# Towards a Multi-Agent Logistics and Commercial Transport Model: The Transport Service Provider's View.


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## Abstract

It is widely recognized that micro-simulation and agent-based approaches can successfully be applied in transport policy analysis. However, logistic decisions and the complex relationships among freight actors make this a challenging task and a reason why the development of freight models is still behind the development of passenger models. In this paper, we present a multi-agent freight transport model in which logistics decisions are separated into two different roles: Transport service providers, which create transport chains, and carriers, which plan tours and schedule vehicles. Both agent types can consolidate on their respective level and realise economies of scale. The lowest tier of the model, which contains individual freight vehicles, is integrated into the MATSim traffic simulation to create an integrated model for freight and passenger traffic. Changes in passenger demand, disturbances in the traffic system or policy measures can be picked up by freight drivers and propagated upwards to influence decisions on the levels of vehicle scheduling and transport chain building. As proof of concept, we set up a scenario with a fictitious freight operator serving a set of customers. We demonstrate that freight traffic can be simulated under different traffic conditions and policy measures.

# 1 Introduction

It is widely recognized that micro-simulation and agent-based approaches can successfully be applied in transport policy analysis. However, the development of freight micro-models is still behind the development of passenger transport models. Recently, however, several promising freight micro-models have been developed. The achievements can be clustered into two groups of models: The first model category transmutes freight flows into shipments and shipments into truck tours (see, for instance, the models described by Ramstedt, 2008; Wisetjindawat, 2007, 2009; Liedtke, 2008 and De Jong et al., 2007). Furthermore, Roorda et al. (2010) proposed a conceptual framework for agent-based modelling of logistic services. The second model category, the tour-based models, focuses on the execution of complex tours in space. Hunt and Stefan (2007), for instance, set up a tour-based micro-simulation of urban commercial movements. Joubert and Axhausen (2010) developed an activity-based model for commercial transport in Gauteng, South Africa.

Whilst the models based on flow and shipments mostly address regional or national transport planning, the tour-based models are generally used for modelling commercial transport in agglomerations and big cities.

For the moment, however, most freight models focus on certain aspects of the model object. They do not map all relevant logistics decision makers and decisions, respectively. Particularly, important logistics decisions such as shipment size, frequency, warehouse location and vehicle routing are disregarded or considered only implicitly. Therefore, the most important driver of logistics decisions is not covered in a satisfying way: cost reduction through the realisation of economies of scale. Thus, there is still a lack of policy sensitive models in order to assess policy measures such as, for instance, the introduction of 'green logistics schemes'. To build such a model, a strong representation of logistics decisions and activities is required. These activities comprise, for example, 'consolidation', 'distribution', 'pick-up' and 'delivery'. Since these activities require the use of physical transport networks where not only freight operators but also passengers compete for capacity, an integrated multi-agent simulation of both commercial and passenger transport is indispensable.

This paper attempts to fill at least part of the gap towards a policy sensitive model by presenting a computational framework for an integrated multi-agent logistics and commercial transport model. It focuses on the detailed representation of the freight transport service provider. The freight transport service provider is responsible for all activities related to carrying cargo from sender to receiver. We model this operator as a software agent participating in the multi-agent passenger simulation MATSim (see Balmer et al., 2009).

The paper is organised as follows: After these introductory remarks, section 2 sets up the background for our work compiling findings from literature on transport research. Then, we briefly present MATSim, the multi agent passenger simulation. Section 3 deals with our representation of the transport service provider. We model the transport service provider as three distinct agents: The *Transport Service Provider Agent*, the *Carrier Agent* and the *Driver Agent*. In section 4 a scenario is constructed in which a fictitious freight operator serves a set of customers. We demonstrate that freight traffic can be simulated under different traffic conditions and policy measures. A conclusion and an outlook finalise the paper.

# 2 Background

### Literature overview on micro freight models

In literature we basically identify two types of micro freight models: commodity flow based and tour based models. The commodity flow based models are typically used to model commercial transport at an inter-regional level, whereas tour based models are applied to model commercial transport in agglomeration and big cities.

De Jong and Ben-Akiva (2007) develop a logistic module for a commodity flow based model in Norway and Sweden. In a sequence of operations, commodity flows between regions are transformed into vehicle-flows. During this process the model focuses on two major logistic decisions: Frequency and shipment size decision as well as transport chain choice. The first are decisions related to shippers and receivers. The latter is a typical decision of a transport service provider that can be further subdivided into the following sub-decisions: (i) Choice of the number of legs in a transport chain, (ii) choice of the use of distribution/consolidation centres and (iii) mode choice for each leg including (iv) choice of vehicle/vessel type and (v) loading unit. Wisetjindawat et al. (2007) develop a micro simulation for modelling urban freight movements. They extend the traditional four-step approach by including logistic decisions such as shipment size and frequency choice, carrier choice, vehicle type choice and routing. The latter decisions are operational decisions of the carrier.

In recent literature, a number of relatively novel approaches occurred representing individual actors as multiple agents. Some of the advantages are the ability of focusing on certain behaviour explicitly. In agent based models market coordination, learning capabilities, restricted agents' perception of the environment and different decisions relating to different time horizons can be mapped. Liedtke (2009), for example, develops such a model for Germany. He explicitly models the decision of two main agent-types: The shipper and the carrier. Shippers can decide about shipment size and carrier choice. Carriers construct truck tours with a vehicle routing heuristic. Both iteratively interact with each other in a market environment and make experiences from past iterations. Roorda et al. (2010) set up a conceptual framework for agent-based modelling of logistic services. They identify a number of agents, their respective behaviour and important facilities in the freight system. The agents coordinate by means of contracts. The contracts are a result of market interactions. Shipper-Carrier relations are set up by logistic contracts. Given those logistic contracts the carrier conducts a number of logistic decisions to fulfil them. First, the carrier decides about the transportation mode. The possibilities include using only trucks as well as intermodal combinations of truck, rail and marine. Secondly, for each of those transport modes – in the following we name this transport chain – further consolidation decisions are conducted. That is, for each leg in the transport chain, vehicle type choice, vehicle scheduling and route choice is made. Davidsson et al. (2008) design a multi-agent based simulation of transport chains. They identify the transport chain coordinator (TCC), the transport buyer (TB) as well as the transport planner (TP) to be key decision makers on the transport side. The TCC is the interface between product demand, production and transportation choice and matching product suppliers with transport service providers. The TB manages the transport chain and its corresponding legs. The TP is the carrier actually owning a vehicle fleet and conducting the physical movement. Thus, transport chain choice and carrier choice are explicitly modelled.

Wrapping this up, many researchers currently include the transport service provider as an autonomous actor in their commodity-flow based freight-model. Some call it "carrier", some call it "transport service provider". As the literature review shows, there are consolidation processes on different levels. In transport logistics, there is consolidation on the level of the transport chain (distribution or generally in transhipment centres), and on the level of vehicle tours. Or to put in other words, economies of scale can be realised both in logistics facilities and within vehicles. These two levels cannot be seen as independent. The consolidation processes are basically modelled by the following decisions: Transport chain choice, vehicle type choice, vehicle routing and scheduling decisions.

Urban commercial transport differs from long-distance (commercial) freight transport in a number of ways (see Hunt and Stefan (2007)). Firstly, certain transport modes are mostly irrelevant for urban goods movements, e.g. rail and marine. Secondly, urban commercial transport is not solely related to goods movement, but also includes movements of persons and services. And finally, transport in cities only relates to certain sub-systems of the interregional transport and logistics systems.
Micro-modelling of urban commercial transport is mostly done by means of tour-based models. Hunt and Stefan (2007) develop a tour-based micro-simulation of individual vehicle movements. They estimate the number of tours in the study area Calgary and construct these tours with a tour expansion process. In this process, they successively assign tour attributes to each tour, i.e. vehicle type, vehicle purpose and starting time. Given those attributes they iteratively let the tour grow by assigning next stop purpose, next stop location and next stop duration. Iterations end with the last stop being the return trip to where the tour has started. Joubert et al. (2010) apply a tour-based approach to simulate a large-scale scenario of both private and commercial vehicles in Gauteng, South Africa. They define a tour to be a sequence of commercial activities and derive those activities from GPS-logs. Based on that, they use conditional probabilities to construct commercial activity chains in time and space. Taking into account passenger activity chains, these commercial activity chains are then simulated with the multi-agent simulation toolkit MATSim.

A relatively novel approach in urban commercial transport modelling is chosen by Tamagawa et al. (2010). They set up a commercial micro-model as a multi-agent system and thus, they address logistics behaviour explicitly. They model the behaviour of a number of agents, such as freight carriers, shippers and several other stakeholders. Carriers can offer services to shippers and can plan shipments in vehicle tours. Shippers however can choose the carrier that fits best. The model partially addresses commercial transport and can elaborate effects of logistics policies.

However, the majority of urban commercial transport research still uses a level of abstraction where logistics decision makers are not included. Particularly, logistics decisions such as shipment size, frequency, warehouse location, vehicle type choice, vehicle routing and scheduling are disregarded or considered only implicitly. Additionally, most of the commodity flow based models represent vehicle tours in a simplified manner. Tour based models on the other hand neglect commodity flows. We identify the Transport Service Provider to be the interface between the commodity flow based and tour based approaches. However, decisions about commodity flow and tours require different views on the transport system. The commodity flow view contains a hyper-network where links represent means of sending goods from one location to another. The tour view relates to vehicle movements in physical networks. MATSim has become a mature simulation framework simulating passengers as agents in physical networks. Passenger vehicles and freight vehicles use the same road network concurrently. Consequently, MATSim is an ideal framework to cover the representation of freight agents in physical networks.

**MATSim: Passenger Simulation**

The travel demand model implemented in MATSim consists of a set of agents representing individual users of the traffic system. Every agent is equipped with a *plan*, which describes locations, times and types of all the *activities* the agent will conduct, with *legs* connecting each physical activity location to the next. Legs can be travelled using different transport modes and, depending on the transport mode, along different routes through the transport system. A choice for all of these options is encoded in the plan.

All agents simultaneously execute their plans in a concurrent simulation of the transport system. The simulation picks up congestion effects, missed public transit connections, delayed arrivals at activity locations, and other effects of multiple agents concurrently using the traffic system. The result of the simulation is fed back to the agent as experience, and it is used to score the plan using a *utility function*, which can be personalized for each individual, for example by depending on their age or income.

At the beginning of the next *iteration*, some agents obtain a new plan by creating a modified copy of one of their existing plans. This is done by several *modules*, which correspond to the choice dimensions available to the agent. One module chooses a new route, while another switches the transport mode, and yet another chooses new times for activities. This step in the process is called *re-planning*. Agents select one of their plans according to a *random utility model*.

The planning and re-planning model employed here is obviously tailored to passengers. Up to now, real-world scenarios set up with MATSim have modelled the freight traffic share of the demand by using a set of plans with two activities labelled *freight-origin* and *freight-destination*, connected with a single leg, and with no variability in any choice dimension except route choice. Freight traffic has essentially served as a background load of the traffic system, without much adaptive behaviour. One of the aims of this paper is to improve on this situation by modelling freight vehicles as non-autonomous agents employed by and serving the interests of transport service providers, which we add to the model. The missing choice dimensions of freight vehicle drivers are then realised as logistics decisions made by transport service providers.

## 3 Methodology – Agent's View

The Transport Service Provider (TSP) is responsible for transporting cargo from the senders to the recipients. To reduce complexity and to take into account the different roles of the TSP, we decided to model the TSP as two distinct agents: the *Transport Service Provider Agent* and the *Carrier Agent*. For each agent type, we identify the most relevant decision types for the transport model. These decisions lead to actions in time and space. The full set of actions corresponds to the agent's *Plan*. However, the agent's plan is based on *knowledge* about the transport system, *capabilities*, which are static individual attributes of the agent, and *contracts* defining business relationships to other agents. The agents, their decisions, knowledge, contracts and plans are described in the next sections.

**Transport Service Provider Agent (TSP Agent)**

The *contracts* of the TSP Agent are manifestations of business obligations to shippers. The contract determines type and quantity of goods to be shipped, their respective origin and destination, as well as the price the shipper has to pay for the service. A "transport service" or "shipment" constitutes an elemental movement of a good from a sender to its recipient.

Each TSP Agent is attributed with *capabilities*. *Capabilities* are resources and skills. Currently, these are transhipment centres this TSP can use.

Based on his knowledge, the TSP Agent can plan the fulfilment of his contracts. For each shipment, the TSP agent creates a transport chain and chooses a carrier for operating each leg.

A transport chain is the sequence of logistics activities and carriers a shipment takes on the way from the sender to the recipient. In our basic model, the TSP Agent can schedule two types of logistics activities: Pick-Up and Delivery activities. A leg is what happens between a pick-up and a delivery activity. The simplest transport chain is the direct chain from the sender to the receiver. More sophisticated transport chains emerge when a TSP operates with a hub-and-spoke network. A transhipment activity is then represented as a Delivery followed by a Pick-Up at the same location.

Each leg of a transport chain is an elementary movement and shipment. For each of these shipments, the transport services of different carriers can be contracted. For example, for the initial and the last leg, a local road carrier could be chosen, whereas a transnational railway company could operate the main leg. Such a transport chain is called an intermodal transport chain.

To summarise, the TSP Agent is modelled as the organizer of the transport chain. Its plan is still shipment related rather than vehicle related. We view scheduling and routing of vehicles as tasks of a different role, the role of the Carrier Agent.

**Carrier Agent**

Carrier Agents have contracts, which, just like the contracts of TSP Agents, determine type and quantity of goods to be carried. A carrier contract contains the respective origin and destination as well as pick-up and delivery time windows. The contracts describe business relations. For our purposes, the customer party in these contracts will be a TSP Agent, but this part of the model can be generalized so that the carrier agent can be responsible for services and the movement of passenger. In that case, the customer would be a household or an entirely different type of agent.

Carriers obtain contracts from TSP Agents by making offers for their services. A TSP can obtain an offer from a carrier by stating origin, destination and shipment size, and the carrier will respond with a price. The TSP then picks an offer and assigns the contract to its preferred carrier. For simplicity, we decided against implementing a more sophisticated market model where a carrier can turn down a contract. Carriers accept every contract for which they have made an offer (see Tamagawa et al. 2010).

Since the Carrier agent is designed to model a transport operator, its capabilities include the locations of its depots and information about its vehicle stock.

The most relevant decisions of a Carrier Agent are:

- Mode choice (including the choice of different types of vehicles) and
- Vehicle routing and scheduling

The plan of a Carrier Agent thus contains a set of vehicles, each equipped with the schedule of a tour. The schedule contains planned pick-up, delivery or arrival times at customer locations and a route, which is the actual path through the physical network. In our basic model, all vehicle schedules begin and end at a depot.

In the physical layer of MATSim, the basic unit of simulation is a vehicle with its driver. Accordingly, at the interface between the freight operators' mental layer and the MATSim mobility simulation, the set of routed vehicles of each Carrier is injected into the traffic demand as individual *Freight Driver* agents. These agents use their tour schedules in the same way as passenger agents use their activity plan.

We modelled Transport Service Providers and Carriers as different roles (and different agent types) in order to create a framework where the coordination between these roles can be as complex as a full-blown transport service market or as simple as arbitrary assignment. It is still possible to represent the case where the two roles are held by a single entity, simply by having one or more carrier agents deal exclusively with one TSP agent, and giving them complete knowledge about each other. Such a composite agent could be used to model a multi-modal logistics provider, which executes a complete transport chain with its own resources.

## 4 Simulation

A simulation run can be broken down into the following steps:

1.) Initialise the world.
2.) Construct the initial plans of various agents.
3.) Execute the mobility simulation.
4.) Calculate scores.
5.) Let the agents improve their plans.

Steps 3 to 5 are repeated until a relaxed state is reached.

In **Step 1,** we initialise our model environment. This amounts to creating the road network and the population of transport service providers with the locations of their transhipment centres, and of the carriers with the locations of their depots and their vehicle fleets.

In **Step 2,** an initial plan is created for each agent. Transport service providers create transport chains to fulfil their set of shipment contracts. Each leg of every transport chain is contracted to a carrier. The carriers then create a schedule for each of their vehicles, including a complete route through the transport network, with pick-up and delivery activities corresponding to their transport contracts. Transport service providers and carriers can base their decision strategies on initial information about the transport system, taking into account the restrictions imposed by their limited capabilities. Routes, for example, are chosen on the basis of travel times on an empty road network.

These initial freight traffic plans are then injected into the mobility simulation of MATSim, where they are represented as vehicle agents moving through the traffic system along with passenger vehicles. In **Step 3**, all these agents concurrently execute their plans and experience the constraints of the physical network. While executing their plans, the agents report their shipment-related activities back to the carrier.

In **Step 4,** agents evaluate the success of their plan. The MATSim passenger model uses a utility function tailored to evaluate the outcome of a travel plan for a person on a typical workday. In contrast, the freight traffic agents introduced here have to use a custom utility function that captures their economic success. Carriers calculate their cost as a sum of vehicle-dependent distance costs incurred by their scheduled vehicles and some individual fixed costs. The transport service providers calculate their cost as the sum of the fees they pay to carriers, plus opportunity costs incurred by missed time windows.

In **Step 5**, agents create new plans to try to improve their performance in the next iteration. For instance, a time dependent vehicle routing heuristic can be plugged-in to re-plan vehicle schedules. Carriers could choose to only re-plan the routes of their drivers, or they could switch shipments between vehicles, or even add or remove an entire vehicle. This is also the point where carriers update their tariff table. The Transport Service Providers in turn can re-plan the layout of the transport chains and the assignment of commissions to Carriers, after obtaining new offers which the carriers make using their updated pricing scheme. One important issue at this point is how carriers incorporate changes in their set of contracts into their plans. If they use a scheme where the vehicle schedule is computed in one step as a function of the set of contracts constrained by the vehicle fleet, this is not an issue. But if a genetic algorithm approach is taken, where applying small local modifications to a previous plan generates the new plan, a way of adapting the new plan to the possibly changed set of contracts must be provided.

During repeated executions of their plans, passengers as well as Carriers and Transport Service Providers collect experience from the transport system. The carriers pick up congestion and other disturbances in the traffic system when they incur a higher cost through longer vehicle usage, or by penalizing missed pick-up and delivery times. The cost incurred by carriers is incorporated into their pricing scheme and in turn picked up by the transport service providers, who can react by switching their contracts to different carriers or modifying their transport chain.

## 5 Proof of Concept

We implemented the multi-agent model presented here, integrated it with MATSim and set up a scenario for a case study. It is important to mention that at this point, we focus on the functional features of our model environment, rather than sophisticated behavioural models. We demonstrate interactions among freight operators by simulating them under different transport conditions, e.g. after the implementation of policy measures such as a city toll.

### Scenario

Our scenario is a simple 8x8 checkerboard with a spike. The checkerboard represents a simplified urban area. It is an undirected graph where all nodes and links have equal characteristics. Each link has a length of 1 kilometre, a capacity of 1000 vehicle per hour and a design speed of 50 km/h. The spike represents the connection from our city to a distant industrial location. It has a length of 80 kilometres and a design speed of 100 km/h.

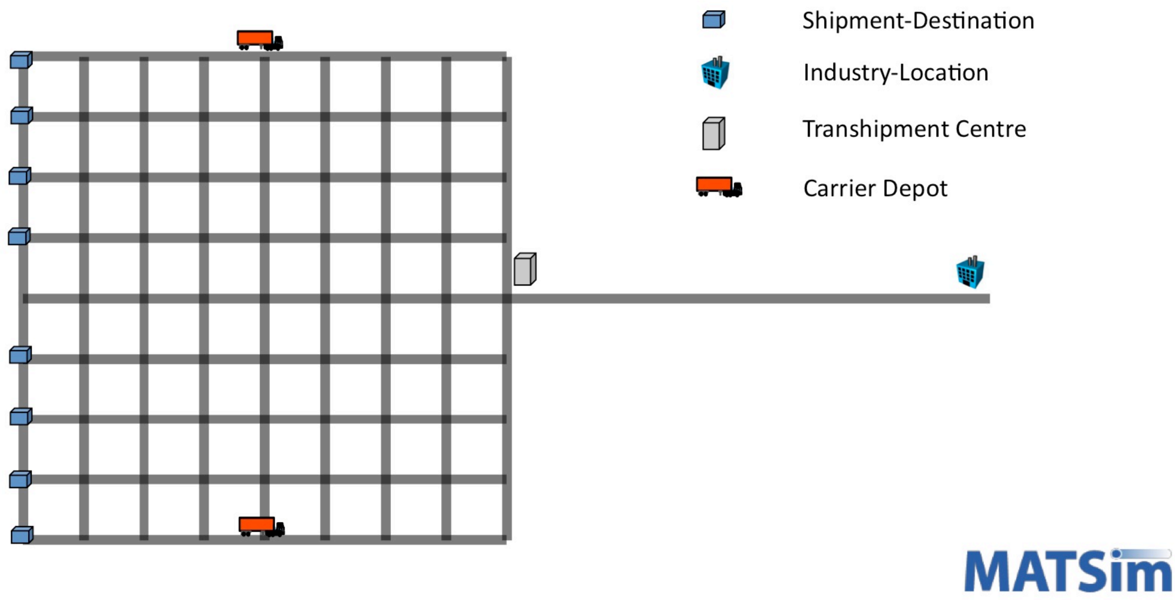


**Figure 1: Scenario**

The freight agents are modelled as follows:

*Transport Service Provider Agent*
We chose to model only one Transport Service Provider. It has contracted eight shipments, each with a size of five units. All shipments originate at the industry location on the right hand side of the spike. The destinations of these shipments are equally distributed along the vertical axis on the left hand side of the urban area (see Figure 1). The logistics network of the TSP agent consists of one transhipment centre that is located where the interurban road (the spike) leaves the city. The TSP agent does not have any obligation to actually use the logistics facility. For now, it is just a capability. Additionally, the TSP agent knows all modelled carriers and thus can request services from all of them.
The behaviour of the TSP agent consists of transport chain choice and carrier choice. With regards to the first choice, it can either carry all shipments on the direct way from the industry location to the destination, or it can carry them all through his logistics facility. Either way, it requests transport offers from all available carriers. The carrier that offers the best price gets the contract.
During the course of the simulation, the TSP agent evaluates both alternative transport chains. It collects information of the performance of each option.

*Carrier Agent*
There are four carriers in our experiment. Two of them are located in the middle of the northern edge of our checkerboard, whereas the other two are located in the middle of the southern edge. Each carrier is equipped with exactly one vehicle (see Table 1). We model three types of vehicles: heavy (40 units), medium (20 units) and light vehicles (10 units).

**Table 1: Carriers**

| Carrier | Location | Vehicle |
|---|---|---|
| Carrier 1 | North | Light |
| Carrier 2 | South | Light |
| Carrier 3 | North | Medium |
| Carrier 4 | South | Heavy |

The behavioural rules of the carriers contain a tour planning behaviour as well as a price setting strategy. Tour planning is modelled using a typical planning heuristic consisting of a tour construction and a tour improvement algorithm. For construction, the well-known Clarke and Wright savings algorithm (Clarke and Wright, 1964) is used. Improvement is conducted by a specific variant of a two-opt algorithm (Laporte et al., 2000).

The price setting behaviour is purely cost oriented, i.e. carriers assume that they cannot influence the market price. If a carrier has no previous experience with a requested shipment, it either chooses a random price (p=0.5) or a forward-looking price (p=0.5). With regard to the forward-looking price, carriers calculate crow-fly distances for the requested service and assume an expected load-factor (which is a random number between 0.2 and 1). If the carrier already has some experience with similar shipments, it takes the price from its personal tariff table with a probability of 0.8. With a probability of 0.2 the offered price randomly deviates from the price in the tariff table. However, the deviation is not higher than fifty percent of the listed tariff.

When scoring its plan, the carrier updates its personal tariff table with the costs of each executed shipment. The cost of each shipment is calculated by allocating the cost per tour proportionally to all shipments in that tour according to the travelled distance and capacity usage.

Table 2 lists the input data for our simulation. For simplicity we assume transport distance to be the main cost driver (see Table 2). Each model run consists of 50 iterations. Since, we assumed a price-setting behaviour with random components, we conducted 10 model runs with different seed-values.

**Table 2: Input data**

| **Cost-Type** | |
|---|---|
| cost per km | 1 [€] |
| cost per transhipment | 5 [€] |
| city toll | 10 [€] |
| | |
| **Simulation** | |
| #Iteration | 50 |
| #Model runs | 10 |

**Cases**

- **Case 1**: Carriers have trivial tour-planning behaviour. They just load their vehicle with one shipment at a time.
- **Case 2**: Tour-planning with Savings algorithm.
- **Case 3**: Tour-planning with Savings algorithm. Heavy vehicles in cities are prohibited.
- **Case 4**: Tour-planning with Savings algorithm. Heavy vehicles in cities are prohibited. City toll for medium vehicles.

**Results**

The relaxed states of all model runs can be found in the annex. In Table 3, we show an excerpt of the simulation results. For each case, we list the best and the second best solution. For each carrier, the total travelled distance is given, and it is shown whether or not the solution makes use of the logistics centre (LC).

**Table 3: Vehicle metres by carrier**

| Cases | Carrier 1 | Carrier 2 | Carrier 3 | Carrier 4 | Total | Use LC |
|---|---|---|---|---|---|---|
| Case 1 | 184.200 | 0 | 366.400 | 903.000 | 1.453.600 | no |
| | 366.400 | 184.200 | 184.200 | 720.800 | 1.455.600 | no |
| Case 2 | 0 | 0 | 0 | 206.200 | 206.200 | no |
| | 0 | 0 | 0 | 206.200 | 206.200 | no |
| Case 3 | 0 | 0 | 62.000 | 180.200 | 242.200 | yes |
| | 0 | 0 | 62.000 | 180.200 | 242.200 | yes |
| Case 4 | 54.000 | 0 | 36.000 | 180.200 | 270.200 | yes |
| | 72.000 | 28.000 | 0 | 180.200 | 280.200 | yes |

In Case 1, almost 1.500 vehicle kilometres are travelled. As mentioned above, carriers just load one shipment at a time. It is surely a quite unrealistic scenario but it serves as an upper cost boundary. All other scenarios can be evaluated in comparison to this case.

In Case 2, we equip each carrier with a more intelligent tour planning behaviour. The best solution in terms of vehicle kilometres travelled is to contract Carrier 4 for all shipments. Carrier 4 then uses his large vehicle capacity for organising a milk run from the industry location to all shipment destinations. In total Carrier 4 travels 206 kilometres. This result is here by far the most efficient solution and thus the lower cost boundary.

In Case 3, we implement a prohibition of heavy vehicles in cities. Here, it implies that Carrier 4 cannot operate in the urban city, thus the efficient milk-run in Case 2 is not feasible anymore. For simplicity, we still allow Carrier 4 to use urban roads to enter and exit the city area. The best solution found here is to use a logistics centre at the entry point to the city. The TSP agent then gives the main leg (from the industry to logistics centre) to Carrier 4. Carrier 4 can then use its consolidation advantages in the long distance. Right from the logistics centre Carrier 3 takes over all shipments. It then organises a milk run from the logistics centre to the shipment destinations. Thus, a two-leg transport chain with the use of a transhipment centre is the most favourable solution for the TSP agent.

In Case 4, we introduce a city toll for medium vehicles. The toll amounts to 10 € per day and vehicle and fall due for payment when entering the urban area. As can be seen, total vehicle kilometres increase by 12 percent and contracts are shifted from Carrier 3 to the carriers with the light vehicles.

# 6 Conclusion and Outlook

In this paper, we presented a multi-agent freight transport model in which logistics decisions are separated into two different roles: Transport service providers, which create transport chains, and carriers, which plan tours and schedule vehicles. Both agent types can consolidate on their respective level and realise economies of scale. The lowest tier of the model, which contains individual freight vehicles, was integrated into the MATSim traffic simulation to create an integrated model for freight and passenger traffic. Changes in passenger demand, disturbances in the traffic system or policy measures can be picked up by freight drivers and propagated upwards to influence decisions on the levels of vehicle scheduling and transport chain building.

The focus of the work has been on identifying the agent types and the information and decisions available to them rather than on behaviour, but the case study demonstrates that the framework can be used with behaviour models of various complexities, from taking one tour per shipment to using sophisticated tour planning algorithms. We think that this multi-tiered framework can serve as a bridge between existing models that specialise on either transport chain building or vehicle routing.

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## Annex

**Table 4: Case 1 – Vehicle metres by carrier without logistics centre**

| Model Run | Carrier 1 | Carrier 2 | Carrier 3 | Carrier 4 | Total |
|---|---|---|---|---|---|
| 1 | 368.400 | 368.400 | 184.200 | 548.600 | 1.469.600 |
| 2 | 184.200 | 0 | 366.400 | 903.000 | 1.453.600 |
| 3 | 184.200 | 184.200 | 368.400 | 722.800 | 1.459.600 |
| 4 | 550.600 | 188.200 | 190.200 | 542.600 | 1.471.600 |
| 5 | 0 | 362.400 | 730.800 | 364.400 | 1.457.600 |
| 6 | 368.400 | 366.400 | 184.200 | 544.600 | 1.463.600 |
| 7 | 184.200 | 544.600 | 364.400 | 366.400 | 1.459.600 |
| 8 | 366.400 | 184.200 | 184.200 | 720.800 | 1.455.600 |
| 9 | 184.200 | 184.200 | 184.200 | 905.000 | 1.457.600 |
| 10 | 0 | 364.400 | 550.600 | 544.600 | 1.459.600 |

**Table 5: Case 2 – Vehicle metres by carrier without logistics centre**

| Model Run | Carrier 1 | Carrier 2 | Carrier 3 | Carrier 4 | Total |
|---|---|---|---|---|---|
| 1 | 0 | 0 | 380.400 | 0 | 380.400 |
| 2 | 0 | 0 | 380.400 | 0 | 380.400 |
| 3 | 0 | 0 | 0 | 206.200 | 206.200 |
| 4 | 0 | 0 | 0 | 206.200 | 206.200 |
| 5 | 0 | 0 | 186.200 | 202.200 | 388.400 |
| 6 | 0 | 0 | 0 | 206.200 | 206.200 |
| 7 | 184.200 | 0 | 378.400 | 0 | 562.600 |
| 8 | 0 | 0 | 380.400 | 0 | 380.400 |
| 9 | 0 | 0 | 0 | 206.200 | 206.200 |
| 10 | 0 | 0 | 0 | 206.200 | 206.200 |

**Table 6: Case 2 – Vehicle metres by carrier with logistics centre**

| Model Run | Carrier 1 | Carrier 2 | Carrier3 | Carrier 4 | Total |
|---|---|---|---|---|---|
| 1 | 0 | 0 | 32.000 | 202.200 | 234.200 |
| 2 | 0 | 26.000 | 0 | 206.200 | 232.200 |
| 3 | 24.000 | 0 | 24.000 | 204.200 | 252.200 |
| 4 | 28.000 | 0 | 0 | 206.200 | 234.200 |
| 5 | 0 | 26.000 | 26.000 | 204.200 | 256.200 |
| 6 | 0 | 30.000 | 0 | 206.200 | 236.200 |
| 7 | 0 | 0 | 24.000 | 206.200 | 230.200 |
| 8 | 0 | 0 | 24.000 | 206.200 | 230.200 |
| 9 | 0 | 0 | 24.000 | 206.200 | 230.200 |
| 10 | 24.000 | 0 | 32.000 | 208.200 | 264.200 |

**Table 7: Case 3 – Vehicle metres by carrier without logistics centre**

| Model Run | Carrier 1 | Carrier 2 | Carrier 3 | Carrier 4 | Total |
|---|---|---|---|---|---|
| 1 | 0 | 0 | 380.400 | 0 | 380.400 |
| 2 | 0 | 0 | 380.400 | 0 | 380.400 |
| 3 | 0 | 0 | 380.400 | 0 | 380.400 |
| 4 | 0 | 0 | 380.400 | 0 | 380.400 |
| 5 | 0 | 0 | 380.400 | 0 | 380.400 |
| 6 | 0 | 0 | 380.400 | 0 | 380.400 |
| 7 | 0 | 0 | 380.400 | 0 | 380.400 |
| 8 | 0 | 0 | 380.400 | 0 | 380.400 |

| | | | | | |
|---|---|---|---|---|---|
| 9 | 0 | 0 | 380.400 | 0 | 380.400 |
| 10 | 0 | 0 | 380.400 | 0 | 380.400 |

**Table 8: Case 3 – Vehicle metres by carrier with logistics centre**

| Model Run | Carrier 1 | Carrier 2 | Carrier 3 | Carrier 4 | Total |
|---|---|---|---|---|---|
| 1 | 0 | 0 | 62.000 | 180.200 | 242.200 |
| 2 | 26.000 | 28.000 | 56.000 | 180.200 | 290.200 |
| 3 | 0 | 34.000 | 56.000 | 180.200 | 270.200 |
| 4 | 0 | 26.000 | 58.000 | 180.200 | 264.200 |
| 5 | 32.000 | 0 | 58.000 | 180.200 | 270.200 |
| 6 | 24.000 | 28.000 | 54.000 | 180.200 | 286.200 |
| 7 | 0 | 28.000 | 54.000 | 180.200 | 262.200 |
| 8 | 32.000 | 0 | 58.000 | 180.200 | 270.200 |
| 9 | 34.000 | 26.000 | 54.000 | 180.200 | 294.200 |
| 10 | 24.000 | 26.000 | 58.000 | 180.200 | 288.200 |

**Table 9: Case 4 – Vehicle metres by carrier without logistics centre**

| Model Run | Carrier 1 | Carrier 2 | Carrier 3 | Carrier 4 | Total |
|---|---|---|---|---|---|
| 1 | 0 | 0 | 380.400 | 0 | 380.400 |
| 2 | 0 | 0 | 380.400 | 0 | 380.400 |
| 3 | 552.600 | 186.200 | 0 | 0 | 738.800 |
| 4 | 0 | 0 | 380.400 | 0 | 380.400 |
| 5 | 186.200 | 0 | 376.400 | 0 | 562.600 |
| 6 | 0 | 0 | 380.400 | 0 | 380.400 |
| 7 | 0 | 0 | 380.400 | 0 | 380.400 |
| 8 | 0 | 0 | 380.400 | 0 | 380.400 |
| 9 | 0 | 0 | 380.400 | 0 | 380.400 |
| 10 | 0 | 0 | 380.400 | 0 | 380.400 |

**Table 10: Case 4 – Vehicle metres by carrier with logistics centre**

| Model Run | Carrier 1 | Carrier 2 | Carrier 3 | Carrier 4 | Total |
|---|---|---|---|---|---|
| 1 | 50.000 | 58.000 | 0 | 180.200 | 288.200 |
| 2 | 76.000 | 28.000 | 0 | 180.200 | 284.200 |
| 3 | 0 | 48.000 | 54.000 | 180.200 | 282.200 |
| 4 | 72.000 | 28.000 | 0 | 180.200 | 280.200 |
| 5 | 54.000 | 0 | 36.000 | 180.200 | 270.200 |
| 6 | 56.000 | 48.000 | 24.000 | 180.200 | 308.200 |
| 7 | 44.000 | 76.000 | 0 | 180.200 | 300.200 |
| 8 | 30.000 | 76.000 | 0 | 180.200 | 286.200 |
| 9 | 0 | 0 | 386.400 | 0 | 386.400 |
| 10 | 96.000 | 26.000 | 0 | 180.200 | 302.200 |