration of collecting data, 15 minutes, could be another reason. Similarly, due to the shortage of the number of lane-changing vehicles in the observed data, the estimated parameters associate to the lane changing rate such as critical gap time, driver's perception factor and risk factor are not reasonable or effective to explain the drivers' lane changing behavior.

The figure 1, however, shows the variation of speed over time at 5th segment in lane 3, which indicates that the model captures the trend of the variation of speed well while the differences are somewhat big.

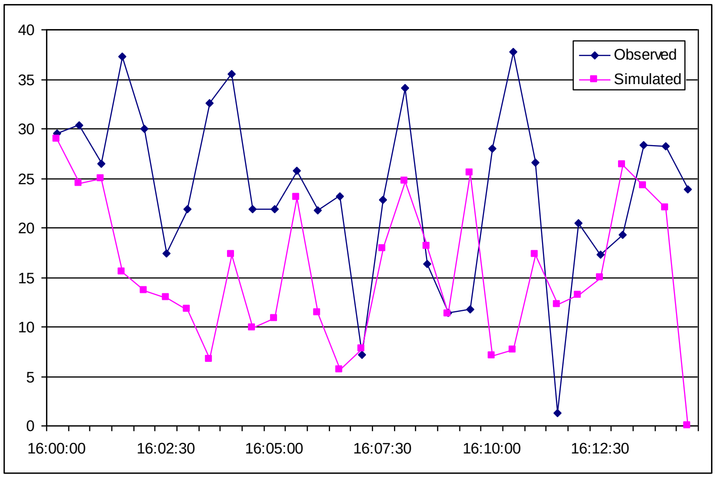

Figure 1. Number of Day Trips

IX. CONCLUSION

In this research, a macroscopic traffic simulation model incorporating drivers' lane changing behavior is developed. The complete formulation of the model involves 1) basic relationship, 2) basic continuity equation, 3) momentum equation and 4) lane change rate. The Payne's model is adopted for momentum equation, and logit model is used for lane change rate. The proposed higher order continuum model is solved by Lax method, one of the numerical methods to handle the continuum model. The probabilistic-based genetic algorithm is employed to solve the complicated minimization problem expressing the summation of mean square error between the observed speed and density and the estimated speed and density.

Unfortunately, the estimated values are not reasonable because of the use of inappropriate data. The proposed model, however, generates a similar trend of variation of speed, which indicates that the model might be improved if the parameters were estimated using other data collected in longer stretch of freeway. These results may have significance for researchers who are interested in macroscopic simulation model.

In addition, some further studies are required. Firstly, the parameters of the proposed model need to be estimated with other data. Secondly, it is better to capture the average value of the several results from GA because GA generates different results in each run. Lastly, it is required to evaluate the efficiencies of different kinds of numerical method such as Euler method, Lax method and cell transmission method.

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