DEVELOPMENT OF A HILS (HARDWARE-IN-THE-LOOP SIMULATION) FOR TRAFFIC SIGNAL CONTROL SYSTEMS

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Abstract: HILS, which is an abbreviation for Hardware-In-the Loop Simulation, has been recognized as an efficient assessment tool in developing traffic signal control technologies. In this paper, a micro-simulation model that can be applied to HILS for traffic signal control systems was developed. The feature of the micro-simulation model for HILS consists of three modules for evaluating traffic signal control strategies: (1) detector emulation module, (2) internal controller emulation module, and (3) micro-simulation module. The proposed model was tested on a test network consists of 9 intersections. The performance of the proposed model was evaluated in link by link comparisons with NETSIM. The results show that the proposed model could appropriately simulate traffic flows of the test network. The model also produces traffic adaptive signal timings, cycle lengths and green times for turning movements, based on the detector data. It implies that the optimization process of the model produces reasonable signal timings for the test network on the cycle basis.

Keywords: HILS (Hardware-In-the-Loop Simulation), Microscopic Simulation Model, Traffic signal Control System, Real-time signal Control, Adaptive Control

1. BACKGROUND

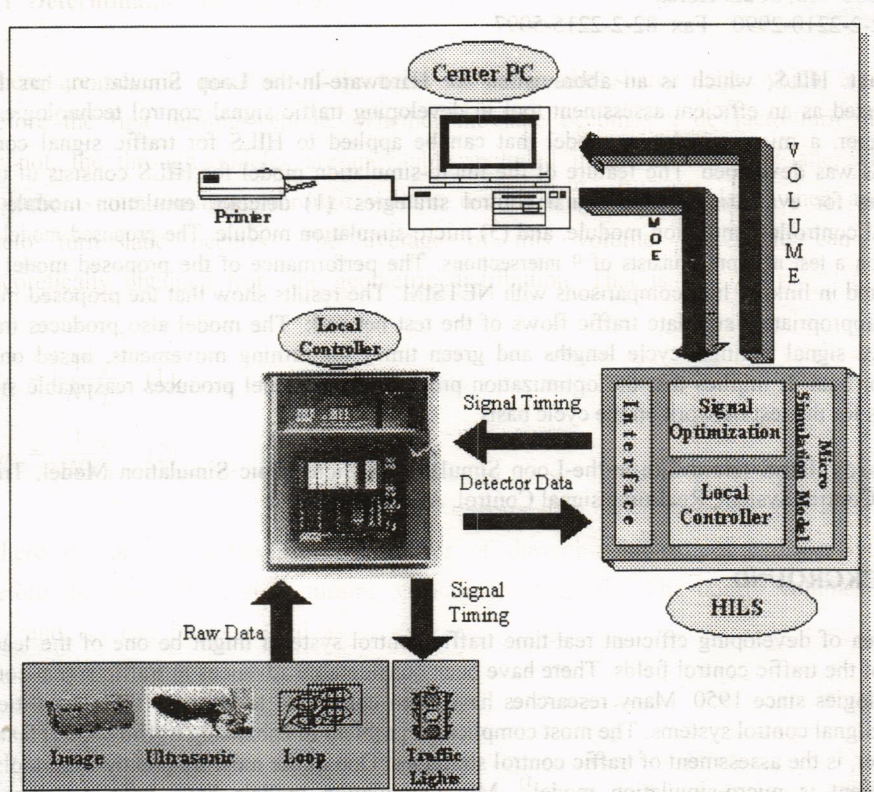
The area of developing efficient real-time traffic control systems might be one of the leading areas of the traffic control fields. There have been considerable advances in traffic signal control technologies since 1950. Many researches have been conducted to enhance the capabilities of traffic signal control systems. The most complicated problem in enhancing traffic control features, however, is the assessment of traffic control strategies. One of the most frequently-used tools for assessment is micro-simulation model[1)]. Micro-simulation models have been developed to estimate the performance of traffic control systems under specific traffic control strategies. The models are used for evaluation prior to or in parallel with on-street operation. It covers many objectives such as the study of dynamic traffic controls or adaptive traffic signal controls.

Recently HILS, which is an abbreviation for Hardware-In-the-Loop Simulation, has been recognized as an efficient assessment tool in developing traffic signal control technologies. HILS (Hardware-In-the-Loop Simulation) consists of a micro-simulation model and a traffic signal controller. The traffic signal controller performs input and output in real-time, and the micro-simulation model simulates traffic flows in real-time. The local controller performs the traffic control components of a micro-simulation model.

There are a few applications of HILS in traffic control fields. HILS-based real-time simulation environment was suggested by Bullock and Catellela[2] in 1998. Another HILS related research work was conducted at TTI (Texas Transportation Institute) in 1999[3]. Engelbrecht et. al[2] described HILS concept, and applied HILS to evaluate the performance of real-time bus priority algorithm. In 2000 Jeong et. al.[4] developed a signal controller which can be applied to HILS. HILS techniques, however, are in the early stage of development.

2. HILS CONCEPTS

In general, HILS consists of local controllers, controller interface devices, and a traffic simulation model. The controller interface device transmits signals between PC and local controllers, allowing the local controller to be operated by the PC. The simulation model simulates traffic flows of signalized intersections operated by local controllers. The architecture of HILS is shown in Figure 1.



<Figure 1> Architecture of HILS

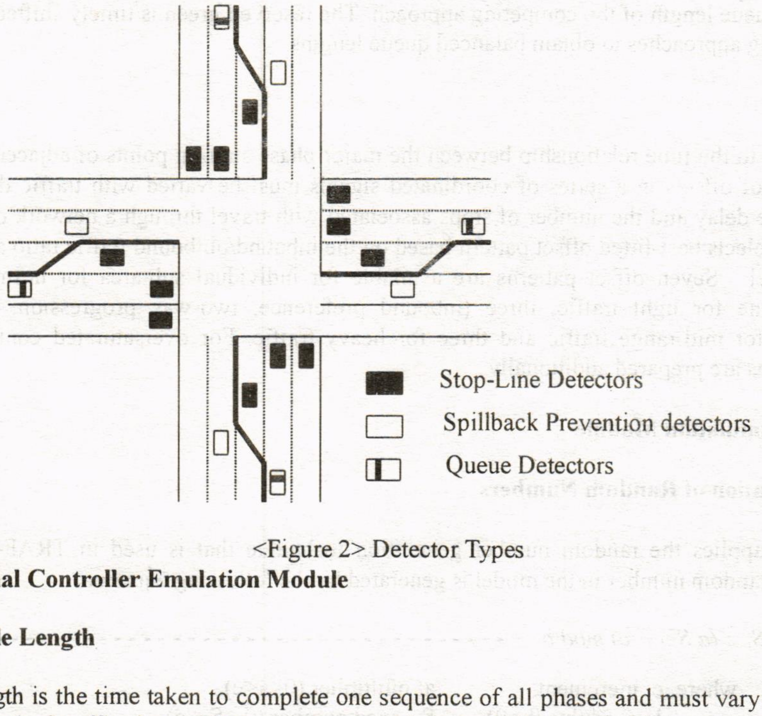
3. MODEL DESCRIPTION

The objective of this study is to develop a micro-simulation model that can be applied to HILS for traffic signal control systems. The simulation model was developed on the basis of a micro-simulation of individual vehicles that are moved through a network along the links, according to specified controls at intersections. Turning movements on the network are determined stochastically, and individual vehicles are investigated by deterministic car following models. The model can investigate a wide mix of traffic control and traffic management strategies such as fixed-time signal control, traffic-adaptive signal control, and traffic-responsive (actuated) signal control strategies. The traffic-responsive (actuated) signal control includes gap actuation. The model can simulate full range of control features including turn controls, fixed-time signals, vehicle-actuated signals, and real-time traffic control. The feature of the micro-simulation model for HILS consists of three modules for evaluating traffic signal control strategies as follows:

- Detector emulation module
- Internal controller emulation module
- Micro-simulation module

3.1 Detector Emulation Module

The basic measurements used in generating the signal timing are the degree of saturation (DS) and queue length on each approach. Traffic data are generated in the simulation process. Traffic data are collected from three kinds of loop-emulated detectors classified by their functions: stop-line detectors, queue detectors, and spillback prevention detectors. Primary detector for signal timing is the stop-line detector measuring DS at major approaches. The queue detectors and spillback prevention detectors are used for the estimation of queue lengths and link speeds. Figure 2 shows the type of detectors used in the system.



<Figure 2> Detector Types

3.2 Internal Controller Emulation Module

3.2.1 Cycle Length

Cycle length is the time taken to complete one sequence of all phases and must vary to meet the overall level of traffic demand because, in general, increased cycle length increases intersection capacity. The model dynamically adjusts cycle length to maintain the highest degree of saturation in a coordinated group of signals within acceptable operator defined limits, usually 0.9. It is not desirable that the cycle-length changes are too sensitive to the random fluctuation of traffic demand, so the model adjusts the cycle length for stable control based on the trend of traffic demand rather than the collected traffic data.

During the normal traffic condition, the cycle length can increase up to maximum extension cycle length. If demand exceeds the level that the maximum extension cycle length can handle, control mode transfers to the oversaturation control. When the cycle length reaches maximum extension cycle length on the oversaturation control, and the extra cycle time required is assigned to the approach having the longest queue length.

3.2.2 Green Splits

Green split refers to the division of the cycle into a sequence of green signals for the competing movements at each intersection and must reflect the relative demands for green time on each approach. The model's determination of green splits is essentially to maintain balanced DS on competing approaches. Sometimes, control may be biased to favor major traffic movements when demand approaches saturation. The model calculates green split using the DS predicted for the next cycle. For unbalanced left-turn traffic, the introduction of overlap phases gives efficient green time allocation, so the model employs NEMA's dual-ring eight-phase scheme (NEMA, 1983). It was found that the dual-ring scheme has advantage over traditional 'step' method in calculating overlap phase lengths.

In oversaturated control strategies, green times are determined based on the queue lengths estimated from mid-block detectors rather than based on the DS. The reserved green time in the state of maximum cycle length is assigned to the approach having the longest queue length. The successive assignment of the reserved green times to a particular approach may result in rapidly increasing queue length of the competing approach. The reserved green is timely shifted between the competing approaches to obtain balanced queue lengths.

3.2.3 Offset

Offset refers to the time relationship between the major phase starting points of adjacent signals. The pattern of offsets in a series of coordinated signals must be varied with traffic demand to minimize the delay and the number of stops associated with travel through a network of signals. The model selects best-fitted offset pattern based on the inbound/outbound traffic ratio and traffic demand level. Seven offset patterns are available for individual sub-area for normal traffic condition; one for light traffic, three (inbound preference, two-way progression, outbound preference) for mid-range traffic and three for heavy traffic. For oversaturated control, three offset patterns are prepared additionally.

3.3 Micro-simulation Module

3.3.1 Generation of Random Numbers

The model applies the random number generation technique that is used in TRAF-NETSIM model. The random number in the model is generated by the following equation.

$$S_i = (a\, S_{i-1} + c) \bmod b \qquad \text{---} \ (1)$$

where, c: increment, a: multiplier ($0<a<c$),
b: modulus ($b>0$), S_0: seed number ($0< S_0<c$)

3.3.2 Vehicle Entering

Entering vehicles are generated at source nodes within the network. Arrivals at input links are based on a negative exponential distribution equation as follows.

$$h = (H - h_{min}) [- ln(1-R)] + H - h_{min} \qquad (2)$$

where, h : headway
H : average headway (= 3600/vehicle)
h_{min} : minimum headway (=1.2 sec/veh)
R : seudo random number (0<R<1)

3.3.3 Car Following Model

Vehicles are processed from upstream to downstream to allow car following and lane changing. Car following behavior is the response of the successive driver in the traffic stream. The response of the successive driver is begun after a time lag T. The successive driver is then to accelerate or to decelerate his running speed in proportion to the magnitude of the stimulus at time t. General Motor's 5th model and Pipe's model were applied in the moving vehicle process in this model. The model parameters were calibrated based on the acceleration, deceleration, stop, and departure conditions, respectively, as follows.

Acceleration: $a_{n+1}(t+T) = 0.3825\, V_{n+1}(t)^{0.0137} [V_n(t)-V_{n+1}(t)]^{0.3095} [X_n(t) - X_{n+1}(t)]^{-0.7502}$ - (3)

Deceleration: $a_{n+1}(t+T) = 0.9128\, V_{n+1}(t)^{0.6540} [V_n(t)-V_{n+1}(t)]^{0.3095} [X_n(t) - X_{n+1}(t)]^{-0.4864}$ - (4)

Stop and departure: $d_{min}\ (gap) = 1.36(X_{n+1}(t)) + 6$ (Pipe's model) - (5)

where, $a_{n+1}(t+T)$: accleration or deceleration rate of successive vehicle n+1 at time t + T (m/sec^2)
t : simulation time
T : reaction time of successive vehicle n+1 (sec)
$V_{n+1}(t)$: speed of successive vehicle n+1 at time t (m/s)
$V_n(t)$: speed of preceeding vehicle n at time t (m/s)
$V_n(t)-V_{n+1}(t)$: relative speed of vehicles n and n+1 at time t (m/s)
$X_n(t) - X_{n+1}(t)$: space headway of vehicles between n and n+1 (m)
$d_{min}\ (gap)$: gap (m)

3.3.4 Signal Status Update

All traffic signals are updated at time step 0.1 second. All nodes are scanned and at the signalized nodes, the current timer is decremented. When the timer reaches zero, the next phase is activated and the timer is reset.

3.3.5 Measures of Effectiveness

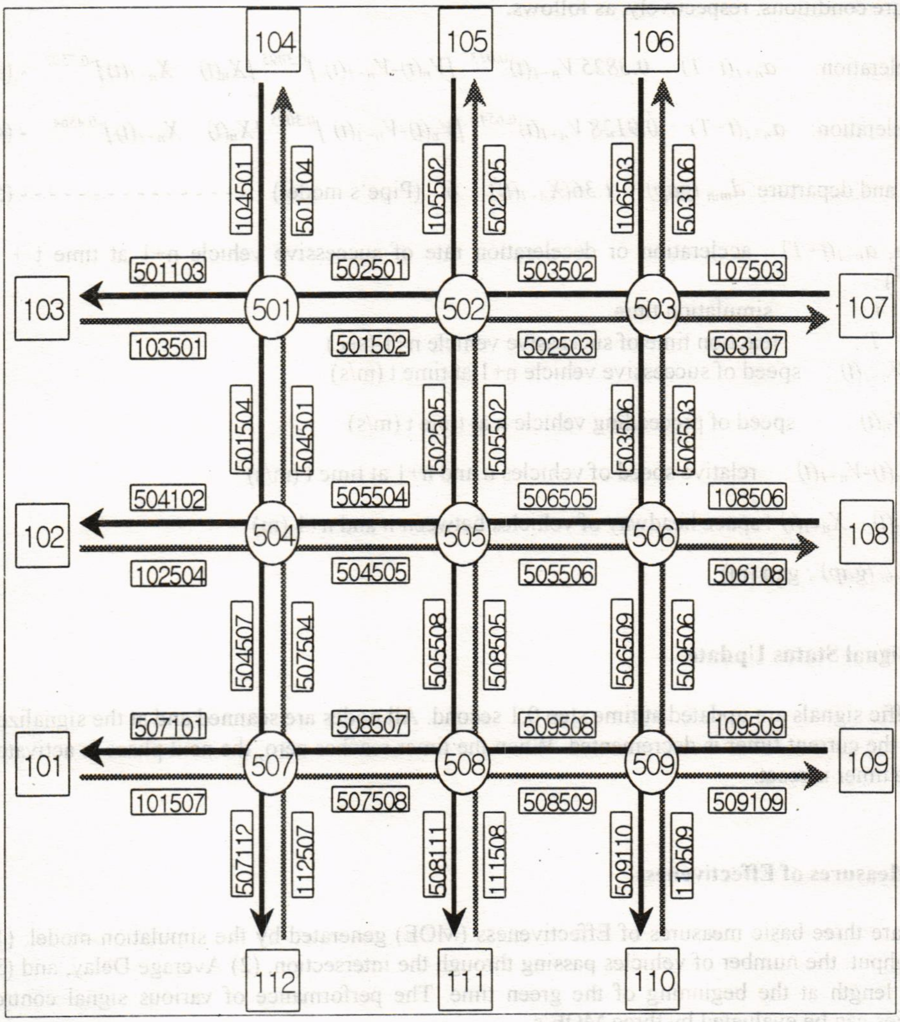
There are three basic measures of Effectiveness (MOE) generated by the simulation model: (1) Throughput: the number of vehicles passing through the intersection, (2) Average Delay, and (3) Queue length at the beginning of the green time. The performance of various signal control strategies can be evaluated by three MOE's.

4. DESIGN OF EXPERIMENT

4.1 Test network

The proposed model was tested on an arterial network consists of 9 intersections. The configuration of the test network is shown in Figure 3. The traffic conditions are as follows:

- number of lanes: right-turn, through, and left-turn lanes
- phase sequence: Lead-Lead sequences, dual ring NEMA types
- minimum cycle length 70-sec. maximum cycle length 160 sec.
- saturation flow rate: 1,800vph
- link traversing speed: 36km/h (10m/sec)
- Yellow time: 3 sec.
- Entering volume: 750 veh/hr/lane



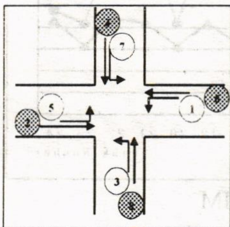
<Figure 3> Test Network

4.2 Input Data

4.2.1 Signal Timing Plan

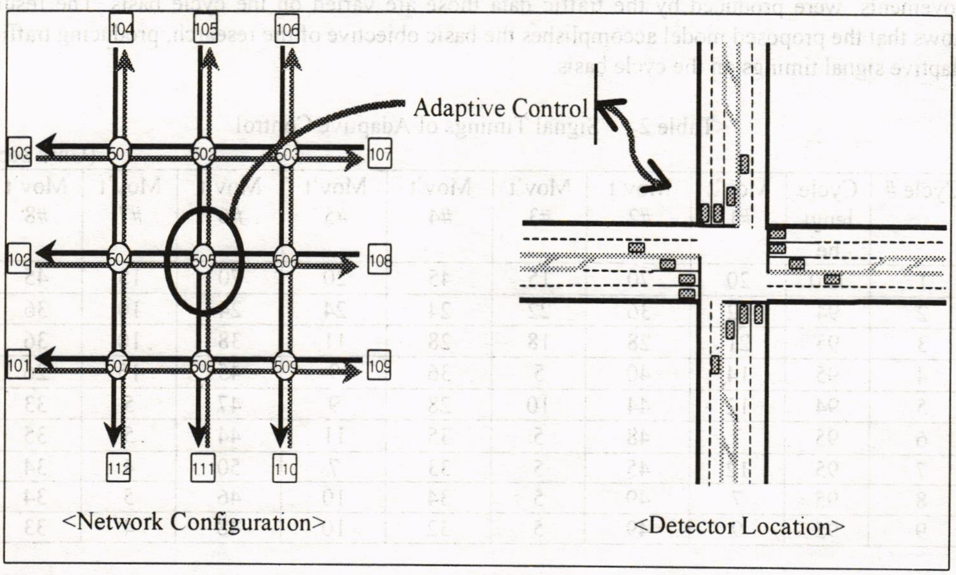
The external intersections are operated by TOD signal-timing plan. and the intersection 505 is operated by adaptive signal control strategy. The signal timing plan for the TOD-operated intersections and the initial signal timing plan for intersection 505 were set up as Table 1.

<Table 1> TOD Signal Timing Plan

	Movement #	#1	#2	#3	#4
	Green time(sec)	20 sec	70 sec	15 sec	45 sec
	Movement #	#5	#6	#7	#8
	Green time(sec)	20 sec	70 sec	15 sec	45 sec

4.2.1 Detector Locations

16 detectors were installed at intersection 505. Figure 4 shows the network configuration and detector locations.

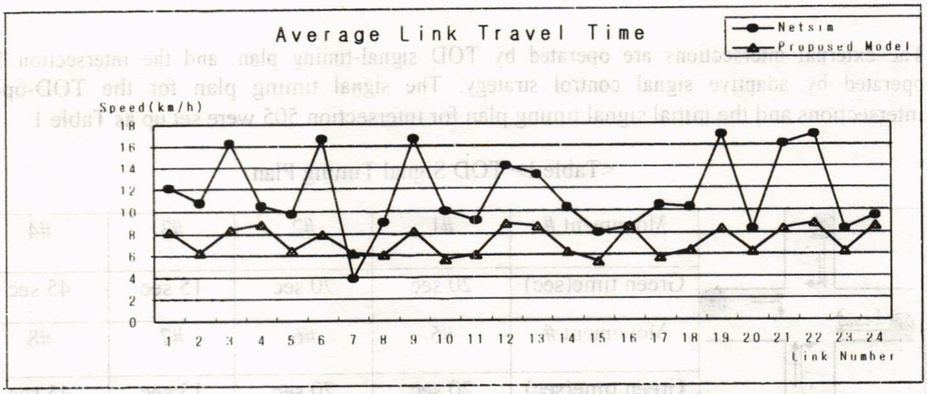


<Figure 4> Network Configuration and Detector Location

4.3 Results

4.3.1 Travel Speeds Comparison with NETSIM

The simulation result of the model was compared to the results of NETSIM. Figure 5 shows the link travel speeds of internal links of the test network. The proposed model produces slightly higher link speeds than the NETSIM. The trend of link travel speeds produced by the proposed model is similar to those of NETSIM.



<Figure 5> Link Travel Time Comparison with NETSIM

4.3.2 Comparison with Fixed Signal Timing Plan

The traffic demands for external intersections are 750 veh/hr/lane, respectively. Table 2 represents the cycle length variations of intersection 505 on the cycle basis. The model produced variable cycle lengths and green times for the intersection 505. It means that the detectors installed at intersection 505 appropriately collect traffic data such as degree of saturation for individual detector. The traffic adaptive signal timings, cycle lengths and green times for turning movements, were produced by the traffic data those are varied on the cycle basis. The result shows that the proposed model accomplishes the basic objective of the research, producing traffic adaptive signal timings on the cycle basis.

<Table 2> Signal Timings of Adaptive Control

(Unit: sec)

Cycle #	Cycle lengthe	Mov't #1	Mov't #2	Mov't #3	Mov't #4	Mov't #5	Mov't #6	Mov't #7	Mov't #8
1	150	20	70	15	45	20	70	15	45
2	94	12	36	22	24	24	24	10	36
3	95	21	28	18	28	11	38	10	36
4	95	14	40	5	36	9	45	15	26
5	94	12	44	10	28	9	47	5	33
6	95	7	48	5	35	11	44	5	35
7	95	12	45	5	33	7	50	4	34
8	95	7	49	5	34	10	46	5	34
9	95	9	49	5	32	10	48	4	33

Two scenarios were set up to evaluate the performance of the model: (1) 9 intersections of the test network were operated by the TOD signal timing plan, and (2) the intersection 505 was operated by the adaptive signal timings, and other intersections were operated by the TOD signal timing plan. Table 3 shows the link travel times produced by two scenarios. In case of scenario 2, the travel times of the intersection 505, which is operated by adaptive signal timings, were improved comparing to the link travel times produced by scenario 1. The travel times of scenario

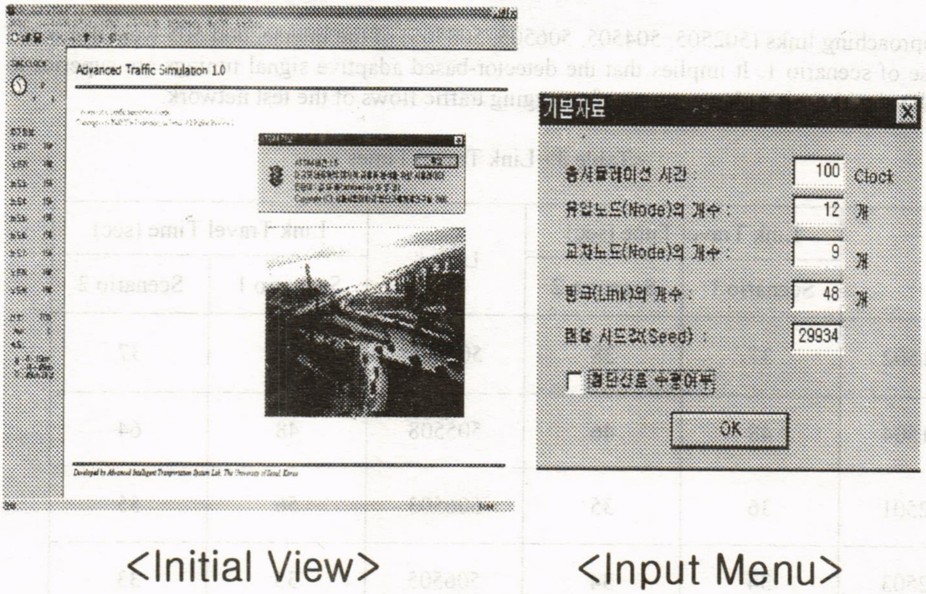
2 at approaching links (502505, 504505, 506505, 508505) of the intersection 505 were decreased to those of scenario 1. It implies that the detector-based adaptive signal timings are superior to the TOD signal-timing plan in terms of managing traffic flows of the test network.

<Table 3> Link Travel Times

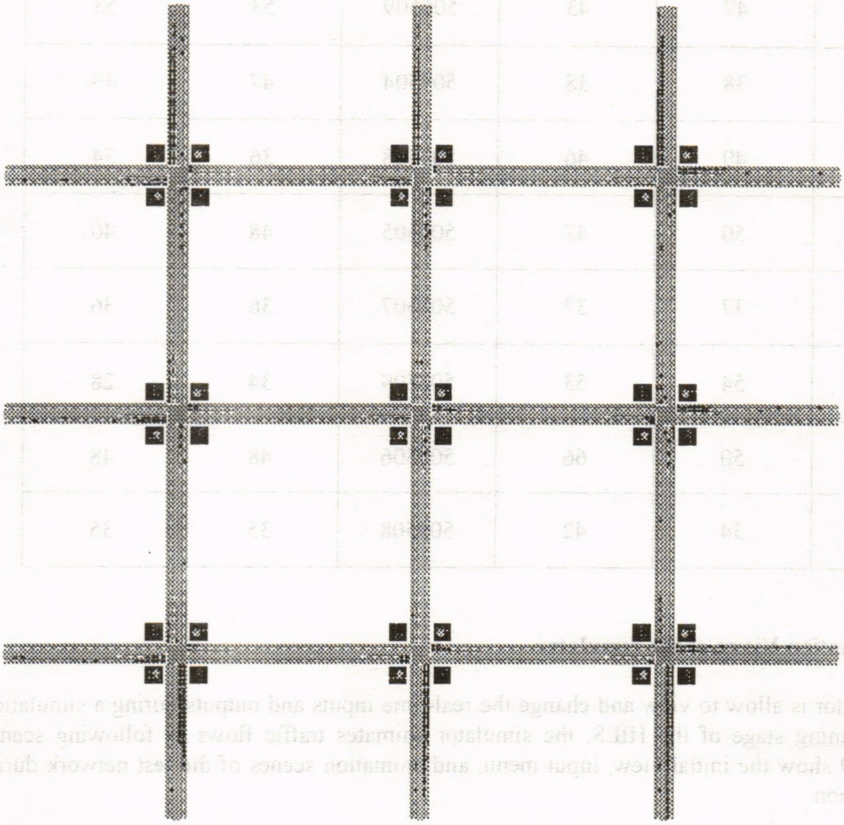
	Link Travel Time (sec)		Link #	Link Travel Time (sec)	
	Scenario 1	Scenario 2		Scenario 1	Scenario 2
501502	37	38	505506	35	37
501504	48	46	505508	48	64
502501	36	35	506503	56	55
502503	34	34	506505	35	33
502505	47	43	506509	53	53
503502	38	38	507504	47	49
503506	49	46	507508	36	34
504501	50	47	508505	48	40
504505	37	37	508507	36	36
504507	54	53	508509	34	28
505502	50	66	509506	48	48
505504	34	42	509508	35	35

4.3.3 Animation Views of the Simulator

The simulator is allow to view and change the real-time inputs and outputs during a simulation. As a beginning stage of the HILS, the simulator animates traffic flows as following scenes. Figures 6-9 show the initial view, input menu, and animation scenes of the test network during the simulation.

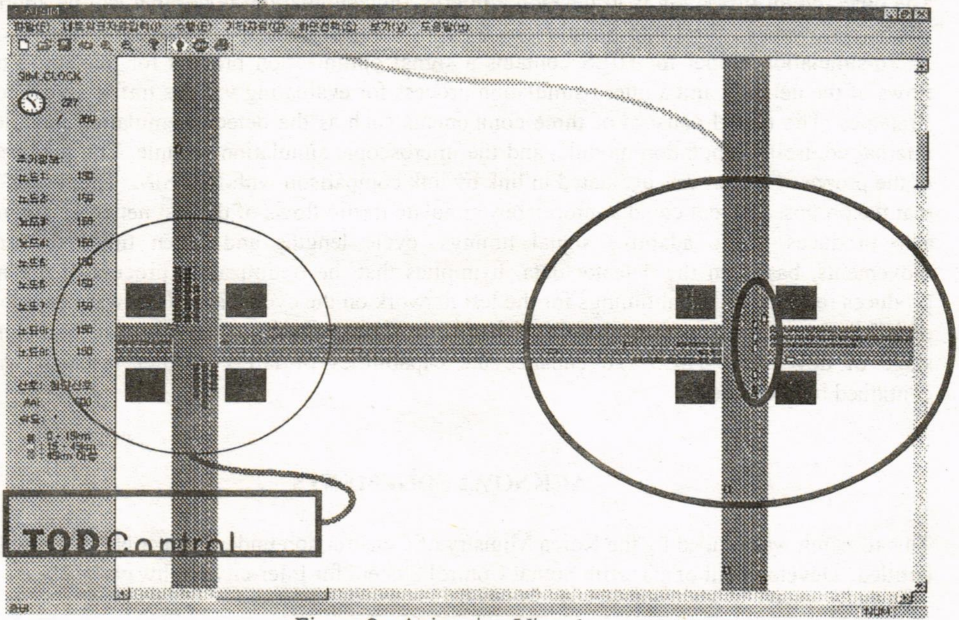


<Figure 6> Initial View and Input Menu



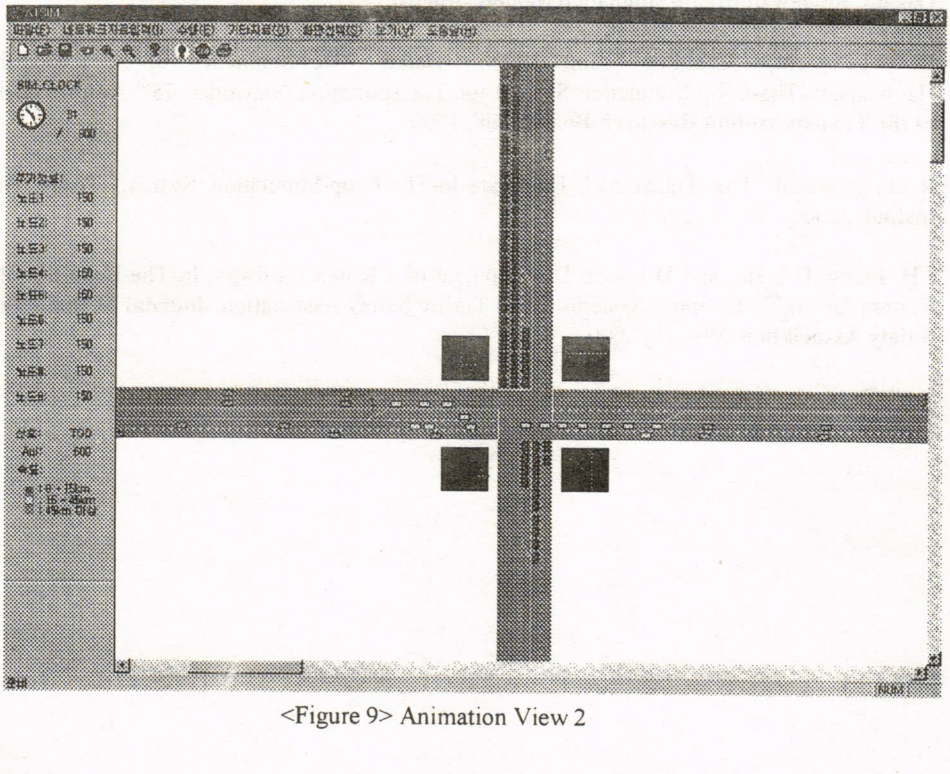
<Figure 7> Network Animation

※ Animation View



<Figure 8> Animation View 1

※ Animation Scene



<Figure 9> Animation View 2

6. CONCLUSIONS

The objective of this study is to develop a microscopic simulation model that can be applied to HILS (Hardware-In-the Loop Simulation) for traffic signal control systems. The feature of the micro-simulation model for HILS contains a signal optimization process for managing traffic flows of the network and a micro-simulation process for evaluating various traffic signal control strategies. The model consists of three components such as the detector emulation module, the internal controller emulation module, and the microscopic simulation module. The performance of the proposed model was evaluated in link by link comparison with NETSIM. The results show that the proposed model could appropriately simulate traffic flows of the test network. The model also produces traffic adaptive signal timings, cycle lengths and green times for turning movements, based on the detector data. It implies that the optimization process of the model produces reasonable signal timings for the test network on the cycle basis. Hardware components of HILS are under developing based on this study. This research, however, is at the beginning stage of developing HILS. To enhance the capabilities of HILS, further research will be continued by the authors.

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