Journal of the Eastern Asia Society for Transportation Studies, Vol.8, 2009

Modeling Of Vehicle Emission Pricing Strategy Using Multi-agent System

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Abstract: This study models the vehicle emission pricing strategy using the multi-agent system (MAS). A two-level hierarchical MAS is adopted. The manager agents are cognitive agents that give instructions while the worker agents carry out the tasks assigned. The agents can also be categorized into two groups. The agents in the air quality group continuously monitoring and collecting air pollution data at the roadside or at the buildings vicinity to the roadways. While the agents in the emission pricing group analyze the pollution data provided to decide when to activate the emission pricing. The evaluation of the proposed framework and strategy is carried out in the microscopic traffic simulation environment. An illustrative case study of a new town in Singapore is adopted. It is shown that the proposed methodology yields promising results. The air pollution level at the roadside or vicinity buildings is reduced.

Key Words: *pollution, multi-agent system, emission pricing, simulation*

1. INTRODUCTION

Vehicle emission is recognized as the major source of air pollutants in urban areas. For example, in Melbourne (EPA, 2007), it is reported that, motor vehicle emission contributes 80% of carbon monoxide, 60% of nitrogen oxides, 40% of volatile organic compounds and 30% of particulate matter to the overall air quality. In United Kingdom (National Statistics, 2007), the emission from transportation industry has increased by 47% between 1990 and 2002, although the total greenhouse gas emissions declined by 10%. Most of the modern cities in Asia, such as Singapore, Hong Kong, Beijing and Kuala Lumpur are designed such that the residential areas or offices are built adjacent to urban roadways. These roads are usually heavily loaded with traffic due to high socio-economic activities in the city areas. Hence, the intensity of vehicle emission is high as well as the pollution level. In addition, tall buildings in these cities act as giant barriers that trap pollutants from dispersing. This has exacerbated the pollution level in the area and has affected the health of the residents.

Alleviating traffic congestion level in urban areas can help reducing emission levels. Mitchell *et al.* (2002) demonstrated that by implementing the congestion pricing on the busy roads to reduce traffic intensity could indirectly bring changes to the redistribution of air pollution level. The single cordon strategy reduced pollutant concentrations significantly but at the expense of the areas surrounding the cordon. However, it is also seen that road pricing only brings major improvements in air quality under high distance charges. In the case of modest distance charge, it is less effective. Following the study, Mitchell *et al.* (2005) evaluated the air quality impacts for five different road pricing schemes. The study concluded that road pricing could help improving air quality by constraining trip demand, i.e. reducing the total

PCU-km traveled in the road network. This is because the road pricing can change the route choice of drivers which help to redistribute traffic intensity pattern, and thus redistribute the air pollution concentration pattern. It means that if we could successfully divert traffic from highly congested major roadways in urban areas to the less congested highways in rural areas, it could significantly reduce the pollution level in the cities.

This paper proposes the vehicle emission pricing as a strategy to reduce emission level in the urban cities. Under the strategy, a penalty charge will be imposed on the drivers based on the air quality level of the study area. This is different from road pricing scheme since the charge is calculated with the aim to achieve a desired air quality level in the study area. The system implemented could be cordon-based or distance-based. The strategy modeled in this study is for the former. The air quality of the study area needs to be monitored closely in order to determine whether or not to activate the strategy as well as to calculate the penalty charge. A monitoring system is required at the roadside or at the buildings vicinity to roadways to measure the air pollution concentration level. Given this piece of information, the system would decide when to activate the strategy, while keep monitoring the concentration level in the study area. Such a strategy could be carried out with the help of intelligent multi-agent system (MAS).

A MAS is a system that comprises an environment, a set of objects and an assembly of agents (Ferber, 1999). There is interaction among the agents in the environment and information is exchanged among the agents. All agents cooperate to accomplish goals that are for the benefit of the overall system. It is appropriate to adopt MAS system in this study due to the following reasons: (i) the emission pricing strategy require information exchange among the three components, i.e. the monitoring component (to monitor the air quality level), the decision component (to decide whether to activate the pricing strategy), and the implementation component (system that charge on the drivers). MAS ensure that these components are well integrated; (ii) each component of the proposed strategy only has a partial view covering its own duty, but the overall system should react in the desired manner and all actions are efficiently coordinated; (iii) the strategy is physically distributed. The components of the strategy might be responsible by two different authorities. For example, the monitoring task is carried out by the Environment Agency, while the emission pricing implementation is carried out by the Transportation Authority. Hence, for both authorities to work under one scheme, agents are hired to facilitate the communication between databases. (iv) an intelligent agent is required to monitor the air quality and activate/deactivate the emission pricing strategy.

The adoption of MAS to study the air pollution issue caused by the vehicle emission is little. For example, Oyabu *et al.* (2000) employed agents as the sensors to detect air pollution at a point with on-site measurement; Kalapanidas and Avouris (2002) developed DNEMO which is a MAS based prototype system to collect and process environmental and meteorological data for pollution assessment; Oprea (2006) adopted ontology mapping to develop a MAS for air pollution monitoring and control in urban regions; Amigoni *et al.* (2006) developed a MAS to measure the chemical substances and meteorological conditions to evaluate air quality; and Dominguez *et al.* (2005) developed a MAS-based traffic simulation model to assess air pollution problem at signalized intersection. In this study, a two-level hierarchical-based MAS is adopted, i.e. the upper level and the lower level. The upper level comprises cognitive agents, known as manager agents that can make decisions and give instructions to the lower level to accomplish the tasks. Two manager agents are modeled at the upper level, i.e. the data collection agent and the traffic control agent. The lower level agents, also known as worker agents, carry out tasks assigned by manager agents. They may not have cognitive "brain" and only carry out activities told by manager agents. Two worker agents are assigned, namely air pollution monitoring agent, and emission pricing agent. The air pollution monitoring agent is responsible for monitoring the air pollution level at the roadside while emission pricing agent would activate the pricing strategy. More elaborated explanation is presented in the following sections.

This paper is organized as follows: section 2 explains in detail the MAS framework proposed for the vehicle emission pricing strategy. Section 3 presents an illustrative case study of a new town in Singapore. The proposed framework and strategy is evaluated in the microscopic traffic simulation model environment. It follows with some discussion of the practical implementation of the strategy. Section 4 concludes the findings of the study.

2. THE MULTI-AGENT SYSTEM FOR VEHICLE EMISSION PRICING STRATEGY

The agents in the two-level hierarchical MAS can be categorized into two groups according to their functions, namely the air quality group and emission pricing group. The air quality group consists of a data collection manager agent, and an air pollution monitoring worker agent. They work together to monitor the air pollution level caused by traffic at the roadside or at the buildings vicinity to the roadways. The data collection manager agent continuously queries the air pollution data, i.e. the concentration level of pollutants and store all these information in the database. At the mean time, the air pollution monitoring agents detect and collect data for their managers. Multiple of air pollution monitoring agents are distributed in the network to gauge the concentration level at different direction of roads. This is because each agent can only detect within certain radius of areas. The data collection manager agent needs to investigate the pollution data gathered from these agents to determine the overall air quality level of the study area. The emission pricing group comprises a traffic control manager agent and an emission pricing agent. It is responsible to the decision on whether to activate the emission pricing strategy. The traffic control manager agent makes the decisions based on the concentration level detected by the air quality group. If it is greater than the allowable level, it will instruct the emission pricing agent to activate the pricing, and vice versa. Figure 1 shows the MAS framework. From the framework, it is observed that there are two ways communication between both groups at the upper level. At the upper level, the data collection manager agent passes the air pollution data to the traffic control manager agent, while the traffic control manager agent notifies it with the emission control decision. The detailed tasks performed by each agent are explained as follows.

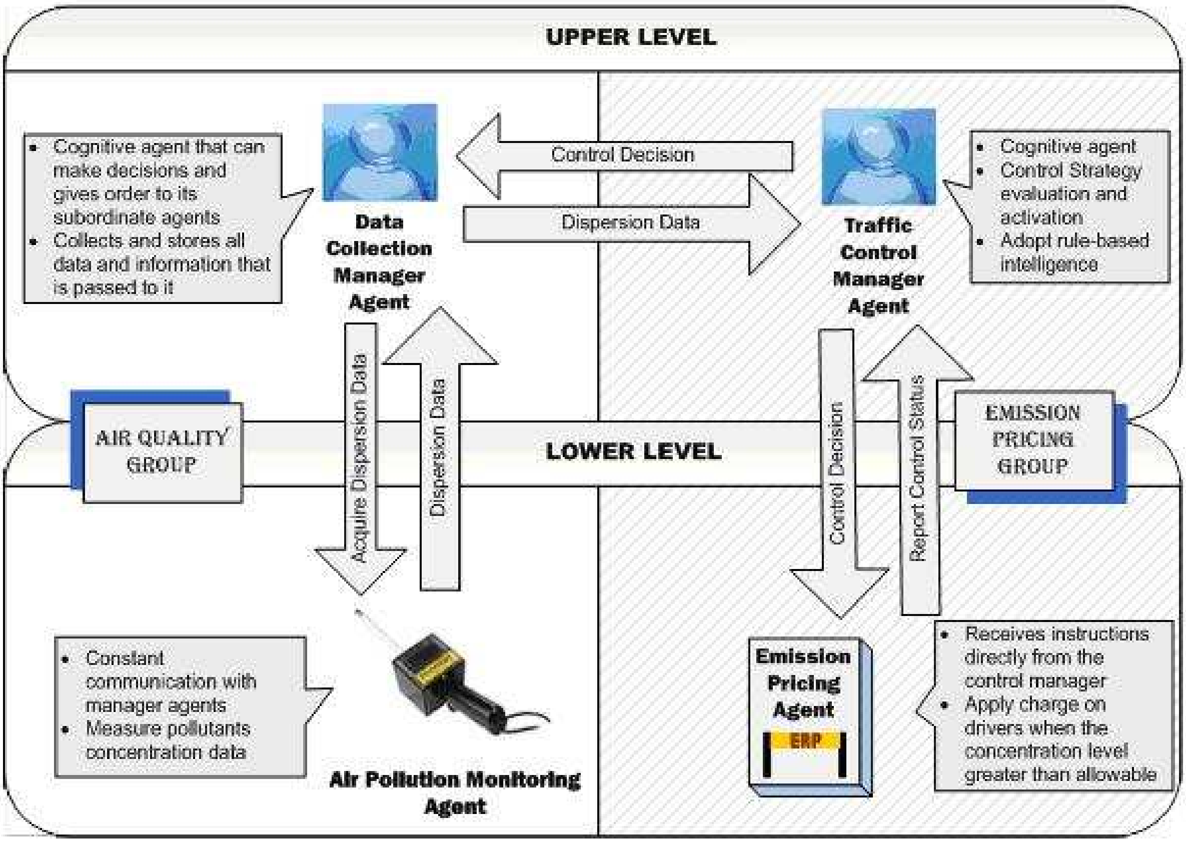

Figure 1 The MAS hierarchical architecture

2.1 Air Quality Group

The function of the agents of this group is to monitor the air pollution level at the roadside or at the buildings vicinity to roadways in the study area. It collects air pollutants' concentration data from various agents and stores them in the database for the access of other agents.

2.1.1 Data Collection Manager Agent

The data collection manager agent is a cognitive agent that makes decision when to acquire air pollution data from its worker agents. It communicates and retrieves data from various worker agents located at different locations in the study area to determine the air quality. To facilitate this, it adopts rule-based intelligence, which is a series of *if…then* logic statement. It notifies the traffic control manager agent about the availability of the air pollution concentration data. The logic statement sounds:

For every time interval t
If pollutants' concentration data is available,
Acquire the data, and store in database
Set parameter $\delta = 1$, *notify the traffic control manager agent from vehicle pricing group to read from the database*

2.1.2 Air Quality Monitoring Agent

It is a module-based agent, and constantly communicates with the data collection manager agent to supply it with the air pollution data. When it receives the order, it will measure the air pollution data using the receivers, which may be allocated at various locations in the study area. The air pollution data collected is then passed over to the management agent for database storage. Since each agent may detect for a limited area, multiple agents are required to cover a wider area.

2.2 Emission Pricing Group

The functions of the agents in the group are to decide when to activate the emission pricing strategy. They constantly acquire air pollution concentration data from the air quality group.

2.2.1 Traffic Control Manager Agent

It is a cognitive agent which can make decision based on the air pollution information received from the data collection manager agent. It will evaluate and determine whether to activate the emission pricing strategy. If the vehicle emission level is greater than the critical limit, it will activate its worker agent to carry out the emission pricing strategy. To facilitate this, it adopts rule-based intelligence to make the decision. The rule-based intelligent is a series of *if…then* logic statement. When the decision is made, it will inform the data collection manager agent as well. The logic statement sounds:

For every time interval t

if pollution data is available, $\delta = 1$

read pollution data from database

if concentration level at agent i *is greater than* α*, set* $\phi_i(t) = 1$*, else* $\phi_i(t) = 0$,

if $\dfrac{\sum_{i=1}^{I} \phi_i}{I} > \dfrac{\beta}{100}$*, set* $\varphi(t) = 1$*, else* $\varphi(t) = 0$

if $\varphi(\gamma)$ *has the same value, activate the emission pricing worker agent else deactivate it*

There are two parameters required in order to judge whether or not to activate the emission pricing. First, the critical limit α is set. The agent scans through the concentration level detected by all agents within pre-specified distance radius of the study area. It marks all the buildings that have the concentration levels greater than the limit, and calculates the percentages. This percentage is compared to another pre-specified level, β. If the percentage is greater than allowable, it triggers the emission pricing worker agent and vice versa. To ensure the stability of the system, the manager agent will only require a change of action (either turn on or off) from the worker agents if at least γ successive time interval that required the same action to be carried out. The parameters: α, β and γ can be determined according to the local emission standard by the authority.

2.2.2 Emission Pricing Agent

This agent is a module-based agent as well. It receives instruction from the manager agent to determine whether the pricing should be activated. To ensure the stability of the system, once the emission pricing is activated, it remains activated for a certain period of time. When it is activated, a certain amount of toll is charged to the users for emitting the pollutants to the study area. It obeys the instruction given by the manager agent without making any decision. The gantry is assumed built at the boundary of the entrance road to the study area.

3. AN ILLUSTRATIVE CASE STUDY

The application of vehicle emission pricing strategy using the MAS framework is evaluated in the microscopic traffic simulation environment. The traffic flow is generated in the simulation model for fixed origin-destination (OD) demand. The MAS framework is embedded in the simulation model to emulate their functions in emission pricing strategy. The air pollution concentration level monitoring activities are simulated by integrating a vehicle emission model with a line dispersion model. PARAMICS Monitor (Quadstone, 2006) is employed in this study to compute the emission of vehicles for different traffic condition. By inputting the vehicle types and speeds, it could give the emission data. The pollution concentration is then calculated using the line dispersion model. In this study, it is assumed that the air pollution receivers are placed on the buildings vicinity to the roadways. Hence, the pollution concentration level is calculated for each of the nearby building.

3.1 The Study Area and Network Setting

Yishun New Town, a town located at the northern part of Singapore is chosen as the study area. It has a total area of 8.1 km^2, with 46,613 dwelling units and a total population of 162,900 people. Figure 2 shows the map of the Yishun New Town in Singapore. The connected links, A:B and B:C is the candidate roadway modeled in the study. It is anticipated to analyze the pollution concentration level dispersed by the traffic along the road to the nearby buildings within 1 km radius from node B, indicated by the circle in the figure. It is a major road of the town and there are many buildings and amenities nearby the road. A total of 499 residential blocks surrounding the road is analyzed to study the impact of vehicle emission to these buildings. The term “block” used in this study means that a stand-alone unit of building which consisted of multi-level with many household units for each level.

The network is coded in PARAMICS Modeler with a total of 399 nodes, 874 links, and 34 zones. The network layout such as the lane marking, traffic signal setting and turning movement are carefully set. The roadway geometry is coded according to the real network including the road curvature, the number of lanes and travel directions, traffic lights location and the signal phases. In addition, the vehicle type and its percentage are properly defined. The vehicle types in the simulation model consists of four major types, namely private cars (84%), light vehicle goods vehicles (11%), heavy vehicle goods vehicles (5%) and buses. A number of bus routes (bus lines: 169, 800,804,811, 812) are coded into the network as well. This is because public transportation is a prevailing transportation mode in the town. The original-destination (OD) demand for the network is assumed. The dynamic feedback assignment is chosen to reflect the route choice behavior of drivers.

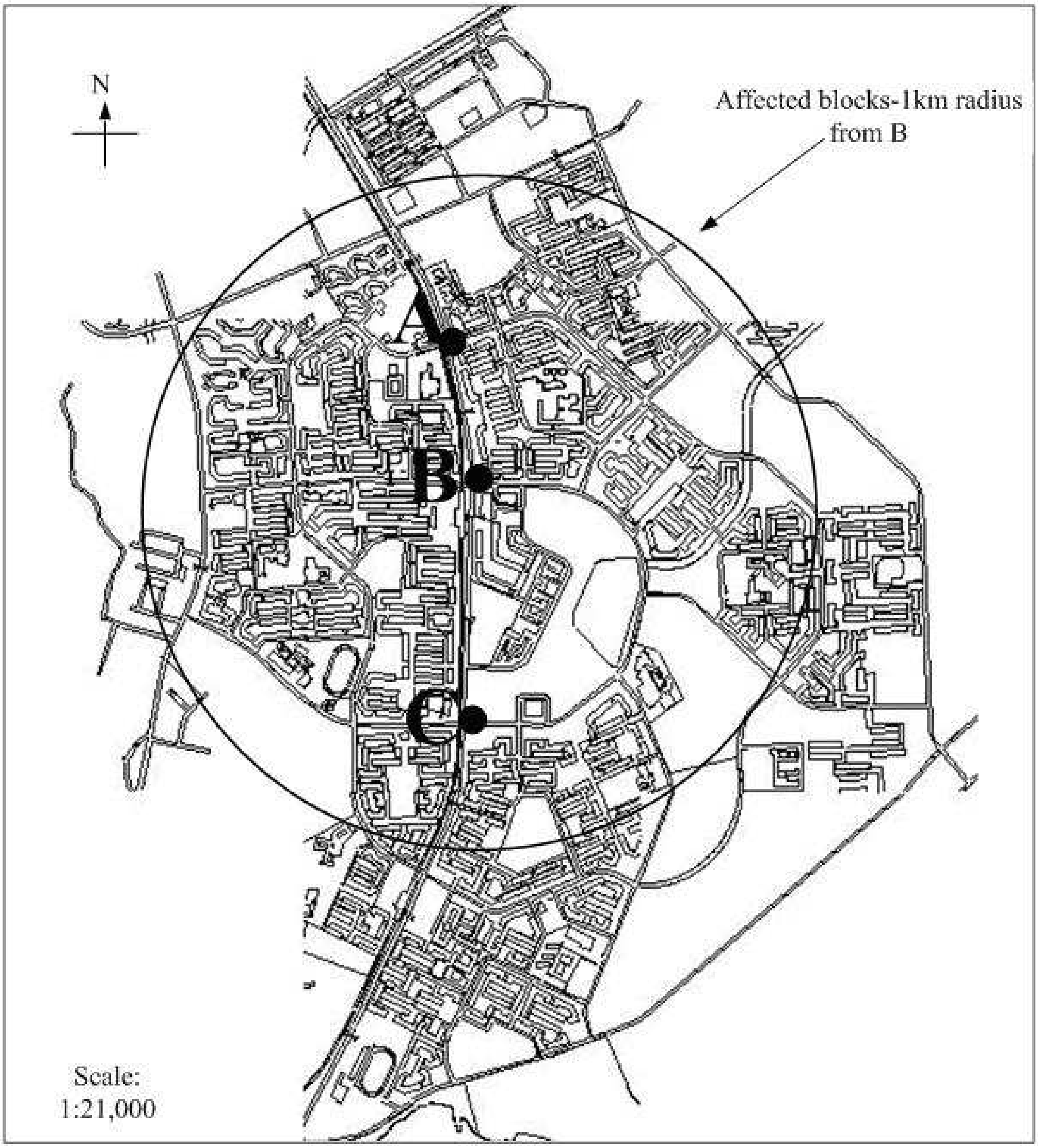

Figure 2 Yishun New Town of Singapore

3.2 The Air Quality Group Agents

3.2.1 The Air Pollution Monitoring Agent

In the real life, monitoring equipment is placed at the roadside or buildings nearby to collect pollutants' concentration data when it is instructed by the manager agent. However, in the simulation environment, the role of this agent is simulated by integrating two models, i.e. the PARAMICS Monitor and Gaussian Line Dispersion model. PARAMICS Monitor computes the emission rate from various types of vehicles for different traffic condition on the road. The roadway is divided into a number of segments based on its geometric condition. For each segment, the emission rate is calculated based on different types of pollutants, and speed of vehicles. The average emission rate for pollutant type l for vehicle type m traveling on segment k of road r at time t, $Q_{ml}^{kr}(t)$ in unit of (g/s) is calculated using the following equation:

$$Q_{ml}^{kr}(t)=\frac{\sum_{n_m=1}^{N_m}\left[\frac{EF_{ml}\times v_m^n}{3600}\right]}{N_m} \tag{1}$$

where $n_m=\{1,2,3\ldots N_m\}$ is the vehicle index, N_m is the total number of vehicle type m, v_m^n is the speed of n^{th} vehicle type m, EF_{ml} is the emission factor (g/km) for pollutant l of vehicle type m. The vehicle emission factor is described as a function of the vehicle speed expressed as follow:

$$EF_{ml}=p_{ml}\times\left(a_{ml}+b_{ml}v_{ml}+c_{ml}\left(v_m^n\right)^2+d_{ml}\left(v_m^n\right)^{e_{ml}}+f_{ml}\ln v_m^n+g_{ml}\left(v_m^n\right)^3+\frac{h_{ml}}{v_{ml}}+\frac{i_{r_s}^{kl}}{v_{ml}^2}+\frac{j_{r_s}^{kl}}{v_{ml}^3}\right) \tag{2}$$

where $p_{ml},a_{ml},b_{ml},c_{ml},d_{ml},e_{ml},f_{ml},g_{ml},h_{ml},i_{rs}^{kl},j_{rs}^{kl}$ are the constant parameters calibrated from experiment. They are deduced from various types of vehicles respectively according to their engine sizes and weights. Furthermore, these parameters are also different for various types of pollutants. In short, the vehicle emission rate is depended on two parameters, namely the vehicle type and its speed. A spreadsheet is prepared for emission rate calculation given the vehicle type, speed, and pollutant type. The spreadsheet is then embedded into PARAMICS Monitor in order to determine the vehicle emission rate for vehicles in the simulation model. It is a plug-in to determine the vehicle emission rate by matching the average vehicle speed on the road to the information provided by the spreadsheet. In the case if any emission value that is not explicitly defined in the supplied data but is within the range of data given in the spreadsheet, Monitor will interpolate from the surrounding values. If a value is outside the range of data, Monitor will select the emission value which is nearest to the boundary value. A systematic procedure on how to use Monitor can be found from its manual (Quadstone, 2006). Given the emission rate for each vehicle and pollutant type, the average emission rate for segment k of road r at time t is the summation of all type of pollutants and vehicle types as indicated in eqn. (3):

$$Q^{kr}(t)=\sum_{l=1}^{L}\sum_{m=1}^{M}Q_{ml}^{kr}(t) \tag{3}$$

where L is the total number of pollutant and M is the total number of vehicle type. Note that, sue to lack of information in Singapore, the input data of Monitor is obtained from the United Kingdom.

When the emission rate for the entire roadway is obtained, the dispersion of the pollutants is modeled using Gaussian Line Dispersion Model. The concentration level of all pollutant type and vehicle type from segment k of road r at building i is expressed as:

$$C_i^{kr}(t)=\frac{Q^{kr}(t)}{2\pi\sigma_{yi}\sigma_{zi}u(t)}\times e^{-\frac{y_i^2}{2(\sigma_{yi})^2}}\times\left(e^{-\frac{(z-H_i)^2}{2(\sigma_{yi})^2}}+e^{-\frac{(z+H_i)^2}{2(\sigma_{zi})^2}}\right) \tag{4}$$

where $C_i^{kr}(t)$ is the concentration of pollutants at block i sourced from road r of segment k at time t (g/m^3); $u(t)$ is the wind velocity in prevailing direction (m/s) at time t, y_i is the horizontal coordinate of block i measured in a direction perpendicular to the axis of the wind movement (m), σ_{yi} is the cross-wind dispersion coefficient (m) for block i, σ_{zi} is the vertical dispersion coefficient (*m*) for block i, z is the elevation of resource above ground, where it is set as zero (*m*) in the study and H_i is taken as half of the total height of the building i. The dispersion coefficients are both functions of downwind distance from the source. Their value is determined by the stability class the location is belonged to (in which depends on the wind speed and the strength of the incoming solar) and the downwind distance from the source. It is assumed that the source of emission is at the mid point of the road segment. Thus, the total concentration of pollutant at building i at time t from vehicles traveling on all the roads of interest is calculated as:

$$C_i(t) = \sum_{r=1}^{R} \sum_{k=1}^{K} C_i^{kr} \qquad (5)$$

where $C_i(t)$ is the total concentration (g/m^3) of block i at time t, K is the total number of segment for road r and R is the total number of road of interest.

The step-by-step procedure applied in calculating the concentration level is outlined as follows:

Step 1: Determine the stability class according to the wind speed and strength of incoming solar radiation at time t (Baratt, 2001).

Step 2: Determine the value for the dispersion coefficients, σ_{yi} and σ_{zi} (Baratt, 2001) using the wind direction information and the downwind distance for each block i.

Step 3: Calculate the concentration level of each block i at time t using eqn. (4) where the emission rate, $Q^{kr}(t)$ is computed using eqn. (3).

Step 4: Calculate the total concentration of the pollutant using the Gaussian Line Dispersion Model according to eqn. (5) for each building i.

3.2.2 Data Collection Manager Agent

In the microscopic traffic simulation model environment, the activity carried out by this manager agent is simulated by integrating the API functions in PARAMICS with the customized algorithms written in C++ language. The algorithm would acquire the dispersion data from the worker agents at every time interval and store them in the Excel database.

3.3 Emission Pricing Group

3.3.1 Emission Pricing Worker Agent

The agent receives order directly from the traffic control manager agent. It is assumed that gantries are built at the entries of the roads leading to the study area. If the pollution level is higher than the critical limit, charges will be imposed on the drivers who used the roads. To model this, an equivalent toll charge in the unit of time (seconds) is specified according to the value of time. When this agent is activated, the sum of penalty time is added to the original turning cost using the API functions provided by PARAMICS. If drivers use the roads with pricing, they will need to pay the penalty time. At the end of each feedback period, the drivers are rerouted according to the updated turning cost.

3.3.2 Traffic Control Manager Agent

Similar to the data collection manager agent, the rule-based logic statement of this agent is carried out by writing the algorithms in C++ language. At the specified time interval, when it receives signals from the data collection manager agent, it would query the Excel database to obtain the pollution data. By setting the value of the parameters in the rule-based logic as $\alpha = 0.1 g/m^3$, $\beta = 40\%$ and $\gamma = 3$, it could determine whether or not to activate the emission pricing strategy at every time interval.

3.4 Results

The proposed methodology is tested using the case study mentioned. To serve the purpose of comparison, a benchmark case of no emission pricing control is performed. For the vehicle emission pricing scenario, a toll charge of S$3 is assumed to charge on drivers using the roads. It is further assumed that the value of time is S$ 12/hour. Accordingly, an equivalent penalty cost of 15 minutes is imposed on the drivers who choose to use the road. The penalty time is added to the turning cost of the entrance junction of the road. The dynamic traffic assignment is carried out to reroute the drivers with the updated turning cost at the end of each feedback period. As such, some of the drivers might be rerouted to the junctions with lower costs. The results obtained are shown in Figure 3. The *x*-axis of Figure 3 shows the real time starting from 8:00 am while the *y*-axis indicates the block number, and the z-axis denotes the concentration of the pollutants.

3.4.1 Benchmark Scenario

Part (I) of Figure 3 shows the output for the benchmark case. The 3D graph shows the concentration versus the blocks and the time. It can be seen that without any control measure, the concentration is high during the simulation period. It is observed that there is about 100 blocks which are situated within the 1 km radius from the study area is affected by the emission. Those blocks (number 200-400) that are not affected or the concentration level is too low to be observed significantly are situated far away from the study area. Hence, the figure shows that residents living near to the busy roadside are exposed to higher level of concentration compared to those live far away from it.

3.4.2 Emission Pricing Scenario

Part (II) of Figure 3 shows the pollutants concentration observed with the vehicle emission pricing strategy is activated. It is observed that with the application, the concentration level is reduced significantly. The average improvement is high, which is about 90%. The result shows that emission pricing could help in mitigating the air pollution problem due to the vehicle emission. While there is some reduction of pollutants concentration on the buildings nearby to the roads when the strategy is activated, there is no significant increment of concentration level is detected for those buildings on alternative roads. One of the reason could be the availability of many alternative roads and the drivers might not choose the same alternative roads. This causes the redistribution of the pollutants level.

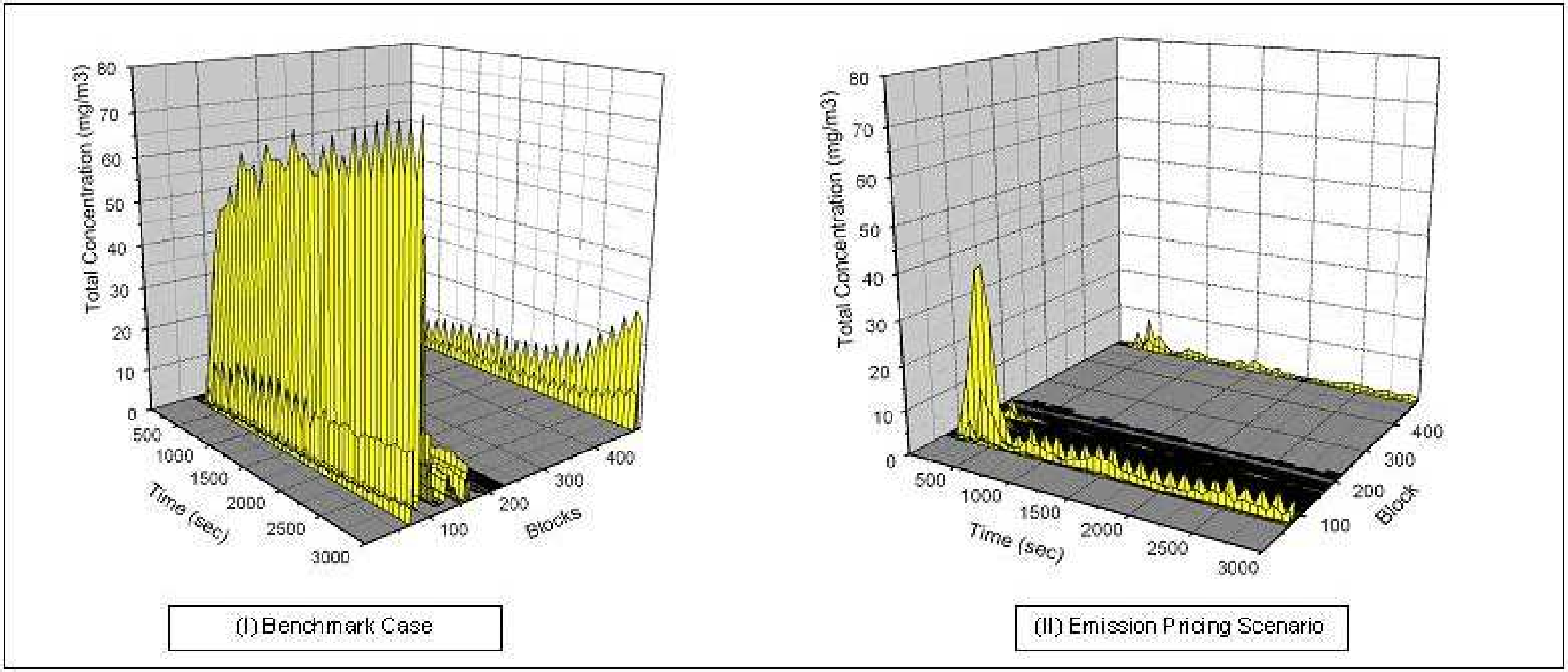

Figure 3 Comparison between benchmark case and emission pricing strategy scenario

3.5 Discussions

The results of the illustrative case study show that MAS framework is a feasible system to model the implementation of the emission pricing strategy. The proposed methodology is workable when it is tested in the simulation environment. From the results, it could be observed that with the emission pricing, the pollutant concentration for the buildings vicinity to the roadway could be reduced with no significant increment of pollution level at the alternative roads. This shows that the emission pricing strategy could redistribute the pollutants' concentration level in the study area. It is important to note that the illustrative case study presented is yet to be calibrated and validated with the field data. Hence, the high percentage of the efficiency shown beforehand is only valid with the current settings and the assumed values used in the case study. The percentage of efficiency might change if the setting has changed. A sensitivity analysis could be carried out to investigate the impact of the change of the input values on the results. However, this would be left for the future study.

The practical implementation of the policy will provoke debates from public as in the case of congestion pricing. In addition, redistribution of air pollutants pattern to rural area may also invoke the equity issue. Nevertheless, with the increasing of public awareness to the green environment, we strongly believe that the emission pricing strategy would become more popular in the near future.

4. CONCLUSIONS

This study adopts the MAS framework to model the emission pricing strategy in the microscopic traffic simulation environment. Two level hierarchical-based agents are defined to automate the detection of air pollution level and the implementation of emission pricing. These agents are categorized into two groups based on their functions, namely the air quality group and emission pricing group. Each of the group consists of manager agent and worker agents. Manager agents are cognitive agents that adopt rule-based intelligent in making decision that is then assigned to the worker agents. The worker agents carry out the tasks given by the managers and provide the required information to them. The results show that the proposed framework and strategy is applicable. It could influence the redistribution of air pollution patterns in the study area. However, to implement it in practical, there are still some remaining issues need to be addressed, especially relating to equity issue. For the future work, the calibration and validation of the simulation model and the framework could be carried out. Besides, sensitivity analysis could be performed to test the effect of the input values on the results.

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