A EXPERIMENTAL STUDY ON MACROSCOPIC CONTINUUM TRAFFIC FLOW MODELS

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Abstract: The objective of this study was to evaluate the performance of macroscopic traffic flow models with the analytical data and field data. Five candidate models were selected as follows; Lax Method Model, Upwind Scheme Model, Hilliges' Model, Papageorgiou's Model, and Cell-Transmission Model. In the analytical test scenario, the traffic condition was assumed that could cause the building and dissipation of queue, and each model was compared with analytical solutions and the numerical results. An analytical test indicated that both simple continuum and high order continuum models are able to reproduce queue building and dissipating behavior in a reasonable way. A field test has shown that Upwind, Cell Transmission, and Papageorgiou, show similar performances. Considering the simplicity in model formulation and numerical computation, we recommend Upwind scheme or Cell Transmission model as candidate model for further development of simulation model for Naebu expressway in Seoul.

Key Words: Macroscopic simulation model, Uninterrupted traffic flow

1. INTRODUCTION

1.1 Background and Objectives

In February 1999, a major Urban Freeway circulating the downtown of Seoul, the capital of Korea, was opened to the public. Total construction cost for the 41.1km of the Naebu freeway was over one billion US $. In order to manage traffic flow and make better use of the Naebu freeway a 20 million US, FTMS project is going to be finished by the end of 2001. The Naebu FTMS system comprises several infrastructure subsystems: RMS(Ramp Metering System), IMS(Incident Management System), TMS(Traffic Information System), 216 image detectors, 30 closed circuit televisions, and 65 variable massage signs as the major system elements. The spacing of detector stations on the systems averages roughly 500m, and CCTV as much as 2km apart.

A major problem with the Naebu expressway operations and traffic management practice is to assess the effectiveness of changes or improvements before implementation. This process includes comparing alternative geometric configurations, determining the adequacy of traffic management schemes, assessing the impacts of control strategies, studying the formation and dissipation of congestion on the freeway and its ramps, etc. Simulation methods have long been recognized as the most powerful tool for such analysis. It was concluded that development of a macroscopic freeway simulation model, which can describe Korean freeway traffic situations, was necessary. As a first step in developing a simulation program, an evaluation of candidate traffic flow models was performed. Although, it is necessary to investigate the traffic simulation models, which are able to describe traffic conditions and to manage in accordance with the operator's intention, for estimating the operation performance of UTMS, however, in Korea, there is a lack of comparative research of these models with field data.

The objective of this study is to evaluate the performance of macroscopic traffic flow models with the analytical data and field data.

This paper is organized as follows: After reviewing the general concept of the continuum traffic flow model, detailed review of candidate models are followed in Section 2. Section 3 presents comparison of candidate models to analytical results using hypothetical data. Section 4 presents a field data test using actual freeway data obtained from California. Section 5 concludes the paper with some remarks about candidate traffic flow models.

2. REVIEW OF TRAFFIC FLOW MODELS

2.1 Macroscopic Continuum Traffic Flow Models

Existing continuum macroscopic traffic flow models fall into two general categories: (a) simple continuum, and (b) high order continuum. The models in the first categories are rather simplistic in that they do not include space explicitly nor do they take compressibility into account. High order models, on the other hand, are in principle more realistic as they include the effects of inertia and acceleration of the traffic mass.

Since the first papers by Lighhill and Whitham(1955) and Richards(1956) and the introduction of high order models by Payne(1971), a number of macroscopic traffic flow models have been developed. The macroscopic continuum models describe traffic dynamics both in time and space via macroscopic traffic variables. They are all based on a few basic macroscopic variables; the flow q(x,t), the density k(x,t) and the mean flow speed u(x,t).

The first basic equation is inherent in the definitions of flow, density, and speed:

$$q = ku \qquad (1)$$

where, q = q(x,t) = traffic volume (veh/h) at location x and time t,
k = k(x,t) = density (veh/km/lane) at location x and t, and
u = u(x,t) = space mean speed (km/h) at location x and t.

A second relationship, the conservation equation, has the following general term:

$$\frac{\partial k}{\partial t} + \frac{\partial q}{\partial x} = g(x,t) \qquad (2)$$

where g(x,t) is a traffic generation rate

The two fundamental equations (1) and (2) must be incorporated in all macroscopic continuum models.
The continuum models are then further separated into the simple continuum models and the high order continuum models. A simple continuum model uses a third reltionship which relates between the mean speed and the traffic density under

equilibrium condition:

$$u(x,t) = u_e(k(x,t)) \qquad (3)$$

where u_e is an equilibrium speed

A high order continuum model requirea an additional momentum equation. They tried to describe explicitly, transitory states, using a relaxation process expressing the tendency of traffic to tend to an equilibrium. For example, equations (1), (2), (3) along with the following momentum equation constitute Payne's high order continuum model:

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} = \frac{1}{T}\left[u_e(k) - u - \frac{\nu}{k}\frac{\partial k}{\partial x}\right] \qquad (4)$$

with ν and anticipation coefficient and T a reaction time.

2.2 Candidate Test Models

It is known that the simple continuum model is easier to implement than high order continuum models, because of its simplicity in formulation and numerical computation. However, the simple continuum model has been criticized as not faithfully describing non-equilibrium traffic dynamics because it does not consider acceleration and inertia effects. High order models, on the other hand, are in principle, more realistic as they include the effects of inertia and acceleration of the traffic mass. High order models, however, still suffer from conceptual inadquacies and numerical computation demands are greater than those of simple continuum models.

Both simple continuum and high order continuum models have been improved by many researchers. To develop freeway simulation programs efficiently, the strength and the weakness of candidate traffic flow models should be evaluated. After literature review, the following five candidate models are chosen; three simple continuum models based, and two high order models based:

a) Lax method model
b) Upwind scheme model
c) Cell-Transmission model (1993, 1995)
d) Hilliges' model (1995)
e) Papageorgious's model (1989)

Clearly, a numerical methodology is needed for numerical implementation of the five candidate models. Most well known numerical methods applied, to solve simple continuum models, are Lax method applied to KRONOS, upwind scheme, Godunov's method applied to Cell-Transmission model. The following present a numerical solution of the five candidate models:

a) Lax method model

$$k(x,t+\Delta t) = \frac{1}{2}[k(x+1,t)+k(x-1,t)] - \frac{\Delta t}{2\Delta x}[q(x+1,t)-q(x-1,t)] \quad (5)$$

b) Upwind scheme model

$$k(x,t+\Delta t) = k(x,t)+\frac{\Delta t}{\Delta x}[q(x-1,t)-q(x,t)] \qquad (6)$$

$$q(x,t) = \alpha \cdot q(x,t)+(1-\alpha)\cdot q(x+1,t)$$

where, $\alpha = \begin{cases} 1 & \text{if shockwave speed } w(x,t) \geq 0 \\ 0 & \text{if shockwave speed } w(x,t) < 0 \end{cases}$

c) Cell-Transmission Model

$$\begin{aligned} k(x,t+\Delta t) &= k(x,t)+\frac{\Delta t}{\Delta x}\left[q(x-1,t)-q(x,t)\right] \\ q(x,t) &= \min\left[S(k(x,t)),\ R(k(x+1,t))\right] \end{aligned} \tag{7}$$

d) Hilliges' Model

$$k(x,t+\Delta t) = k(x,t)+\frac{\Delta t}{\Delta x}\left[k(x-1,t)\cdot u(x,t)-k(x,t)\cdot u(x+1,t)\right] \tag{8}$$

$$\begin{aligned} u(x,t+\Delta t) &= u(x,t)+\frac{\Delta t}{\tau}\left[u_e(k(x,t))-u(x,t)\right] \\ &\quad +\frac{\Delta t}{2\Delta x}u(x,t)\left[u(x-1,t)-u(x+1,t)\right] \end{aligned}$$

where, τ = reaction time
u_e = an equilibrium speed

e) Papageorgiou Model

$$\begin{aligned} u(x,t+\Delta t) &= u(x,t)+\frac{\Delta t}{\tau}\left[u_e(k(x,t))-u(x,t)\right] \\ &\quad +\frac{\Delta t\,\xi}{\Delta x}u(x,t)\left[u(x-1,t)-u(x,t)\right] \\ &\quad -\frac{\nu\Delta t}{\tau\Delta x}\frac{\left[k(x+1,t)-k(x,t)\right]}{\left[k(x,t)+K\right]} \\ &\quad -\frac{\Delta t}{\tau\Delta x_r}\frac{\delta\cdot u(x,t)\cdot r(x,t)}{\left[k(x,t)+K\right]} \end{aligned} \tag{9}$$

where, τ = reaction time
u_e = an equilibrium speed
ξ = convection term
ν = an anticipation coefficient
δ = an additional term to influence the rate of change $\partial v/\partial t$ $(0\leq\delta\leq 1)$
χ = a constant parameter to limit in case of very low density values.(veh/km)
r = r(x,t) = injection rate at the point x

3. TEST RESULTS USING HYPOTHETICAL DATA

3.1 Test Scenario

On the Naebu expressway, the recurring congestion has happened at specific sites, it makes a long queue in a short time. Then, it is important to track the queue from the bottleneck. Before we tested the candidate models using real data, it was first desired to see if the candidate models could produce reasonable behavior at bottlenecks. The test scenario is as follows: first, hypothetical freeway geometry and demand pattern is given. Using the analytical method, calculation of queue length is performed. Finally, we compare the models results with the analytical ones. The analytical solutions can be very instructive in that they offer a better understanding of the inner workings of traffic.

Figure 1 shows the hypothetical 13 km long freeway section. Here the number of lanes is reduced from three to two from the 9 km mark, to the end. The capacity of each lane is set to carry 2,000 vehicles per hour. A 120-minute simulation started with a demand of 3,000 vehicles per hour (vph) and then increased to 5,000 vph, which exceeds the capacity of the two-lane section by approximately 25 percent. The demand of next 20 minutes is 4,000 vph, which equivalents the capacity of the bottleneck section, and then is decreased to 3,000 vph during the last 40 minutes.

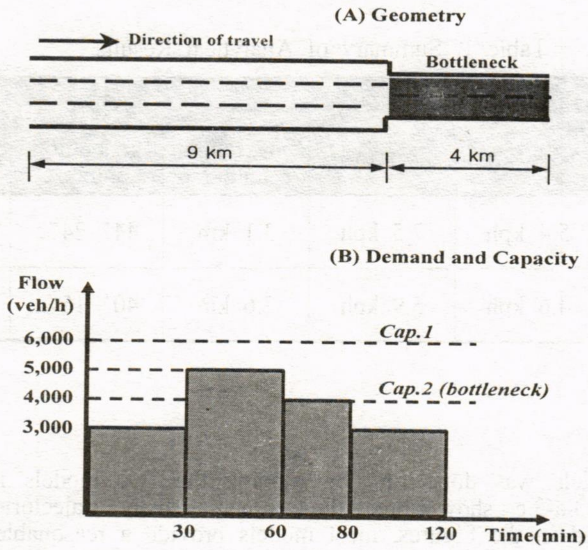

Figure1. Geometric and Demand Pattern

Equation 8 shows Bell-type speed-density relationship (Drake et al., 1965) which was used in this simulation.

$$u = u_f \exp^{-\frac{1}{2}\left(\frac{K}{K_c}\right)^2} \qquad (8)$$

3.2 Analytical Results

Here, we expect that the queue of traffic builds from 30 minutes, and stays uniform during next 20 minutes, and reduces after that. Figure 2 shows a time-space diagram representing dynamic change of queue sizes which are calculated by analytical procedures. Here, congestion starts in front of the bottleneck (point A) and moves in upstream direction, and finally dissipates.

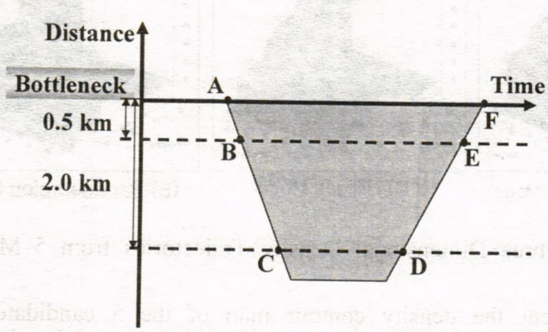

Figure 2. Conceptual Diagram Representation Dynamic Change of Queue Sizes

Table 1 summarizes some statistics for shock wave speed as well as queue sizes from analytical results. We basically used Bell-shaped speed-density relationships, except the Cell Transmission model which incorporates Triangular-shape.

Table 1. Summary of Analytical Results

Speed-Density Model	Shockwave speed		Queue		
	forward	backward	maximum length	generation (point A)	exclusion (point F)
Triangular	5.4 kph	7.5 kph	3.1 km	44′ 24″	123′ 47″
Bell-shape	4.6 kph	5.9 kph	2.6 km	40′ 15″	119′ 57″

3.3 Test Results

Testing of the models was done first by running the five models for hypothetical situations. Figures 3.a-3.e show three dimensional density trajectories from all 5 models. As illustrated in the Figures, most models provide a reasonable description of queue build up and dissipation behavior in that: congestion starts above the bottleneck and moves in the upstream direction, while the density within the bottleneck section remains around the critical density.

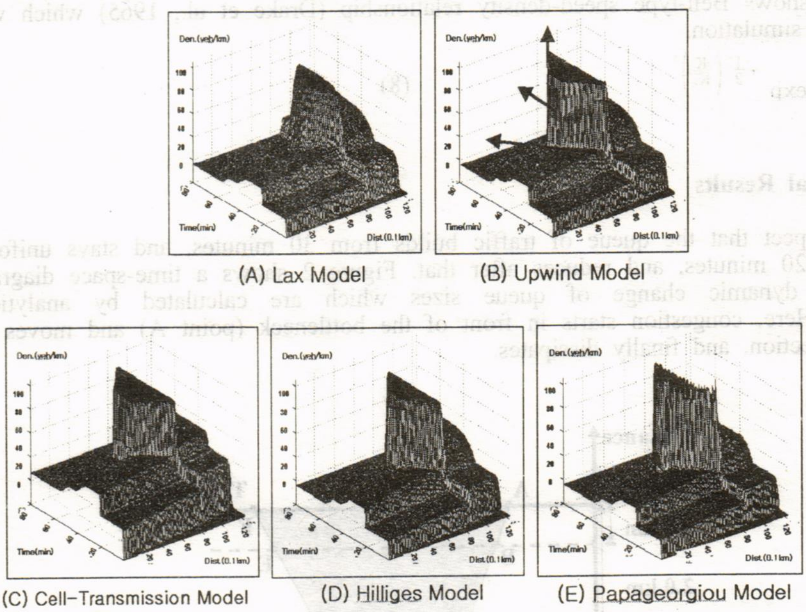

Figure 3. Three Dimensional Density Trajectories from 5 Models.

Figures 4.a-4.e represent the density contour map of the 5 candidate models results, along with queue sizes of analytical results, which are indicated by the dotted line. The comparison of queue sizes generally indicated a good agreement between candidate models results and the analytical results, except the Lax Model.

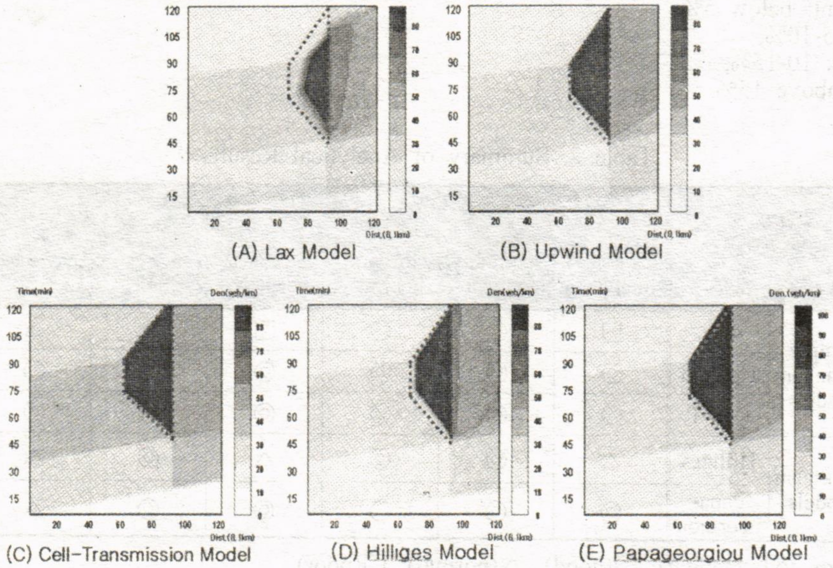

Figure 4. Density Contour Map from 5 Models

In order to evaluate the candidate models performance quantitatively, the following error measurements are calculated.

percentage difference = (analysis - model)k/(analysis)k

As indicated by the error measures for shock wave speed and queue size in Figures 5.a-5.d, upwind scheme and Cell Transmission provided better results.

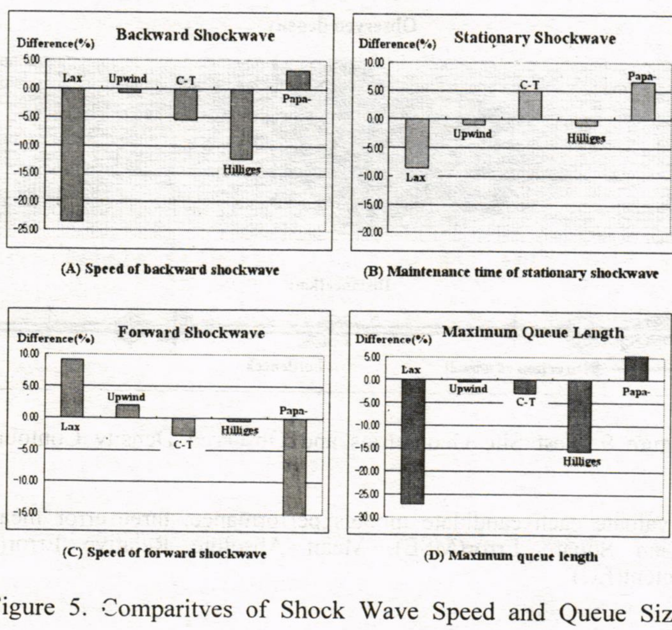

Figure 5. Comparitves of Shock Wave Speed and Queue Size

Next, the consistency analysis were performed using 4 scales:
excellent: below 5%,
good: 5-10%,
normal: 10-15%,
poor: above 15%.

Table 2. Summary of Analytical Results

Models		Reality				Stability	
		backward shockwave	stationary shockwave	forward shockwave	max.queue length	convergence value	convergence time
Simple continuum models	Lax	□	○	○	□	△	△
	Upwind	◎	◎	◎	◎	◎	○
	Cell-T	○	◎	◎	◎	◎	◎
momentum models	Hilliges	△	◎	◎	△	◎	△
	Papa-georgiou	◎	○	○	◎	◎	△

where, ◎(excellent), ○(good), △(normal), □(poor)

4. FIELD TEST

A 15.7 km section of the Nimitz Freeway was selected as the field test site. The section contains 16 ramps and consists of 3 lanes. The density and volume data, which were collected using aerial photography and detectors from 6:15 a.m. to 8:21 a.m. in Nov. 1 1967, were available. Figure 9 shows the schemetic diagram of test site geometrics and the observed density contours.

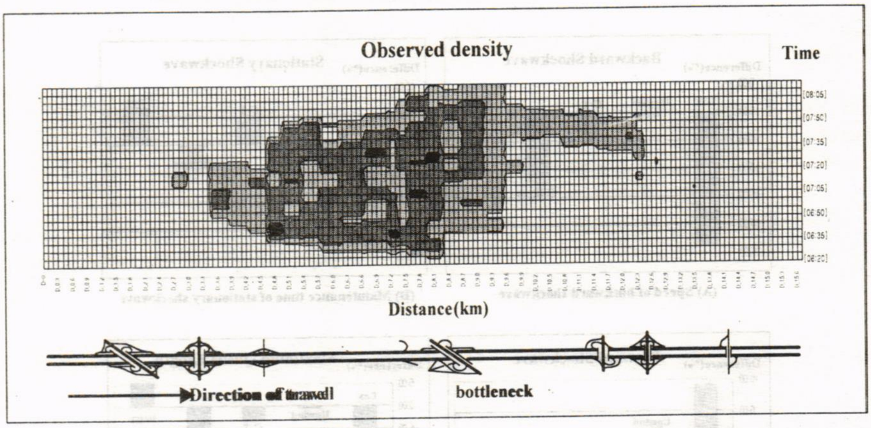

Figure 9. Test Site Geometrics and Observed Density Contours

In order to evaluate each candidate models performance, three error measurements are calculated: Mean Square Error(MSE), Mean Absolute Relative Error(MARE), and Equlity Coefficient(EC).

Table 3 shows the parameter values for mainline and ramp section to run simulation.

Table 3. Traffic Parameter Values in Sections

Section	capactiy (veh/hour/lane)	critical density (veh/km)	free flow spd (km/h)	max. density (veh/km)
basic	1,862	34.5	89	120
diverge	1,820	34.1	88	120
merge	1,683	31.9	87	120
bottleneck	1,585	30.4	86	120

Table 4 represents error measurements and queue sizes from the models. As indicated in this table, three models, Upwind, Cell Transmission, and Papageorgiou, show similar performances.

Model		MSE	MARE	EC	Queue	
					maximum length	generation time
observed value		-	-	-	6.1 km	06:50
simple continuum model	Lax	0.464	404.1	0.6	2.6 km	06:40
	Upwind	0.374	133.7	0.83	4.9 km	06:50
	Cell-T	0.284	136.1	0.80	4.9 km	06:50
momentum equation model	Hilliges	0.377	138.9	0.82	4.8 km	07:05
	Papa-georgiou	0.343	120.1	0.84	4.9 km	06:50

Figures 10.a-10.e show the density contours for the test site from five candidates model runs.

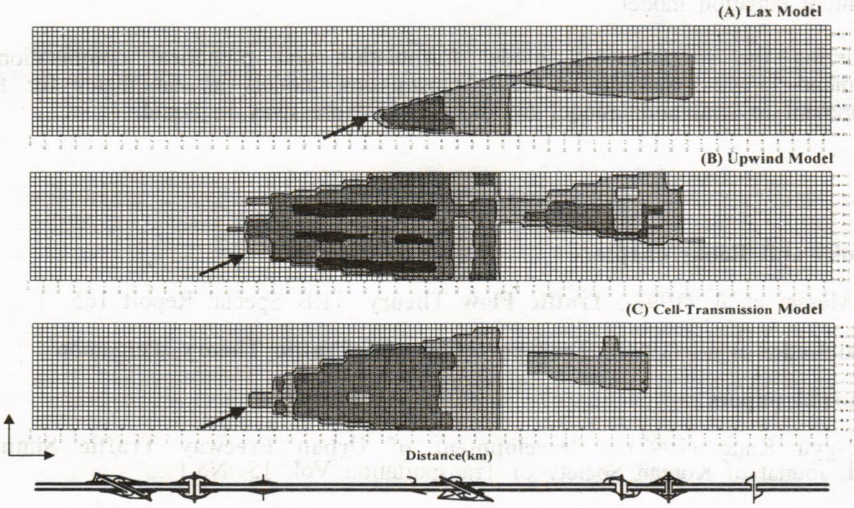

Figure 10. Density Contour Map from Five Cadidates Model Runs

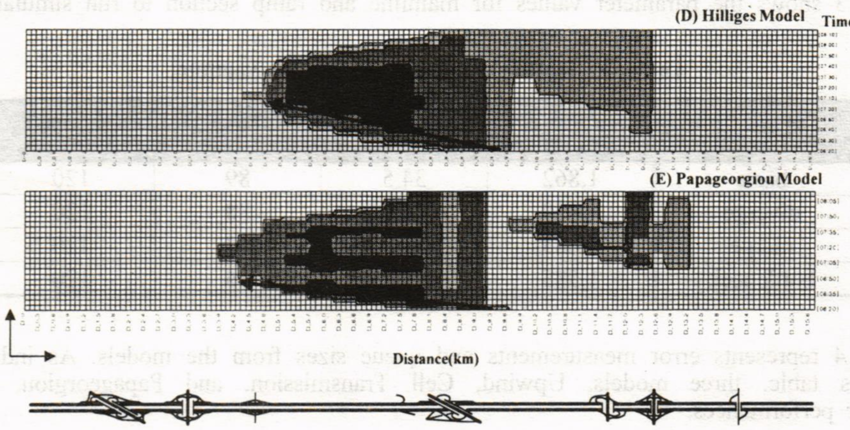

Figure 10. Density Contour Map from Five Cadidates Model Runs(Continue)

5. CONCLUSION

The objective of this study was to evaluate the performance of macroscopic traffic flow models, with the analytical data and field data. Five candidate models were selected as follows; Lax Method Model, Upwind Scheme Model, Hilliges' Model, Papageorgiou's Model, and Cell-Transmission Model.

An analytical test indicated that both simple continuum and high order continuum models are able to reproduce queue building and dissipating behavior in a reasonable way. Further, simple continuum models have shown faster convergence than high order ones.

A field test has shown that Upwind, Cell Transmission, and Papageorgiou, show similar performances. This suggests that the performance of the simple continuum model, in spite of the simplicity of the equation, show better than the models using momentum equation model.

Considering the simplicity in model formulation and numerical computation, we recommend Upwind scheme or Cell Transmission models as candidates for further development of simulation model for the Naebu expressway in Seoul.

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