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J.S.E. Teo[a], E. Taniguchi[a] & A.G. Qureshi[a]

[a] Department of Urban Management, Graduate School of Engineering, Kyoto University, C-1 Kyotodaigaku Katsura, Nishikyo, Kyoto 615-8540, Japan

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Multi-agent systems modelling approach to evaluate urban motorways for city logistics

J.S.E. Teo*, E. Taniguchi and A.G. Qureshi

Department of Urban Management, Graduate School of Engineering, Kyoto University, C-1 Kyotodaigaku Katsura, Nishikyo, Kyoto 615-8540, Japan

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Government road authorities are constantly faced with the challenges of urbanization and traffic congestion requiring them to make good decisions for infrastructure developments. Several developed and developing countries have focused their concerns on building motorways for private and public transports for intercity connectivity and economic growth in the past. However, very few evaluation models were concerned about urban motorways for the benefit of urban freight transport. There may not even be an evaluation model for urban motorways development, which has considered the routing behaviour of truck movements in urban areas, especially if the main purpose for the urban motorway is for improving city logistics. Faced with the problems and concerns of the road authorities in Japan regarding capacity increase measures or other freight management schemes, this paper is an initial step to explore and provide the methodology to support the road authorities in their decision for urban motorway alternatives.

Keywords: multi-agent; freight; city logistics; evaluation; road authorities; urban motorway

1. Introduction

Transportation infrastructure is vital to the economy and connecting people, which led to several countries including the USA (US Department of Transportation, 2013) and China (Transport Business International, 2013) to announce their plans to fund the infrastructure projects. Large amount of budget has been allocated to road and bridge improvements and construction, for example, the USA has assigned about $305 billion over the next six years (US Department of Transportation, 2013). Due to the large financial investments typically involved in roads and bridge construction, transportation authorities and planners perform extensive evaluation and impact studies to justify and support their decisions on the location and construction of the new motorways. Besides the purpose of increasing the road capacity for private cars and public transport, motorways may help to reduce the inner city pollution level. In the context of urban freight movement or city logistics (Taniguchi, Thompson, Yamada, & van Duin, 2001), delivery trucks may use urban motorways as alternative paths to improve on their delivery time.

Urban freight transport has gained more attention in many cities of the world due to the concentration of more population into urban areas as well as social and environmental problems relating to urban freight transport. The typical problems we face in urban areas are concern about: (1) how we can create efficient urban freight transport systems with

*Corresponding author. Email: joel.teo@kiban.kuciv.kyoto-u.ac.jp

higher services and lower costs and (2) how we can ensure the better environment, safer community and well-being of people who are living there. The idea of city logistics has been proposed (Crainic, Ricciardi, & Storchi, 2009; Taniguchi et al., 2001) for establishing efficient and environmentally friendly urban freight transport systems towards sustainable and liveable cities by balancing the above-mentioned two issues. The essential aspect of city logistics is that although the logistics activity is mainly carried out by private companies, the intervention of public authorities are required to achieve the goals of city logistics by implementing government-driven policy measures (PIARC Technical committee B.4 freight transport and inter-modality, 2012). In the procedure of public private partnerships for identifying current problems, discussing appropriate approaches and measures as well as evaluating them are important. Sharing data and information among stakeholders and assessing the policy measures before implementing them would also be essential. In this context, modelling city logistics policy measures, including truck ban, access control, road pricing, setting urban distribution centres, off-peak hour delivery, load factor controls and new motorways construction plays a crucial role for the evaluation.

Few studies in the past have studied the impact of urban motorways on urban freight movement and the effect on the stakeholders in the city. Although it may seem that motorways are the natural choice to improve road capacity and travel speed, but the selection of the new motorways, given several options, is usually difficult to determine. A cheaper motorway construction may not lead to a useful infrastructure if it does not attract road users, especially if the motorway is intended to relieve urban freight traffic and eliminate 'rat-running' in the city centre. This paper seeks to provide a unique modelling framework to support government transport authorities in decision-making especially on the location of constructing new motorways to improve freight activities and reduce negative environmental impact. The model in our research has incorporated an autonomous road administrator while considering the objectives of the stakeholders involved within the urban freight environment.

2. Literature review

A recent publication by Cambridge Systematics, Inc. (2013) provides a summary of the current practice of integrating freight in the highway planning process in the USA, which focused on three major points. The first is about freight self-assessment, which includes existing logistics patterns, logistics bottlenecks and needs identification. The second element is concerned about the stakeholder outreach where public and private freight stakeholder groups are formed. The third major point is about data analysis like forecasting freight volumes and evaluating existing performance measures. These are the major elements that are common for the macro-level evaluation of freight policies. Studies in the past reflected three groups of people, who have concerns related to new motorway developments. One group typically supported the plans for the development, while the second group felt the necessity of such projects but were not convinced on the economic growth and development that such motorways will bring. The last group of people were the critics, who were against the investment and totally disagreed with the theoretical and empirical studies (Rephann & Isserman, 1994). These are the groups of people that the evaluation models for motorway investments can consider. There are many existing models developed that has provided support for government road authorities with a motorway investment plan for bridge preservation, road safety improvements, pavement maintenance, intelligent transport systems and new constructions (Li, Madanu, Zhou, Wang, & Abbas, 2010). Transportation investments look at two analytical steps of project evaluation and selection and projection selection usually involves choosing the best economically projects with maximum benefits

(Li et al., 2012). Cook and Seiford (1984) introduced an ordinal ranking model to select the best option for motorway corridor based on some corresponding qualitative dimension. A benefit–cost analysis to evaluate new capacity motorway projects was proposed by An and Casper (2011) where they considered the logistics benefit, which included the time and shipping cost savings. However, there are limited papers that studied the micro-level of evaluating impact of new urban motorways while considering the objectives of carriers, shippers, administrator and residents and the effects they have on urban freight activities. This research aims to contribute to the literatures to cover the initial step of covering the topic on micro-level analysis of freight carriers' optimized and current practise of last-mile operations and the impact of new motorways on other major stakeholders.

3. Methodology

Based on the literature reviews, none of the models have considered the routing behaviour for carriers when considering urban motorway options relating to freight operations. Our research hopes to consider such activities of the carriers and the interactions of the stakeholders within the context of city logistics especially when the purpose of constructing a motorway is to improve urban freight traffic.

In a recent research, the evaluation of cordon-based and distance-based urban freight road pricing was done using a multi-agent systems (MAS) modelling approach incorporating vehicle routing problem with time window (VRPTW) model solved with insertion heuristics, Q-learning algorithm and second price auctioning model (Teo, Taniguchi, & Qureshi, 2012a). It is observed that researchers, who tend to use the MAS approach, inevitably attempt to include several cross-disciplinary models, which was helpful to model the rationality of urban freight agents' behaviour.

The flexibility of MAS modelling makes it an attractive modelling alternative for complicated problems. Davidsson, Holmgren, Persson, and Ramstedt (2008) and Holmgren, Davidsson, Persson, and Ramstedt (2012) developed the Transportation and Production Agent-based Simulator (TAPAS) that consists of a physical simulator and a decision-maker simulator to evaluate the impact on shippers, carriers and customers due to the implementation of schemes such as fuel taxes, road tolls and vehicle taxes. They recommended that more sophisticated optimization algorithm can be used for the agents' decision-making and agents' learning from experience can be included, along with other recommendations in their study.

A vehicle routing problem with time window – dynamic (VRPTW-D) and Monte Carlo learning model were found to increase the profit of carriers and decrease the shippers' costs with the MAS modelling approach (Taniguchi, Yamada, & Okamoto, 2007). Further evaluation of city logistics schemes such as road pricing and cooperative freight transport systems could also be done using the same methodology. In another research, a VRPTW-forecasted (VRPTW-F) model with the combination of Q-learning algorithm, which is a form of reinforcement learning, was used to evaluate truck ban and motorway toll policy schemes on the impact on administrators, carriers, shippers, residents and motorway operators (Tamagawa, Taniguchi, & Yamada, 2010). In a complex logistics environment having several stakeholders acting on their own interest, it is unavoidable that most modellers face problems anticipating future situations and instilling fixed solutions to all problems may not be the best option. This is the reason why reinforcement learning is one of the important topics in MAS modelling especially in modelling the evaluation of new motorways in the context of urban freight activities or city logistics as shown in Figure 1.

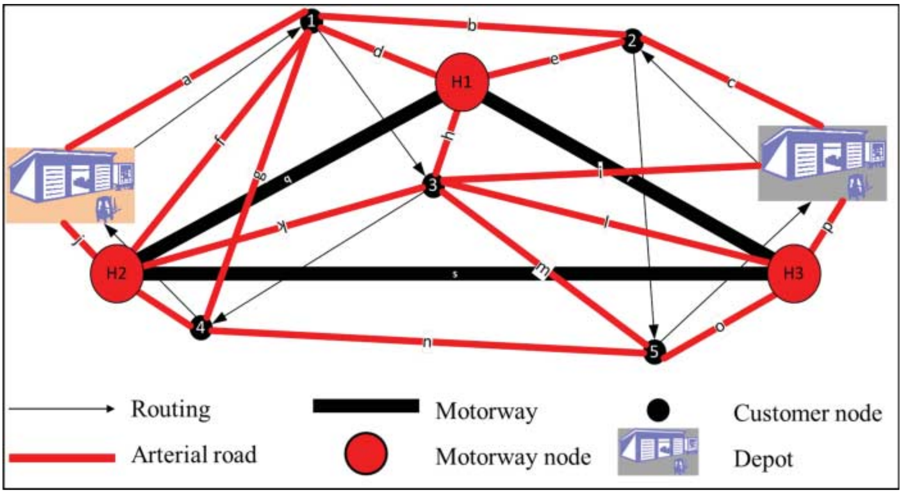

Figure 1. An example of an urban motorway road network in city logistics.

Reinforcement learning has two most critical distinct features that differentiate itself with other learning which are the trial-and-error search and delayed reward (Sutton & Barto, 1998). The simple idea of learning through experimenting and experiencing the consequences makes reinforcement learning close to reality of how human beings learn in any given environment. In this sense, it is expected that the learning model includes the ability to sense the environment, take actions that will change the state and must include the goals that direct the actions. These three aspects provide a suitable condition for research in the area of city logistics due to the involvement of multiple stakeholders that require goal-directed action policies. Another area of consideration is the issue of exploitation and exploration actions. When an agent learns from experience, the next dilemma is to consider whether to take the action that provides the best results every time or to try a new action that has the possibility of achieving a better result. Exploring a new action gives the agent a more complete experience and in some scenarios where competition is involved, it is more rational to switch between actions to make the environment more unpredictable, especially when the agents are in a competitive market.

4. Modelling framework

One of the unique features in this research is the use of object-oriented programming structure with the concept of MAS modelling as compared to previous modelling approach (Teo et al., 2012a; Teo, Taniguchi, & Qureshi, 2012b). Similar attempt by Nilesh, Yang, van Duin, and Tavasszy (2012) was done to facilitate developers to understand the modelling framework for city logistics in MAS models. The framework shown in Figure 2 is the modelling structure used in this research. The arrows connecting each of the class refers to the transfer of information and interaction. Within each class are the associated objects where each of them has their own actions.

The administrator's reinforcement Q-learning algorithm is shown in Equation (1). The algorithm will provide updated learning values for the administrator's action. The administrator's action consists of new urban motorway alternatives. Each alternative includes bi-directional links in the road network. There are three scenarios tested in this research.

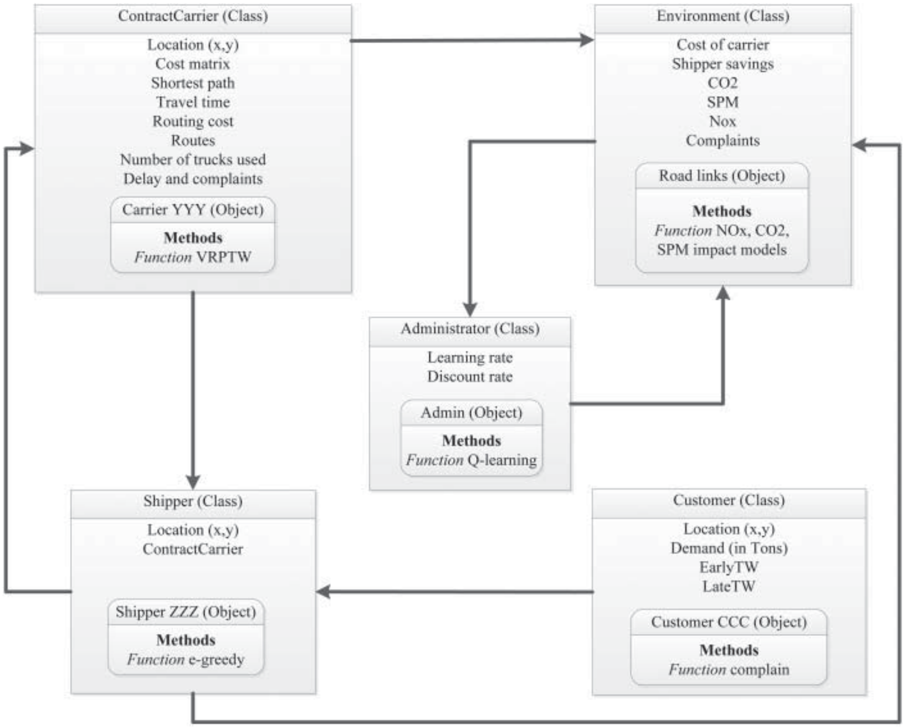

Figure 2. Object-oriented programming MAS framework.

The first scenario is the base case where the administrator was an inactive agent and did not learn from the emissions. In the second and third scenarios, the administrator received emission information from the environment and learnt using the Q-learning algorithm for different motorway connection pattern for each scenario, respectively. The emission level of carbon dioxide, nitrogen oxide and suspended particulate matter are calculated using the equations as found in Equations (2)–(4) (NILIM, 2003).

$$Q_n(s_{n,t}, a_{n,t}) \leftarrow (1-\alpha_n)\, Q_n(s_{n,t}, a_{n,t}) + \alpha_n \left[r_{n,t} + \gamma_n \min_{a_{n,t+1}\in A_n} Q_n(s_{n,t+1}, a_{n,t+1}) \right], \tag{1}$$

where $Q_n(s_{n,t}, a_{n,t})$ is the expected emission level received by administrator n in state t due to action in state t; $Q_n(s_{n,t+1}, a_{n,t+1})$ the expected emission level received by administrator n in state $t+1$ due to the action in state $t+1$; γ_n the discount rate for administrator $n (0 < \gamma_n < 1)$; α_n the learning rate of administrator $n (0 < \alpha_n < 1)$ and $r_{n,t}$ the immediate emission level received by administrator n in state t.

$$\mathrm{CO_2} = l_{ij}\left(278.448 + 0.048059 v_{ij}^2 - 5.1227 v_{ij} + \frac{2347.1}{v_{ij}}\right), \tag{2}$$

$$\mathrm{NO}_x = l_{ij}\left(1.06116 + 0.000213 v_{ij}^2 - 0.0246 v_{ij} + \frac{16.258}{v_{ij}}\right), \tag{3}$$

$$\mathrm{SPM} = l_{ij}\left(0.03442 - 0.000039391 v_{ij}^2 + 0.0036777 v_{ij} + \frac{1.2754}{v_{ij}}\right), \tag{4}$$

where CO_2 is the expected carbon dioxide emission in grams; NO_x the expected nitrogen oxide emission in grams; SPM the expected suspended particulate matter in grams; l_{ij} the length of road link between nodes i and j in kilometres and v_{ij} the speed of vehicle traveling on road link between nodes i and j.

5. Experiment set-up

This research sets up the basic structure with a simplistic road network as shown in Figure 3. This road network is not meant to be a generic representation of realistic cases but is meant to explain how the modelling framework and methodology can be applied. The hypothetical network consists of two shippers with two contract carriers and 21 customers. In the experiment, each of the customers generated dynamic demands, early and late time window for each day. The shippers are assumed to receive all information regarding their customers and passed on this information to the carriers for delivery service. For this experiment set-up, carrier at Node 1 is contracted to shipper at Node 5, while carrier at Node 12 is contracted to shipper at Node 25. This type of contracts reflects the typical industry practice where shippers and carriers are engaged in long-term contracts for regular deliveries. The flow of delivery involves each carrier to pick-up all demands with full truck load as much as possible from their contracted shipper and return to the depot for repacking. The delivery service to the customers is based on the optimized routing using insertion heuristics and the other parameters that were used are shown in Table 1. The learning and discount rates of the administrator are set at the mean of 0.5 in this initial experiment. The demand of customers are assumed to be less than the capacity of the truck for simplicity of one visit to service each customer at the given time window. As for the speed of the motorways, they are set at a higher travelling speed than the normal road links, which are commonly found in real scenarios. The simulation of the MAS model was done for 1080 days, which was about 3 years.

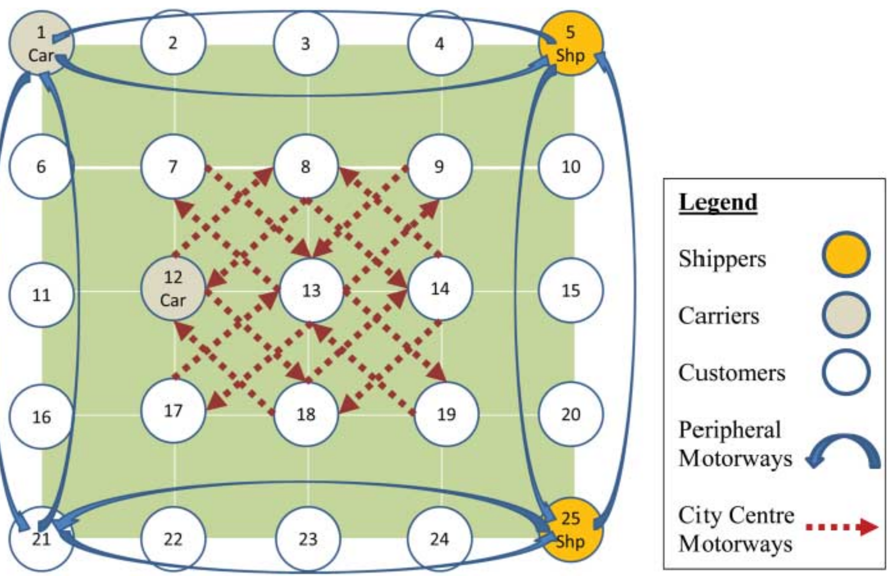

Figure 3. Hypothetical road network with motorway options.

Table 1. Parameters for experiment.

Learning rate of administrator, α_n	0.5
Discount rate of administrator, γ_n	0.5
Maximum capacity of trucks (units)	200
Maximum demand for each customer (units)	100
Length of each road link (km)	5
Length of peripheral motorway (km)	20
Length of city centre motorway (km)	7
Speed of typical truck (km/hr)	30
Speed of peripheral motorway (km/hr)	80
Speed of city centre motorway (km/hr)	60

6. Results and discussion

The current analysis shows the plots of the SPM, CO_2 and NO_x emissions for the entire network. It is assumed that the peripheral highway links provided a travel velocity of 80 km/hr that could entice the carriers to change their path choice. It is shown in Figures 4–6 that the CO_2, SPM and NO_x has increased by 10% after the implementation of peripheral motorways and by 20% after the implementation of city centre motorways. One likely cause of an increase for peripheral motorways is due to the trucks choosing a combination of normal roads and motorways resulting in faster travel time but leading to the consequence of longer distance travelled on the motorways. However, the introduction of the highway schemes have led to fewer complaints by the customers, with the least complaints encountered due to lesser late deliveries with the city centre motorways as shown in Figure 7. In a survey done on two Italian regions, Friuli Venezia Giulia and Marche, it was found that the shippers viewed quality attributes of freight transport services such as reliability and safety more than the cost (Danielis, Marcucci, & Rotaris, 2005). Such findings were also similar to the survey done in Switzerland and other reports reviewed by Fries, de Jong, Patterson, and Wiedmann (2010) where shippers view on-time reliability more important than cost.

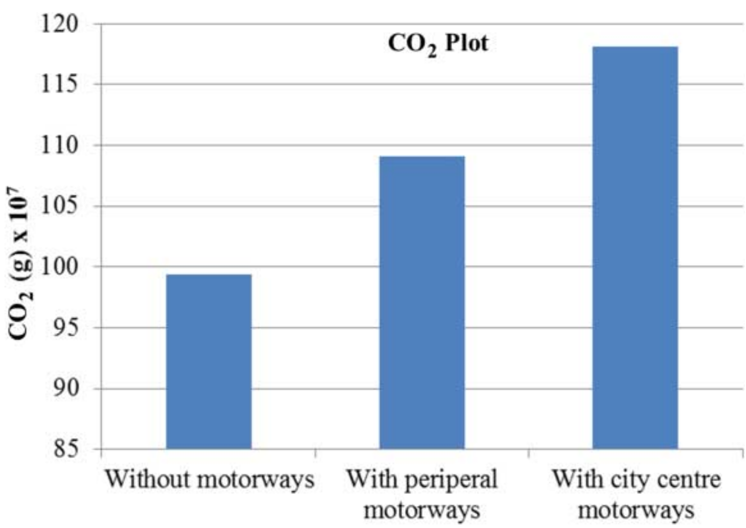

Figure 4. Average CO_2 emission comparison for different motorway schemes.

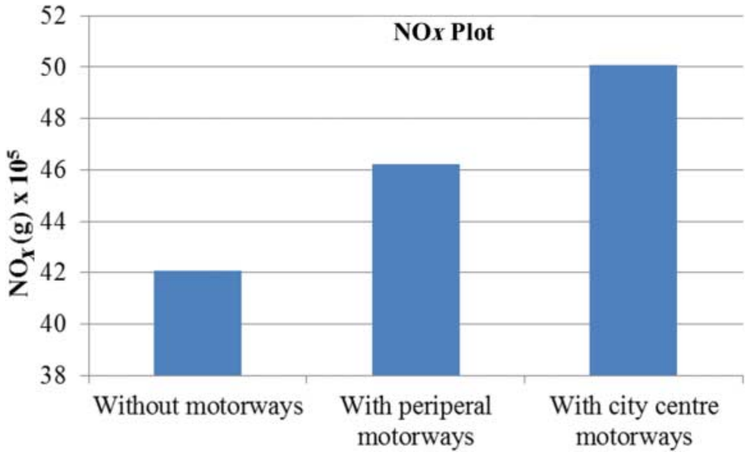

Figure 5. Average NO_x emission comparison for different motorway schemes.

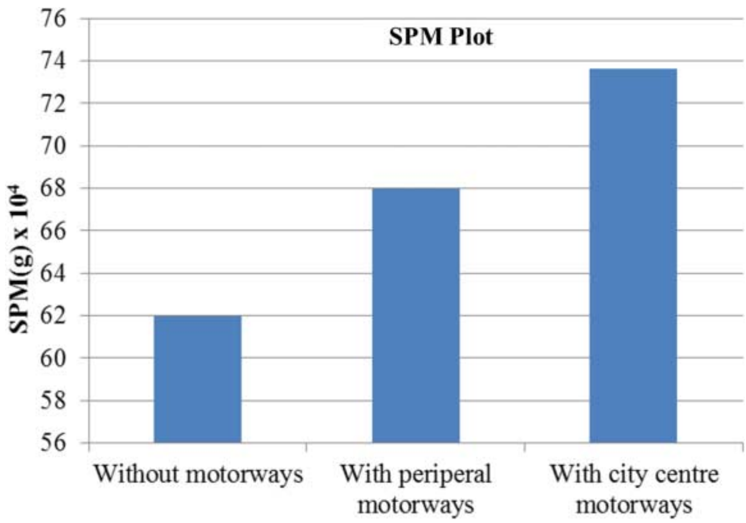

Figure 6. Average SPM emission comparison for different motorway schemes.

Carriers are also considered the last players in the supply chain that could affect the reputation of the shippers from the perspectives of the customers (Patier & Alligier, 2003). To study the impact of how policy schemes can be introduced to cope with the problems, it is necessary to understand the behaviours of the consumers. It was found that consumers in France have several expectations including short delivery times within specified time slots and on-time delivery (Patier & Alligier, 2003). Therefore, the complaints should be validated further especially when it shows the advantage that the introduction of highway created fewer complaints.

Figure 8 shows the savings for shippers as compared to the case if they have chosen the alternative carrier to deliver their goods. The savings experienced by the shipper is the difference between the calculated cost of the alternative carrier and the real cost paid to their own contracted carrier. Figure 8 shows that the contracted carriers provided savings without the highway schemes, which meant that it is a cost-effective way for delivering

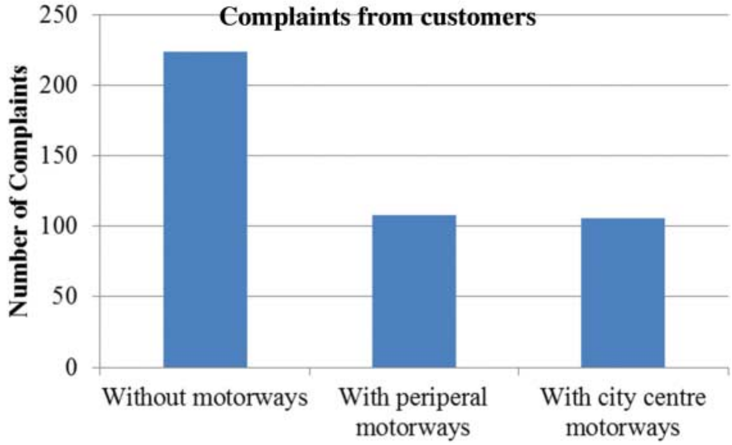

Figure 7. Average complaints comparison for different motorway schemes.

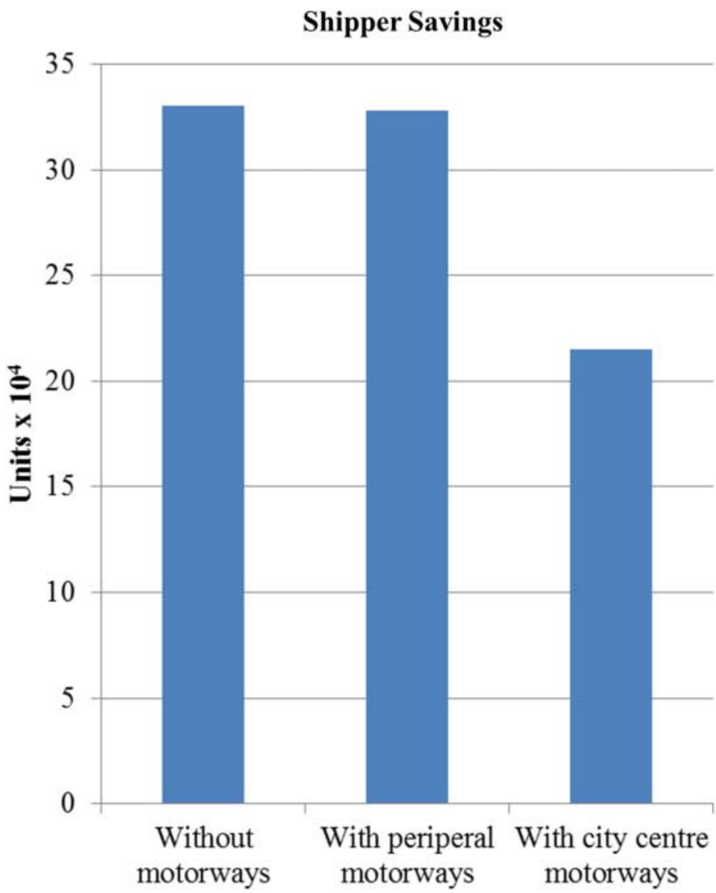

Figure 8. Average savings comparison for different motorway schemes.

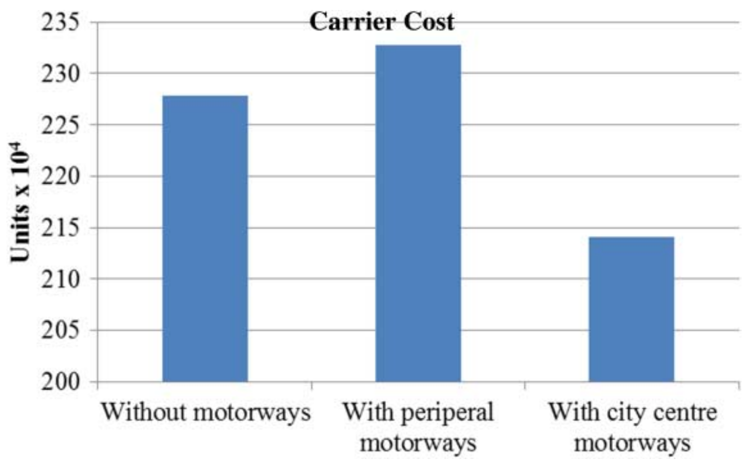

Figure 9. Average carrier cost comparison for different motorway schemes.

their goods if they continue to be contracted to their current carrier. The introduction of motorways has caused the savings to increase further as shown in the figure, especially for the city centre motorway scheme. The city centre motorways may have provided a faster delivery service to the customers. An alternative analysis can be done to consider the effect of having auctioning within the MAS model and how it can translate to more cost savings for the shippers. Such auctioning and e-marketplace are gaining more interest, like a recent project initiative in Singapore for a synchronized last-mile delivery (De Souza, Goh, Lau, Ng, & Tan, 2013). The results shown in Figure 9 shows the lower carrier cost when the city

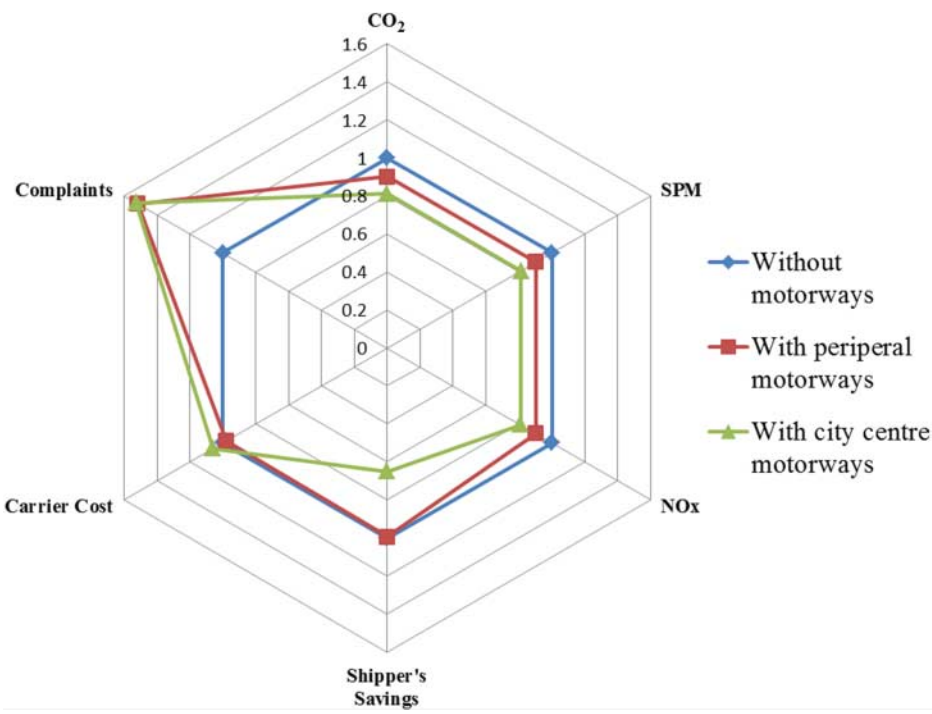

Figure 10. Radar plot for all performance measures.

centre motorways are constructed. This could be the effect of carriers opting to use the city centre motorways that resulted in lesser routing cost and late penalty cost. This experiment have shown how the MAS model can be used to evaluate the highway corridor options and as shown in Figure 10, there will be a trade-off for the different schemes and it seemed that city centre motorways benefit carriers the most but may not be desired by the road authorities since there will be a rise in the emission.

7. Conclusion

Developed and developing countries are facing an urgent need for improving or expanding their infrastructure due to the rapid rate of urbanization. The increase in the migration of population into urban areas has escalated the urban freight activities in recent years. This research was initiated due to the lack of evaluation models for handling new highway corridors for the purpose of improving urban freight transport and city logistics. The results in this paper are meant to provide an understanding of how the methodology is applied in this research and to verify the logics underlying the model. The advantage of this model is the incorporation of an autonomous administrator to represent the road authorities and the logical behaviour of the stakeholders involved in urban freight and city logistics. Future contributions in this area of research may include the modelling approach on realistic road networks such as the Osaka city network and some integration of micro and macro simulation software for generating the dynamic travel time for the MAS model.

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