Multi-agent model approach to evaluate distance-based urban freight road pricing

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The rising trend of business-to-consumer (B2C) electronic commerce (E-commerce) has initiated our research interest on how e-commerce will affect the urban road network and how distance-based urban freight road pricing can help to reduce the impact. The preliminary results from the multi-agent model evaluation showed that distance-based urban freight road pricing was able to reduce the entire city and city center NOx level and the distance travelled by the trucks. The carriers' profit was increased due to the second price auctioning and road pricing, which increased their competitors' price, while the shippers will have to pay more for the service of delivery. We have used a Multi-agent Systems (MAS) modeling approach, which is thought to be appropriate for evaluating policy measures, incorporated with vehicle routing problem with time window, freight electronic marketplaces and Q-learning to solve our problem.

Key Words : *multi-agent model, city logistics, e-commerce, urban freight road pricing, Q-learning,*

1. INTRODUCTION

(1) Trend of B2C E-commerce

The proliferation of broadband internet services has seen business-to-business (B2B) and B2C e-commerce thriving in recent years [1,2,3)]. Although B2B e-commerce transactions amounts to larger volumes compared to B2C and should gain more interest in research, the following factors like advances in technology, cheaper on-line purchases, new online business start-ups during economic crisis and change of consumers' shopping behavior have caused the B2C e-commerce to be successful and require renewed research attention. The wider product range, lower costs and convenience of B2C e-commerce has threatened the retail stores in the city, like in Australia where some major retail chains are placed in receivership or forced to close stores[4)] . Several studies have been done to identify city logistics measures and they proposed solutions that can be implemented to solve many difficult and complicated problems due to urban freight movement[5, 6, 7)]. In general the measures that apply to city logistics can be categorized into government driven or company driven[8, 9)]. Government driven measures include road pricing, truck ban and regulating co-operative facilities while company driven measures like facility locations and warehouse management are usually proposed.

(2) Urban freight road pricing

Road pricing has been implemented in London, Singapore and Stockholm and limited implementations can be found in other countries despite the Government authorities' effort to convince the general public that the implementation of road pricing is not a revenue generating tool[10)]. It is known that road pricing is a measure for allocating limited road space and there are basically four methods of road pricing schemes listed as facility-based schemes, cordons, zonal schemes and distance-based schemes[11)]. There are several studies done on road pricing in general but few of them place emphasis on the impact of road pricing on freight operations. Some research were done to study the expected influence of distance pricing on freight transport in urban areas based on in-depth interviews on carriers[12], comprehensive studies on carriers responding to time of day pricing based on data obtained from implemented road pricing scheme[13], and discussion on the myths and possibility of freight road pricing based on empirical evidence supported with game theoretic analysis[14]. This paper aims to complement past studies by simulating the home delivery system in an e-commerce environment using the MAS modeling approach and to evaluate the effectiveness of urban freight distance-based road pricing.

(3) Overview of MAS modelling and validation

MAS approach is recognized as a useful methodology to consider the multi-objective nature of an urban logistics system and study the behavior of the stakeholders who are influenced by policy measures[15]. Our problem considered in this paper fits into the characteristics for MAS approach listed by Parunak[16] along with several other agent-based approaches to transport logistics papers reviewed by Davidsson et. al.[17]. MAS consist of an environment with multiple autonomous agents with the ability to sense, perceive and take action while incorporating the interactions of other agents. Further reading related to MAS can be found in books written by experts in this field[18,19].

VRPTW is used in several studies that require solution for assigning trucks to customers and minimizing the cost of delivering goods with a feasible route within the given time window[20]. One example of an agent-based approach research, which helps authorities decide on a best location for logistic transit point location and customer service point, is the use of a combination of VRP models and microscopic approach using AIMSUN in a decision support system[21]. Another example of an agent-based model to optimize the location of intermodal freight hubs by considering hub owners, transport network providers, hub users and communities is presented by Sirikijpanichkul et. al.[22]. There are existing models that predict the impacts of e-commerce[23,24] but our proposed model proceeds to include the behaviours of multiple stakeholders, including the administrator.

MAS model approach and simulation is thought to have the same complexity as the real world freight transport environment, where policies can be evaluated for the reasons of appropriateness, cost effectiveness and time efficient[25]. The common critique of MAS model is the lack of data to establish the model parameters and to prove that the model output is comparable to the measurements of the real world. It is noted that data collection in urban goods movement systems are difficult to achieve as the information of companies is still preferred to be kept private[26]. However, the task of data collection and standadized methodology for data collection should not be viewed as impossible. Therefore, the viewpoint is to ensure that something can still be learnt from MAS models despite the missing data. The purpose of our research is to determine if freight road pricing, and especially distance-based pricing, has any effects on agents that seek to optimise their objectives in every actions they make. The results of the model have been discussed with relevant subject matter experts who varies in terms of their experience, foundations of knowledge and assumptions.

(4) Freight transport service marketplace

The models discussed in the previous sections have tried to evaluate the impact of freight policies, but none of them have incorporated freight transport service marketplace explicitly within their models. Traditional method of transport service procurement, where shippers search for reliable carriers and perform negotiations, are gradually replaced by smoother negotiation process and lower transaction costs like electronic markerplaces. Such online marketplaces can be categorised into clearing houses, auction houses and freight exchanges, which provide platforms where transportation capacity is bought and sold. In clearing houses, a database collects the loads posted by the shippers or capacity posted by carriers. Both parties search for their preferred choice and negotiate one-on-one for the price of delivery. In auction houses, both carriers and shippers engaged in an auction to sell their capacity or search for delivery services respectively at the best price. The auction system for clearing freight transport marketplace is found to contribute to higher degree of consolidation and carriers are able to improve their occupancy rate of transport vehicles while shippers can obtain better rates under spot market circumstances[27,28]. In freight exchanges, shippers post their demands and carriers posts their capacity in an online marketplace where each of them will be allocated to their respective services required at a competitive price. For information regarding current freight transport service marketplace, more can be found in the report by Nandiraju & Regan[29].

This paper continues in section 2 to explain our research model. The setup of our experiment is described in section 3 followed by preliminary results and discussion in section 4.

2. MODELLING

(1) Multi-agent model

The MAS model flow, as shown in Fig. 1, goes

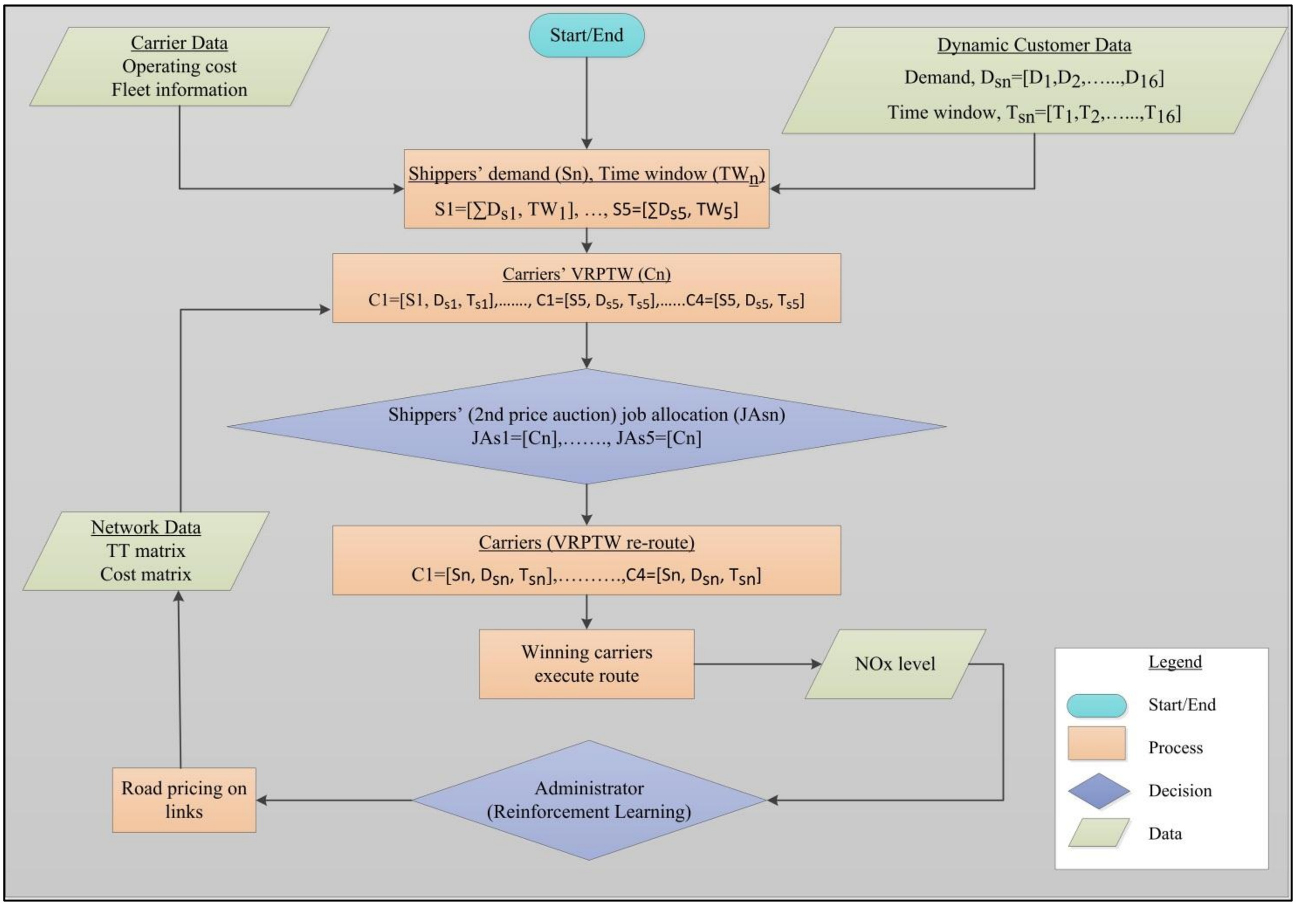

Fig. 1 MAS model flow for evaluating freight vehicle road pricing

through the process of receiving the carrier, customer and network data to run the insertion heuristics for VRPTW model. Carriers are considered to use VRPTW to optimize their delivery and they will utilize the VRPTW for bidding and re-routing in the model. As explained in previous section, one of the efficient method to consolidate goods for carriers and to receive "truth telling" quotations for shippers is second price auctioning[29]. The MAS model includes the second price auctioning from auction theory[30], which is optimal for bidders to report their true value, no matter what other bidders do. Such behavior is the dominant strategy and leads to Nash equilibrium in game theory. We assumed that producers (or shippers) employ the second price auctioning to determine which carriers should service their delivery.

The payoff typically shown in second-price auction seeks for maximum bid while the second-price auctioning in freight delivery aims to reduce the bid. In the case of bidding for delivery, carriers will try to bid as low as possible to acquire the job. The payoff of the winning carrier is shown as follows:

$$\pi_i = \begin{cases} min_{j\neq i} b_j - x_i & if\ b_i < min_{j\neq i} b_j \\ 0 & if\ b_i > min_{j\neq i} b_j \end{cases} \quad (1)$$

where,

π_i : Payoff of carrier i
x_i : Bid of carrier i
b_j : Bid of other carriers, excluding carrier i

The process of competitive pricing benefits all parties with common interest to transfer their job from one to the other at a compromised agreement. In this research, the producers demand delivery service from carriers at a low price while carriers prefer to profit from a higher price. Such conflicts arise and a game theoretic second price auctioning can model this behavior to represent the interaction between carriers while retailers can obtain the best and truthful price for the delivery service. Typical agents like carriers, shippers, administrators, motorway operators and residents in previous model[31] represent the key stakeholders involved in a logistics platform meeting. In our approach, the model considers the producers as shippers in B2C e-commerce engaging in a negotiation-like process using second-price auction theory.

Reinforcement learning is used in this model to represent the behavior of the administrator. It has been agreed that intelligent agents should be able to learn and those systems with agents capable of learning can be called intelligent. The administrator is treated as an intelligent agent where it will learn through Q-learning. The process of reinforcement learning includes administrator sensing the environment and taking actions to change the current state to reach its goals[32]. The administrator is assumed to learn after receiving the pollution level from the executed route by the successful bidders (carriers). The reinforcement learning we use is the Q-learning algorithm, first introduced by Watkins[33] due to its efficiency tested in previous study[34]. The updating algorithm in Q-learning for administrator is as follows:

$$Q(s_t, a_t) \leftarrow (1-\alpha)Q(s_t, a_t) + \alpha\left[r_{s_t,a_t} + \gamma \min Q(s_{t+1}, a_{t+1})\right] \quad (2)$$

where,

$Q(s_t, a_t)$: expected NOx level in state t due to action in state t

$Q(s_{t+1}, a_{t+1})$: expected NOx level in state t+1 of all actions

γ : discount rate for administrator $(0 < \gamma < 1)$

α : learning rate of administrator $(0 < \alpha < 1)$

r_{s_t,a_t} : immediate NOx level in state t due to action in state t

The learning rate of 1 represents that the administrator will consider the most recent information while 0 means the administrator does not learn. Discount rate set at 1 means that the administrator will consider the long term reward while 0 means that the administrator is concern only on current rewards. The oxides of nitrogen (NOx) emission is estimated using equation 3[35] assuming light delivery vehicles using diesel fuel.

$$NOx = l_{ij}\left(1.06116 + 0.000213v_{ij}^2 - 0.0246v_{ij} + \frac{16.258}{v_{ij}}\right) \quad (3)$$

where,

NOx : expected nitrogen oxide emission in grams

l_{ij} : length of road link between nodes i and j in kilometer

v_{ij} : speed of vehicle travelling on road link between nodes i and j

3. EXPERIMENT SETUP

The MAS model is used on the test road network as shown in Fig. 2. Four carriers are located at nodes 1, 5, 21 and 25 and they are named as Carriers 1, 5, 21 and 25 respectively. Nodes 8, 12, 13, 14 and 18 are the locations of producers while the rest of the nodes represent the customers

We have considered two scenarios to evaluate the policy measure of urban freight road pricing. The first scenario will be the base case (Scenario-B) where the administrator does not implement pricing and does not perceive from the environment. Therefore the general output from the model is the NOx level of each link on each day. The second scenario is to follow the model flow shown previously in Fig. 1 and to consider a distance-based freight road pricing (Scenario-DB). The evaluation parameter for the comparison of the two scenarios will be the NOx level as calculated using equation 3, the distance travelled by the trucks, average profit of carriers and average of shippers. The entire road network's NOx level of Scenario-B and Scenario-DB will be measured and compared. As our concerns are also in the city center, the NOx level of road links 8-13, 12-13, 13-14 and 13-18 will be measured and compared between the two scenarios.

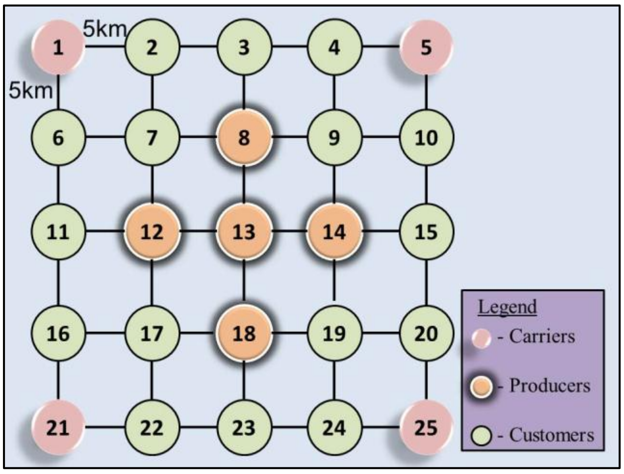

Fig. 2 Test road network

The demand and time window of each customer from each of the five producers is generated randomly. The assigned pick-up time windows of the producers are in the morning while the delivery time windows of the customers are set in the afternoon. Each producer will consolidates the demand from each customer and requests for delivery at specific time window generated randomly. The carriers' initial step is to find the shortest path to pick up the goods from the producers. As it is assumed that there is no affirmative information about the chance of winning the delivery, therefore all jobs are equally likely to be won and lost. Considering such circumstance, we have assumed that the carriers choose to

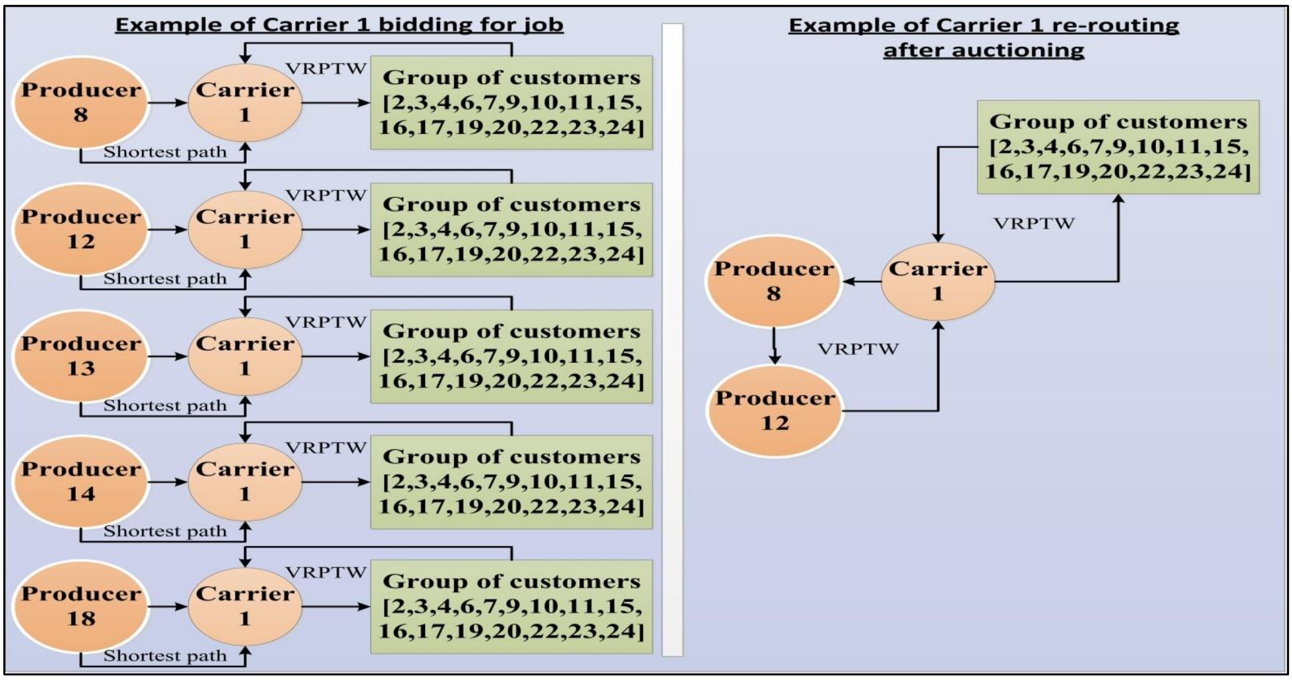

Fig.3 Example of Carrier 1 job bidding and re-routing.

bid for each job separately. The goods that are picked-up from the producers are assumed to be brought back to the carriers' depot for consolidation through the shortest path followed by using VRPTW with insertion heuristics to find the optimized route to deliver the goods to the customers of the producers. Each carrier will find the cost of pick-up and delivering goods for each producers' demand and bid for all five jobs of the producers in a second-price auction as shown on the left side of Fig 3. The winning carriers of the auction will consolidate the jobs acquired and re-route the jobs according to the demand requirement. An example of Carrier 1, who has won the job of delivering goods for Producers 8 and 12, is shown on the right of Fig. 3. We have assumed that the time window of each customer from each producer is the same, which means that the consolidated goods from different producers will be delivered to their respective customers at the same time. The truck capacity is limited to 2 tons and we have assumed that if a customer has a consolidated demand of more than 2 tons, the carrier will initiate a full truck load service to the customer prior to the execution of routing based on VRPTW.

The MAS model is iterated for two years, which is equivalent to 720 days. The randomly assigned pick-up capacity from the producers is equivalent to the delivery demand of the customers and they are assumed to be fixed during each day of the model run for different scenarios and the velocity of truck is assumed to be 30km/h. We have set the discount rate, γ, and learning rate, α, to 0.5 in our experiment to evaluate the impact and influence of distance-based urban freight road pricing.

4. RESULTS AND DISCUSSION

The preliminary results show that distance-based urban freight pricing was able to reduce the cumulative NOx level for the entire city as well as within the city center. The total distance travelled by the trucks was also reduced. The carriers' average profit was increased due to the road pricing and auctioning which caused their competitors to cost more for the delivery. However, it was noted that the shippers will have to pay more for the delivery service when the roads are priced. The comparison of results obtained from different Q-learning parameters will be discussed further during the conference.

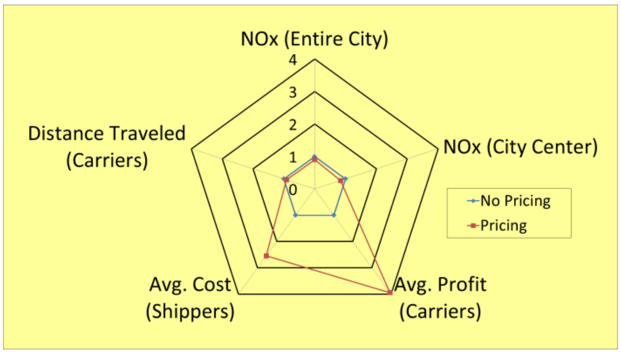

Fig. 4 Impact of distance-based freight road pricing

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