COMPARISON BETWEEN A MACRO AND A DES APPROACH TO THE TRANSPORT MODE CHOICE PROBLEM

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ABSTRACT

One of the main problems in the freight transport is the congestion that can occur in multi-modal nodes and how this may affect the use that the load makes the entire transport system. Aggregate transport models take into account congestion in a simplified way, which may introduce bias in the estimation. Discrete events simulation provides a better tool for explaining the mechanisms that lead to congestion. This paper presents a comparison between an aggregate transport model and a model of discrete events that takes into account the delays caused by congestion at the nodes and how they affect modal choice. The goal is to assess the bias caused by the aggregated approach and whether it compromises the validity of the modal split estimation.

Keywords: transport model, discrete event simulation, multimodal, mode choice

1. INTRODUCTION

The development of transport infrastructure involves the disbursement of large investments. Errors in the initial studies of a project may cause deviations in the budget or lead to underutilized and unprofitable infrastructure. Thus, it is of the uttermost importance to employ appropriate modelling tools in order to obtain accurate estimations of the attractiveness of a project for its potential users.

Several initiatives in the last years have focused in promoting Multimodal transport as a means for achieving a sustainable and efficient transport network (European Transport Commission 2011, Ministry of transport of Colombia and EPYPSA 2013, Geerts and Jourquin 2001, SteadieSeifi et al. 2014). Providing a fast and reliable connection among all the transport modes (maritime, rail, air, road, waterways and ducts) allows to minimize costs and environmental and social impacts; as well as giving greater accessibility and improving the mobility of passengers and cargo. Improving multimodal networks requires acting on both the links and the nodes of the system. Without railways and roads in good conditions a complete multimodal network is unfeasible. However, often, the nodes of the transport system are the actual constraints to the growth of multimodality. For instance, even if the rail transport is expected to be more efficient in terms of cost and environmental impact for medium distance shipments, in countries such as Spain it only reaches a small market share due to inefficiencies at the terminals and other managerial factors.

Nodes are key elements of a transport network since they can greatly increase inventory costs and delays in a supply chain. Hence, modelling methodologies must take into account the delays and costs caused by them. Particularly, when the terminals are highly congested, long delays may occur that reduce the attractiveness of the intermodal alternatives. Any model that intends to represent a multimodal transport network in a reliable way must account for the delays at the terminals.

A transport model is used to predict the traffic flows and the behavior of a transport system under different conditions. The most common approach for evaluating infrastructure projects is to develop an aggregate macro-model, following the classical Four Step Model (Ortúzar and Willumsen 2011). These kind of models use aggregated data, representing the flow of cargo as a continuous variable given by its expected value.

Micro-simulation models are used for detailed evaluation of congestion in road transport, such as crossings or urban networks. They describe the behavior of system's entities and interactions between them (Kumar et al. 2014). For example, considering an intermodal node as a train terminal, an aggregate model would use the average time at the terminal to estimate the total travel time while a micro model would take into account the times of all the operations at the terminal as well as the operational rules.

For evaluating multimodal networks, one of the most critical steps of a transport model is the "mode choice". This component of a model determines the distribution of the flow of cargo from a given origin to a given destination among a set of competing alternative modes (Habibi 2010, García-Menéndez and Feo-Valero 2009). The mode choice step forecasts how many shipments choose each mode so it determines the accuracy of the results (Crespo-Pereira, Rios-Prado, and De Gregorio-Vicente 2014) . Thus, many previous authors have addressed this issue considering how different factors such as the characteristics of the trip maker, the journey and the transport facilities affect the decision.

The most used mathematical models in this step are the logit models, as we can see in the some of the transport models developed in Europe: MODEV model (de Jong et al. 2013), WORLDNET (Sean Newton 2008), NORWAY (Kleven 2011) or SAMGODS (de Jong and Ben-Akiva 2007), among others. This kind of models are based on utility functions of each alternative, it means, how attractive is an alternative for each trip. Kreutzberger (2008) states that the distance and the time, along with the cost, are the main variables that make competitive a transport alternative so they are used as the factors to predict a decision.

Aggregate models deal with this issue in a *static* way, since they estimate the expected modal distribution in stationary conditions. Congestion is dealt with in this way, since the existing methods for traffic assignment with congestion seek to obtain an "equilibrium" solution on which no user obtains a benefit from changing his decision (Matsoukis 1986, Rajagopalan and Yu 2001, Benedek and Rilett 1998). Dynamic effects such as transitory effects and adaptive behavior are not naturally covered by this approach.

Four steps models usually take into account the congestion in the arcs of the system, using speed-flow or cost flow functions. However, for multimodal freight transport this is not usually the main source of delays. For example, for long distance transport the travel times by ship are usually in the order of several weeks while the delays due to road congestion would amount only to a few hours. However, the delays at the maritime ports could be of several days and even weeks due to ship queues for unloading, material handling or delays in customs inspections.

Taking as an example the movement of goods between the south of Europe and China, the road link could have some delays due to congestion of some minutes or hours compared with a travel time of weeks. However, if the port is congested, the vessel can wait days for a berth and that is not a negligible time.

Due to this reasons, including the effects of the congestion at the nodes of a multimodal transport system is one of the ways to improve the model accuracy, mainly with respects to the modal choice problem but also for a reliable estimation of travel times. This paper presents a comparison between a macro and a micro transport model in order to stablish the differences in the results and how these differences may affect the conclusions of a simulation study. A macro model based on the four steps methodology is compared to a discrete events simulation model.

The case study used for the simulation experiment is based on the real case of the "Central Bioceanic Railway Corridor" in South America (Rios Prado et al. 2013, Crespo-Pereira et al. 2014, Rios Prado et al. 2013). The real data from the study is not used due to confidentiality issues, but the scenario analyzed contains a similar but simplified network, similar transport costs and travel times and a realistic distribution of freight.

The section 2 presents an introduction about logit models and the consideration of congestion in nodes. Section 3 describes the macro and micro models. Section 4 contains the experimentation and results and, finally, section 5 presents the conclusions.

2. MODE CHOICE.

Mode choice is the step of a transport model that divides the freight flow among the alternatives in the system. It allows to:

- Assess the competitiveness of transport infrastructure and stablish investment policies.
- Analyze the attractiveness of a multimodal transport service.
- Perform "what if" analysis varying the characteristics of the infrastructure or the transport service.
- Stablish transport policies.

There are two main types of models for modal split: deterministic or probabilistic. Deterministic models assume that the decision of a shipper is completely determined by a set of decision factors such as the time and cost while probabilistic models assume that there always exist a set of *hidden* or circumstantial factors which make each individual choice possibly differ from the optimal choice in terms of cost and time. In general, probabilistic models are preferred for large scale transport systems because they better reflect the diversity of decision criteria among shippers.

Some different methodologies employed for modelling the modal split are logistic regression, Bayesian networks or neural networks.

As it was said previously in the paper, the most popular are the logit models. The main logistical models are Multinomial Logit Model, Binary Logit Model and Nested Logit Model, these discrete choice models are based on random utility theory. Linear regression models are discarded because the assumptions of ordinary least squares are violated (John H. Aldrich; Forrest D. Nelson. 2014).

The bases of the discrete choice model (Ortúzar and Willumsen 2011) are that there is a homogenous population of individuals who know the characteristics of a set of available transport alternatives. Each transport alternative has a net utility for each individual. The utility is then assumed to be the sum of two components, a measurable function of certain factors that affect the transport choice (V_{jp}) and a random component which reflects the idiosyncrasies and particular tastes of each individual as well as measurement and observational errors (ε_{jp}) ($U_{jp} = V_{jp} + \varepsilon_{jp}$).

The Multinomial Logit Model (MNL) is a very popular one in practice due to its simple assumptions and robustness (Domencich and McFadden 1975). It relies on the assumption that the random errors are Gumbel IID distributed, which leads to the well-known equation of a MNL for calculating the share of kth alternative (P_k):

$$P_k = \frac{e^{V_k}}{\sum_j e^{V_j}} \qquad (1)$$

Due to all these reasons, this is the type of model used in the paper for the simulation experiment. The variables of the utility function are the cost and the time of the travel. Congestion at the nodes affect the travel times so it influences the modal distribution accordingly.

Most of the studies that consider delays at the nodes deal with the delays at the ports terminals. There are different modelling approaches to estimate the influence of waiting times. Fan, Wilson, and Dahl (2012) stated that the capacity of the port is assessed in a practical manner by using a model based on queuing theory. Leachman and Jula (2012) developed a model based on queuing theory to obtain the total time for different supply chain strategies. The model calculates changes in the times caused by changes in the flows that use a common channel. The model estimates the value of the waiting time and, iteratively, this new value affects the estimation of the total time when it is calculated again. This new value feeds the ***mode choice*** giving the new modes share. All this process has to be repeated until it converges.

3. CASE STUDY.

To create the macro and the micro models, the network shown in Figure 1 is used. The network has two ports in the extremes and three intermediate points of demand and production of freight. Each trip has two alternatives: only road or multimodal road-train. The distances between each pair of nodes are the same for road and for train, so the modal choice is only affected by differences in price, velocity and delays at the terminals.

The arcs of the system are characterized by a speed (both road and train) and a price *per* kilometer. The units of cargo are assumed to be only containers in order to simplify the model and focus the analysis on the modal choice.

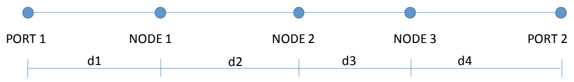


Figure 1: Transport model network.

The values that complete the characterization of the system for the macro model are the capacity of the nodes and the waiting time at these nodes.

As the multimodal alternative considered is train-road the nodes that will be modeled in the micro model are the train terminals. The micro model reflects a simplified but realistic characterization of the processes that take place at the terminals which may cause congestion. The following characteristics are specified:

- Train capacity in containers.
- Entry time of a truck in the terminal.
- Delay at the gates and gates capacity.
- Upload time of a truck. Capacity of the handling equipment.
- Load time of a train. Capacity of the handling equipment.
- Load time of a truck. Capacity of the handling equipment.
- Unload time of a train. Capacity of the handling equipment.
- The number of train platforms.
- The travel times and capacity of the internal transport system.
- Maneuver times at arrival and departure.

3.1. Macro model description

Most of the aggregated transportation models at national or regional levels are based on the Four Steps methodology. This methodology begins with the estimation of productions and consumptions of all the origin and destination nodes of the system; this is the Generation step. These values are used to build the origin-destination matrices (ODM) in the distribution step. This paper is focused on the mode choice step so the ODM are kept fixed. The ODM is the same for both the micro and the macro models. The appendix A shows the data used for this scenario.

The next step of the model is the mode choice. Two options are available: train and truck. The logit model uses utility functions to predict the share between transport alternatives. The logit model was proposed by the researchers (based on realistic values from the experience withdrawn from real projects whose results were confidential). The utility functions used for this simulation experiment were:

$$U_{ij}^{Train} = -0.0476 \times Time_{ij}^{Train} - 0.006493 \times Cost_{ij}^{Train} \qquad (2)$$

$$U_{ij}^{Truck} = -0.0476 \times Time_{ij}^{Truck} - 0.006493 \times Cost_{ij}^{Truck}$$

With this functions the probability of chose each one of the transport alternatives is:

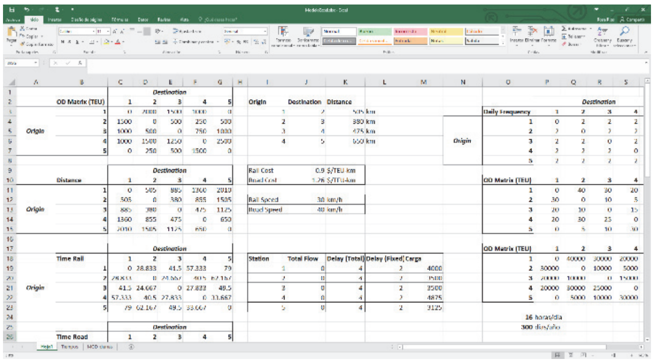
$$P_{ij}^{Train} = \frac{e^{U_{ij}^{Train}}}{e^{U_{ij}^{Train}} + e^{U_{ij}^{Truck}}} = \frac{1}{1+e^{U_{ij}^{Truck} - U_{ij}^{Train}}} \qquad (3)$$

The probability of truck is:

$$P_{ij}^{Truck} = 1 - P_{ij}^{Train} \qquad (4)$$

Three matrices were used to obtain these probabilities. First one is a OD matrix of distances. These distances are the same that in the micro model. Other matrix is the OD matrix of cost. As in the other model a cost by TEU and kilometer is defined, using this cost and the matrix of distances, a OD matrix of costs is build. The travel time between an origin and a destination is obtained using the speed and distance of each travel plus the time at the terminals. The time at the terminals is estimated adding the mean times for each operation.

The model is implemented in an Excel spreadsheet.



		Destination				
	OD Matrix (TEU)	1	2	3	4	5
Origin	1	0	2000	1500	1000	0
	2	1500	0	500	250	500
	3	1000	500	0	750	1000
	4	1000	1500	1250	0	2500
	5	0	250	500	1500	0

		Destination				
	Distance	1	2	3	4	5
Origin	1	0	505	885	1360	2010
	2	505	0	380	855	1505
	3	885	380	0	475	1125
	4	1360	855	475	0	650
	5	2010	1505	1125	650	0

		Destination				
	Time Rail	1	2	3	4	5
Origin	1	0	28.833	41.5	57.333	79
	2	28.833	0	24.667	40.5	62.167
	3	41.5	24.667	0	27.833	49.5
	4	57.333	40.5	27.833	0	33.667
	5	79	62.167	49.5	33.667	0

		Destination				
	Time Road	1	2	3	4	5

Origin	Destination	Distance	
1	2	505	km
2	3	380	km
3	4	475	km
4	5	650	km

Rail Cost	0.9	$/TEU-km
Road Cost	1.26	$/TEU-km
Rail Speed	30	km/h
Road Speed	40	km/h

Station	Total Flow	Delay (Total)	Delay (Fixed)	Carga
1	0	4	2	4000
2	0	4	2	3500
3	0	4	2	3500
4	0	4	2	4875
5	0	4	2	3125

		Destination			
	Daily Frequency	1	2	3	4
Origin	1	0	2	2	2
	2	2	0	2	2
	3	2	2	0	2
	4	2	2	2	0
	5	2	2	2	2

OD Matrix (TEU)	1	2	3	4
1	0	40	30	20
2	30	0	10	5
3	20	10	0	15
4	20	30	25	0
5	0	5	10	30

OD Matrix (TEU)	1	2	3	4
1	0	40000	30000	20000
2	30000	0	10000	5000
3	20000	10000	0	15000
4	20000	30000	25000	0
5	0	5000	10000	30000

16 horas/día
300 días/año

Figure 2: Macro model in Excel Spreadsheet.

3.2. Micro model description

The micro model was developed using the discrete events simulation software ExtendSim. The main elements simulated are the ones shown in Figure 3:

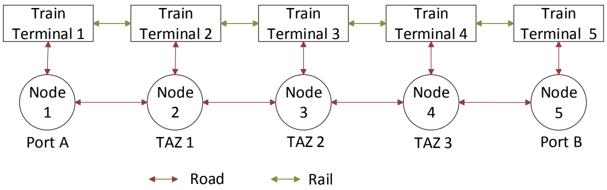


Figure 3: Micro model diagram.

This model represents the transport network of Figure 1. Node 1 and 5 represents the ports of the system, and node 2, 3 and 4 represents the cities that also generate and consume freight.

The transport options considered to move freight between an origin and a destination are road or railroad. The three nodes as well as the ports generate random shipments with a random destination. The "Create" blocks that generate the shipments from each origin to each destination employ an exponential distribution for the time between arrivals (TBA). The mean time between arrivals is calculated from the annual flow defined in the OD matrixes of the macro model.

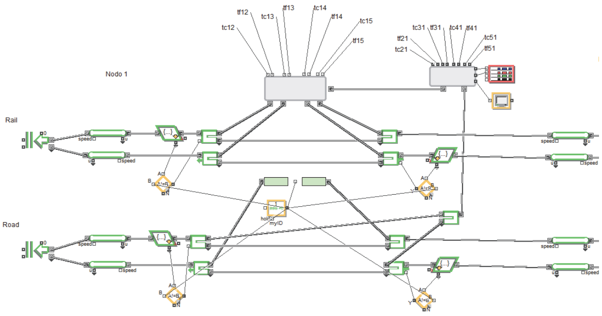


Figure 4: Representation of a node and its transport options in ExtendSim.

Each time a shipment is generated, the first element of the model is a logic decision for selecting which mode to use. The selection is performed using a random model. The probability of each transport mode is calculated according to a Multinomial Logit Model that uses the cost and the time as decision factors. This corresponds to the underlying assumptions of a discrete choice model: each decision maker selects the transport mode depending on a set of measurable factors (cost and time) as well as a set of subjective or hidden factors that cause the observed randomness. The MNL model employed is the same as in the macro model. However, there is a key difference in how the decision is taken. In both models, the modal split is made according to the price difference between modes and the time difference. But the time difference between the modes is calculated differently. In the macro model, the time at the terminal is estimated from the mean times of each operation plus the travel times through the network. In the DES model, the time differences are calculated during the simulation and are affected by the congestion in the system. Thus the DES model takes into account the expected adaptive behavior of shippers who may change their decisions depending on the delays observed through each alternative.

The road transport is defined by the distance, the speed in each link and the cost per kilometer of each container (Twenty-foot equivalent unit, TEU). Trucks are assumed in the model to be readily available so the effect of a possible delay due to truck fleet constraints is not considered.

Five train terminals were modelled. The behavior of the terminal is the following. The trucks arrive to the terminal through a gate where there is a reception process. Then, material handling equipment is used to unload the containers (for instance, it could be assumed that the equipment are reach stackers). The containers are then transported to the yard where they are stored in the first available position. In order to simplify this aspect of the model, detailed operations at the yard are omitted. The yard is represented by a queue and a random load, unload and transport time. When a train arrives, it reserves a platform and the containers which are going to be loaded in the train. Transport orders are sent to the load terminal to move the reserved TEUs to the platform.

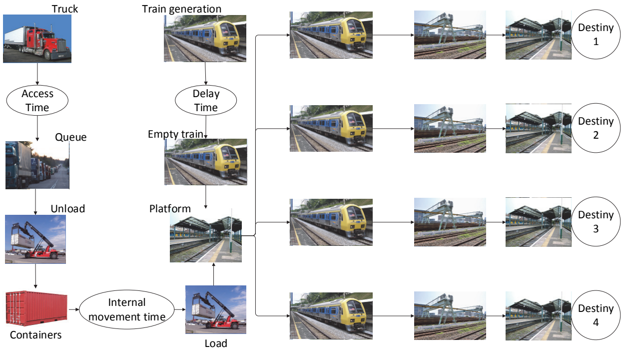


Figure 5: Terminal performance.

Once the TEUs are in the platform, they are loaded in the train, using cranes and internal transports such as reach stackers.

This leads to the establishment of operation times for all the process on the terminal:

- Truck access time (4 mins).
- Truck unload time (3 mins).

- Train arrival and maneuvering time (30 mins).
- Internal movement time and yard storage (15 mins).
- Train load time (5 mins per container).
- Train departure and maneuvering time (30 mins).

All these times were defined for this simulation experiment based on realistic values. Exponential probability distributions were assumed in order to evaluate the performance of the system introducing variability.

4. EXPERIMENTATION AND RESULTS.

Both models were configured with the same data, so differences between the results can only be explained by three reasons:

- In the aggregated model the times at the terminals are assumed fixed while in the micro model the times depend on the congestion level and the delays at the terminal queues.
- In the aggregated model, the effect of the delay caused by the train service frequency is introduced by increase the travel time by the half of the time between train departures. However, in the DES model the travel times for the train are dynamically calculated depending on the train schedule. Thus, if a train departs into 3 hours, the model takes this into account.
- The shipments are generated randomly in the DES model. However, due to the length of the simulation runs, this source of variability is heavily damped so its effect on the results is insignificant. The small confidence intervals of the response variables are proof that the conclusions are not sensitive to this source of variability.

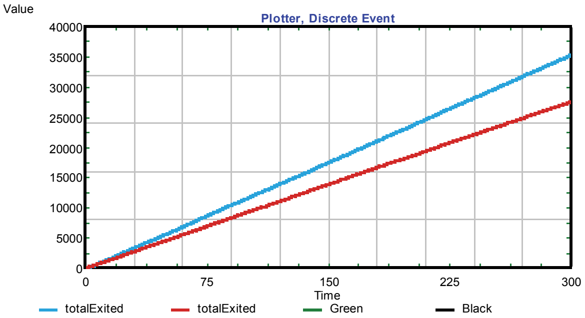


Figure 6: Number of containers arrived by rail (red) and by road (blue) to a node.

Table 1 presents a comparison between both models in terms of percentage of use of the train, for each destination. In general, the election of train is lower in the DES model. This can be explained considering that the DES model reproduces congestion effects in a realistic way.

The differences between the DES and the macro models are significant for all the nodes of the network at the 95% confidence level. The largest differences observed occurred at the nodes 1, 4 and 5.

The Table 2 and Table 3 show the occupation of the maximum train system in both models.

Table 1: Train share percentage.

Node	Train % (5 runs)			
	Macro Model	DES Model	Confidence Interval (95%)	Difference
1	46,98%	42,62%	0,40%	4,36%
2	44,11%	42,84%	0,21%	1,28%
3	42,29%	41,86%	0,14%	0,44%
4	45,39%	39,82%	0,30%	5,57%
5	47,91%	43,67%	0,09%	4,24%

Table 2: Train occupation, macro-model.

		Destination				
		1	**2**	**3**	**4**	**5**
Origin	**1**		75.06%	100%	80.48%	
	2	56.30%		32.72%	18.16%	41.37%
	3	40.49%	32.72%		50.14%	42.37%
	4	44.20%	60.38%	46.62%		66.62%
	5		20.69%	38.41%	57.99%	

Table 3: Train occupation, DES model.

		Destination				
		1	**2**	**3**	**4**	**5**
Origin	**1**		67,46%	95,80%	55,97%	0,00%
	2	48,98%		34,19%	17,69%	34,51%
	3	36,32%	32,62%		49,88%	35,84%
	4	41,00%	57,10%	46,52%		61,89%
	5	0,00%	20,98%	37,20%	53,65%	

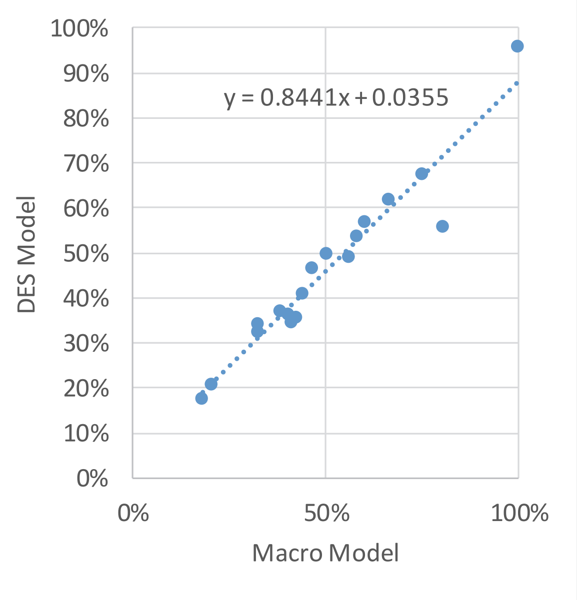


Figure 7: Relation between the train occupation estimated by the macro model and the DES model.

Figure 7 shows a scatter plot of the train occupation values estimated for the macro model and the DES model. Each point of this graphs correspond to one of the Origin-Destination pairs and the values of the X and Y coordinates are the train occupations estimated by the macro and the DES models. The plot shows that the results are consistent between the models in the sense that there is a strong correlation between them.

However, the slope of the regression line is negative, which indicates that as the occupation of a train increases, the DES model forecasts a relatively lower usage of the train.

This result is consistent with the previous observation that the congestion effects estimated by the DES model lead to a lower estimation of the train share.

5. CONCLUSION

A simulation experiment based on a realistic scenario has been shown that compares the estimations of the modal split between road and train given by a conventional aggregated transport model and a discrete events simulation DES model. The simulation results highlight the utility of DES for estimating the modal split when congestion happens at the nodes of the multimodal network. Common practices for assessing infrastructures often omit this congestion effects or consider them in a simplified way by queuing theory methods. However, queuing theory methods provide simple approximations that do not capture the real behavior of a terminal.

The results of this simulation experiment show significant differences between both approaches. The differences correlate with the level of occupation of the transport services and thus indicate that this is a source of error in aggregated models.

The practical consequence of the results is that, although the observed differences are not drastic, a macro model may overestimate the competitiveness of a multimodal transport. Further research is required to evaluate the potential impact of this bias in other type of cases.

APPENDIX A

Table 4: Origin-Destination matrix used in the scenario. The units are TEUs.

		Destination				
		1	**2**	**3**	**4**	**5**
Origin	**1**	0	40,000	30,000	20,000	0
	2	30,000	0	10,000	5,000	10,000
	3	20,000	10,000	0	15,000	20,000
	4	20,000	30,000	25,000	0	50,000
	5	0	5,000	10,000	30,000	0

Table 5: Origin-Destination matrix of distances in kilometers.

		Destination				
		1	**2**	**3**	**4**	**5**
Origin	**1**	0	505	885	1,360	2,010
	2	505	0	380	855	1,505
	3	885	380	0	475	1,125
	4	1,360	855	475	0	650
	5	2,010	1,505	1,125	650	0

Table 6: Unit costs and speed assumptions adopted in the simulation experiment.

Rail Cost	1.08	$/TEU-km
Road Cost	1.26	$/TEU-km
Rail Speed	30	km/h
Road Speed	60	km/h

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