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Application of an empirical multi-agent model for urban goods transport to analyze impacts of zero emission zones in The Netherlands

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A R T I C L E I N F O

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A B S T R A C T

Reducing emissions caused by urban freight transportation is an increasingly important policy objective for transportation planners around the world. New and innovative ways of data collection provide new possibilities to analyze these issues. In this paper we present MASS-GT, a new multi-agent simulation system for urban goods transport. The empirical basis is provided by an exceptionally large dataset of truck trip travel diaries for The Netherlands that was collected from transportation management systems using an automated data collection interface. The dataset is very dense and includes information on vehicles, routes, and shipments carried.

The strategic part of the model simulates the formation of individual shipments based on logistic processes at a strategic level, such as sourcing, distribution channel choice and shipment size choice. At tactical level disaggregate choices are simulated for tour formation, vehicle type- and time of day choice, based on observed distributions. The multi-agent approach allows to implement heterogeneous preferences and thus differentiated responses to new policies.

We present an application of the model to study the impacts of urban consolidation centers (UCC) and zero emission zones. The freight transportation volumes transported to these UCC and their impact on logistic indicators are analyzed. Simulation results show that vehicle kilometers travelled within the wider region increase with the introduction of UCC, and at the same time the efficiency of deliveries increases as well. Thus the model allows to study trade-offs between regional and local systems that emerge from different behavioural responses to policies.

1. Introduction

Reducing emissions caused by urban freight transportation is an increasingly important policy objective for transportation planners around the world. For instance, in The Netherlands, large cities are participating in a collective effort called the Green Deal Zero Emission City Logistics (GDZES), in which they strive for zero emissions in city logistics (Connekt, 2018). However, to develop urban freight transportation policies there is a lack of strategic approaches to design and review the expected impacts of measures, as a result of a lack of resources (Akgun et al. (2019). At the same time supply chains and transportation logistics are becoming more complex, making it more difficult to understand responses to urban freight transportation policies and the impacts on urban freight transport.

Multi-agent urban freight models have the potential to simulate the impacts on logistic decision making and the heterogeneity behind freight transportation demand: they simulate urban freight distribution patterns and identify the relevant agents for urban freight transportation (Nuzzolo et al., 2018), and in this way these models are more suitable to account for the heterogeneity in logistic decision making (Gatta and Marcucci, 2014).

Literature provides multiple examples of relevant disaggregate freight transportation demand models that simulate the logistic choices of micro agents, such as Anand (2015), Alho et al. (2017), Davidsson et al. (2005), de Jong and Ben-Akiva (2007), Liedtke (2009), Roorda et al. (2010), Tavasszy (2006), Wisetjindawat et al. (2007). However, for different reasons these models have not been applied for urban freight policy studies: models are still conceptual (and not empirical), or applied to a single freight segment, or developed for interregional freight transportation demand. These approaches either miss sufficient detail to simulate agent behavior in an urban context, or lack empirical data to be used for urban freight transportation policies: empirical agent

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based simulation models still need to be fully developed (Nuzzolo et al., 2018). Since most of the operational logistic choices take place at the level of shipments, it is preferred to apply a shipment based approach such as Wisetjindawat et al. (2007), Liedtke (2009), Samimi et al. (2009), Roorda et al. (2010), Holguín-Veras et al. (2013), Alho et al. (2017), (Mommens et al., 2017), instead of a trip based approach such as Hunt and Stefan (2007).

The stakeholders behind urban freight transportation are very diverse and have very heterogenous preferences (Marcucci et al., 2017). Based on review of empirical and descriptive freight transportation demand models two important conclusions were drawn from the perspective of supply chain management (Tavasszy et al., 2019): decisions are taken by different agents operating at different functional areas, and choices that are up- or downstream of the supply chain are interdependent.

One of the most important challenges in developing multi-agent simulation models for urban freight transportation demand is the collection of disaggregate data (Samimi et al., 2009). Data collection is time and cost intensive, but innovations and new ways of data collection are providing efficient ways to get access to disaggregate freight transportation data.

In this contribution we use an extensive database with collected freight transportation data in The Netherlands to develop an empirical logistic simulation model for urban freight transportation. In our approach we combine three features: it is multi-agent, empirical and shipment based. We develop a multi-agent approach to explicitly address all stakeholders and the heterogeneity of all agents. Second, we use an extensive dense dataset on freight transport, to simulate representative freight transportation patterns and calibrate logistical choice models. We simulate shipments as this is a more realistic level at which decision making takes place. In this article we discuss the application of our approach in an explorative case-study on the introduction of a zero-emission zone in Rotterdam and the impact on tactical logistic decisions, and resulting logistic indicators such as load per tour or vehicle kilometers travelled (VKT).

First, the conceptual model and incremental development path is described. Next the data that is used is described. Next we discuss the current version of our model: we explain the model structure and present aggregate validation results. The possibilities and limitations of the presented approach are illustrated in a case study on urban consolidation centers and a zero emission zone in the city of Rotterdam.

2. multi agent model for freight transportation

2.1. Conceptual model

The objective of the Multi-Agent Simulation System for Goods Transport (MASS-GT), is to develop a multi-agent model for urban freight transport. To conceptualize such a model for urban goods transportation we first define the urban markets, the relevant agents, and logistical choices that are relevant for the urban goods context.

Agent based models for freight transportation explicitly distinguish different types of decision makers (agents) that make logistic decisions one or more of the freight transportation markets (Marcucci et al., 2017): producers and shippers who supply the goods, receivers, who are the consumers of the goods, and freight carriers or third party logistic service providers (3 PLs) that take care of the transportation of the goods. Different freight ttransportation markets can be distinguished, such as the commodity and freight market (Cavalcante and Roorda, 2013), or the commodity, transportation services, traffic services, and infrastructure markets (Boerkamps et al., 2000). At commodity markets sourcing decisions take place: firms decide from which producer to buy products for their own production process (consumption). At the transportation market, the physical transportation of goods is organized. The logistical decisions on this market include mode and vehicle choice, tour formation, scheduling and route choice. At the logistic services market, distribution channel choice and the sourcing of transportation takes place. Finally, infrastructure networks are represented at the supply side of the transportation market. These networks are developed and managed by public authorities. Therefore policy makers or urban planners are a separate category of agents. Their behavior is not predicted in the model, but the model is used to do 'what-if' scenario studies on alternative policy strategies. Policy measures or other relevant developments are scenario input and set the conditions for freight transport. Examples of such measures include infrastructure planning (investment in infrastructure or logistical network), environmental zones, pricing measures, subsidies, land-use planning.

To conceptualize a multi-agent simulation framework we have to distinguish at least the producer and consumers of the goods: the firm population. Some shipments are transported directly from producer to consumer but many goods are transported via distribution channels with one or more logistical nodes. Therefore logistic nodes are included to represent transportation flows that are part of a multi-tier distribution channel. Fig. 1 illustrates how the goods are transported as shipments between producer and consumer, and where which logistical choices are made. It illustrates strategic choices, such as distribution channel choice, shipment size, and tactical choices such as vehicle type and tour formation.

3. Development strategy: MASS-GT version 2

To manage the complexity of the presented conceptual model, the MASS-GT model is being developed following an incremental development strategy. The first prototype started from a simple but functional baseline simulation model, see de Bok and Tavasszy (2018), which explicitly represented the agents (firms) and simulated freight transportation patterns. These patterns were not simulated with logistic choice models but with Monte Carlo simulation and observed market shares and characteristics of the freight and transportation market. One of the advantages of the step-wise approach, is that each intermediate prototypes can already be used to explore policy scenarios, such as a zero emission case study presented in this article. A second advantage of the step-wise approach is that the experience from earlier prototypes helps in managing complexity and optimizing the design of the agent-based framework.

In this article we present the second prototype of the simulation model. This second version of the MASS-GT is based on the conceptual model presented in Fig. 1: the multi-agent simulation framework explicitly represents producers and consumers of the goods, and distribution channels for goods transports that are transported through logistic nodes. It includes a discrete choice model for tour formation, and distribution channels and logistic nodes are explicitly represented. Table 1 gives an overview of the methodologies applied in the second version of MASS-GT. These will be further explained in the empirical section of this article.

4. Data

An empirical model should reproduce observed trip patterns, preferably at the level of individual agents, which requires disaggregate freight data. These data, however, are scarce because they are difficult and costly to obtain (Samimi et al., 2009). The appropriate data to build empirical freight models are either commodity flow surveys (shipper- or establishment based), carrier activity surveys, or truck trip travel diaries (Southworth, 2003). The empirical basis for this is provided by an exceptionally large dataset of truck trip travel diaries for The Netherlands, collected by Statistics Netherlands (CBS) using an innovative automated procedure to collect the truck trip diary data. The database includes information on the vehicle, the route, and shipments that were carried, and has a high data density. First of all, the survey is mandatory: carriers are obliged to report truck trip travel diaries for the trucks in their fleet that were included in the sample of CBS. On top of

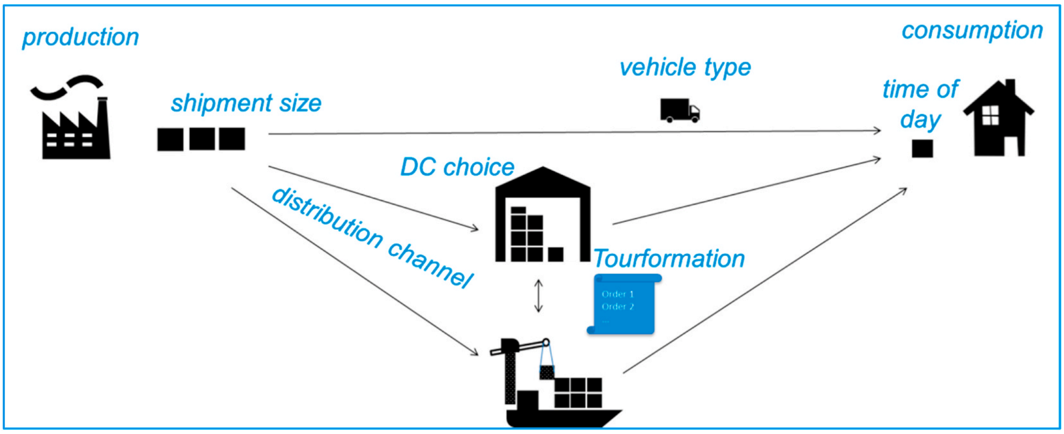

Fig. 1. Conceptual model for logistic choices in MASS-GT.

Table 1
Overview of methodology in prototype (version 2).

	Logistic decision	Modeling method in MASS-GT v2
Strategic choices	Commodity supplier choice	Simulation, based on make/use statistics
	Transportation supplier choice	Not represented
	Distribution channel	Simulation, based on observed market shares
	Frequency/shipment size	Simulation, based on observed market shares
Tactical choices	Vehicle type choice	Simulation, based on observed market shares
	Tour formation	Choice model (constraints and utility based)
	Time-of-day	Not represented
Operational choices	Route choice	Static network assignment (external model)

that, the data was collected using an automated XML-interface with the transportation management systems that reduces the administrative burden for carriers to complete the survey.

As a result, the database that was available in this study contains millions of truck trips of raw data. After cleaning the raw data from obsolete or inaccurate registrations and selecting only the trips related to the study area, we have a database of over 200 thousand observed truck trips for empirical analysis. This database offers a rich source for the calibration of logistic choice behavior. In addition to the transportation database we use data on the firm population from the CBS.

The study area of the second version of MASS-GT is the province of South-Holland (Fig. 2). This area is the most highly urbanized region in The Netherlands and has a population of 3.3 million, and 1.8 million jobs. Furthermore, it also contains the most important seaport in Western Europe, the Port of Rotterdam, which has the main industrial regions in Germany in its hinterland. As a result it is a highly relevant study area to analyze impacts of new policies for freight transportation.

The scope of the presented approach is urban freight transport. Interregional, and in particular intermodal freight flows are an important part of the freight transportation patterns in the study area. Therefore, we consider logistical nodes as generators of freight transportation demand. Logistical nodes are multimodal transshipment terminals and distribution centers as explained in the conceptual models. From the freight transportation data, we can derive the demand shares of freight trips originating and arriving at these nodes. The locations of logistic nodes were derived by combining the firm population data with the transportation data. Distribution centers and transshipment terminals were identified if these locations have registered logistic service providers, and a substantial number of arriving or departing trips. Fig. 2 also shows the location of main logistical nodes.

5. Model description MASS-GT version 2

5.1. Introduction

The prototype simulates all urban freight transportation taking place to/from and within the study area, for ten goods types. Since the logistic decisions presented in Table 1 take place at different scale levels, MASS-GT applies a similar layered structure as the SimMobility Freight model (Alho et al., 2017). The second prototype of MASS-GT consists of three modules: a shipment synthesizer, a tour formation model and a network model. First, the shipment synthesizer simulates logistic processes at the strategic level, such as sourcing, distribution channel choice and shipment size choice. The tour formation module simulates tactical choices and simulates the allocation of shipments to tours and vehicles. Finally, the simulated freight tour patterns, are assigned to the urban network to visualize vehicle type or goods type specific truck flow patterns and to derive network performance indicators. The structure of each module will be explained first.

5.2. Shipment synthesizer

The shipment synthesizer simulates the strategic processes behind freight transportation demand, such as distribution channels, sourcing and shipment size decisions. The result is a set of all shipments to and from sender and receivers and/or logistic nodes in the study area. Many multi-agent models calculate freight transportation demand from firm level regression models for freight trip production- and attraction in a bottom-up approach (Wisetjindawat et al., 2007; Abed et al., 2015; Transportation Research Board, 2012). MASS-GT follows a top-down approach from aggregate to disaggregate flows, such as used in the ADA-model (de Jong and Ben-Akiva, 2007), SimMobility Freight (Alho et al., 2017). Starting point is an aggregate freight transportation demand matrix, that is first split into different types of distribution channels, then discretized into shipments and finally allocated to the senders and receivers of these shipments, or to logistic nodes. Where freight demand at firm level, is poorly explained by bottom-up regression models, in our top-down approach we reproduce representative shipments, and are consistent with aggregate freight transportation demand. The synthesizer procedure has an aggregate phase at regional level (NUTS 3 regions), and a disaggregate phase where individual shipments are synthesized and allocated to loading and unloading locations. The flowchart in Fig. 3 describes the procedure.

The aggregate commodity flows matrix covers all freight transportation demand between the regions inside and outside of the study area. The matrix is at the level of NUTS 3, at which most open

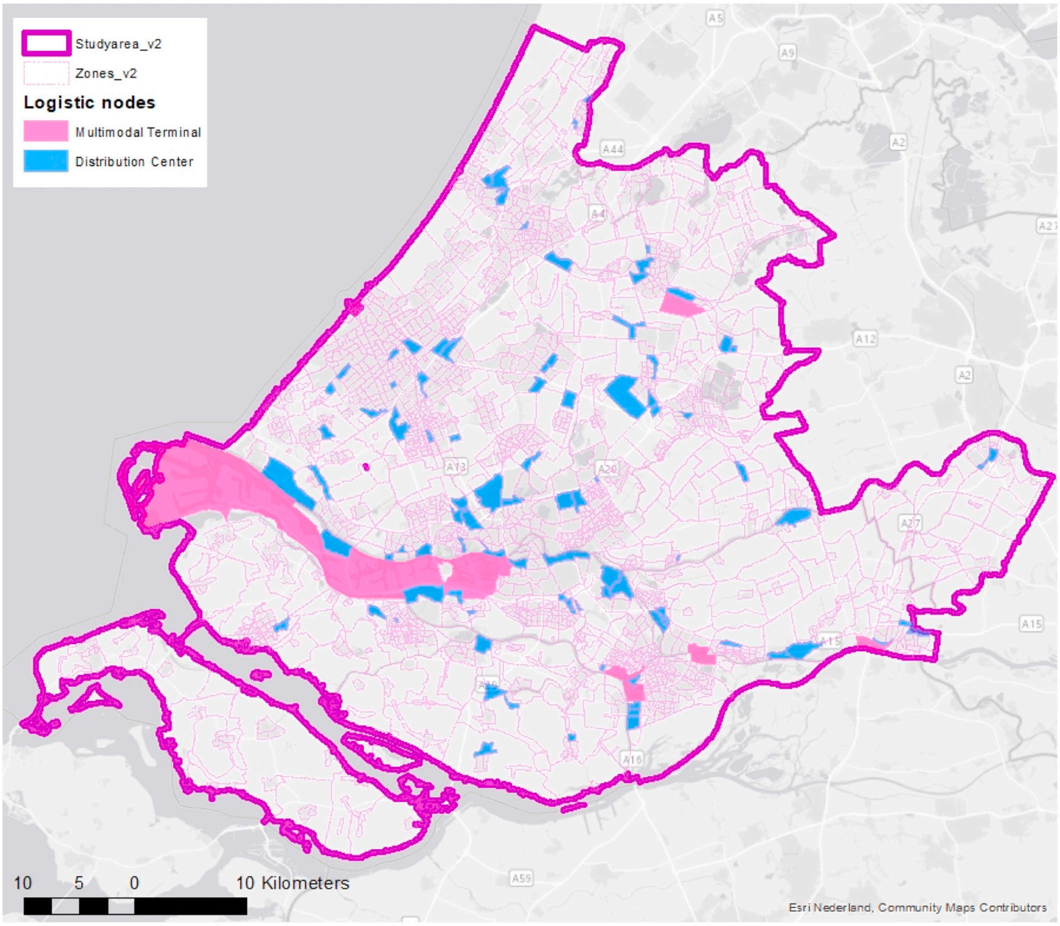

Fig. 2. Study area: the province of South Holland in The Netherlands.

transportation data in Europe is available, and European models deliver outputs for. The first step is to split the commodity flow matrix into different logistic flow types for transports taking place between producer, consumer and logistic nodes; there are 9 possible flow types between producer, consumer and logistic nodes. This step uses observed market shares for each type flow type that was derived from the available truck trip diary data.

Next, the aggregate transportation flows are disaggregated into individual shipments using Monte Carlo Simulation to replicate observed shipment size distribution. Since shipment sizes are very heterogeneous, the shipment size distribution is not only specific for the type of goods, but also for the type of transportation flow. From the observations we measure that average shipment sizes from a transhipment terminal are different compared to the shipment size from a distribution center to a final consumer. The shipment size is drawn from an observed standard distribution, which is derived from the data for each goods type and type of transportation flow:

$$f(x|\mu,\sigma^2) \tag{1}$$

Next each shipment is allocated to an origin: if this is a producer, the allocation is based on the firm's industry type, size and location. Make/use tables describe the market share of the production either consumption of each industry sector for any commodity type. These market shares are used to calculate the 'make probability' of each goods type *gt* and industry sector *s*, $p^{make}_{s;gt}$. This make probability is used to calculate the probability of firm *f*, belonging to sector *s*, being the **sender** of a shipment. In addition, each firm is weighed by its firm size (number of employees): bigger firms have higher probabilities of having produced the shipment. The sender probability for firm *f*, located in the origin region, for a shipment with goods type *gt*, is expressed as:

$$P^{sender}_{f;gt} = \frac{E_{f;s} * P^{make}_{s;gt}}{\sum_{i \in orig}\left[E_{i;s} * P^{make}_{s;gt}\right]} \tag{2}$$

If the shipment starts from a transshipment terminal or a distribution center, the size of each logistic node is used to calculate the sender probability.

In the following step the destination of the shipment is determined: if this is a consumer, the allocation is now based on the 'use' probability of goods type *gt* by industry sector *s*,$\mathrm{P}^{\mathrm{use}}_{\mathrm{s;gt}}$. Again the firm size is accounted for to increase the probability that a shipment is received by a larger firm. The receiver probability for firm *f*, located in the destination region, for a shipment with goods type *gt*, is expressed as:

$$P^{receiv}_{f;gt} = \frac{E_{f;s} * P^{use}_{s;gt}}{\sum_{i \in dest}\left[E_{i;s} * P^{use}_{s;gt}\right]} \tag{3}$$

If the shipment is delivered to a transshipment terminal or a distribution center, the size of each logistic node is used to calculate the receiver probability.

The result is a dataset with individual shipments between firms and/or logistic nodes, containing the goods type and gross weight of shipments, and the attributes of sending and receiving firms.

5.3. Tour formation

The second module simulates tactical processes, such as vehicle type selection, tour formation and time-of day. The module includes the first operational choice model for tour formation. This model simulates the

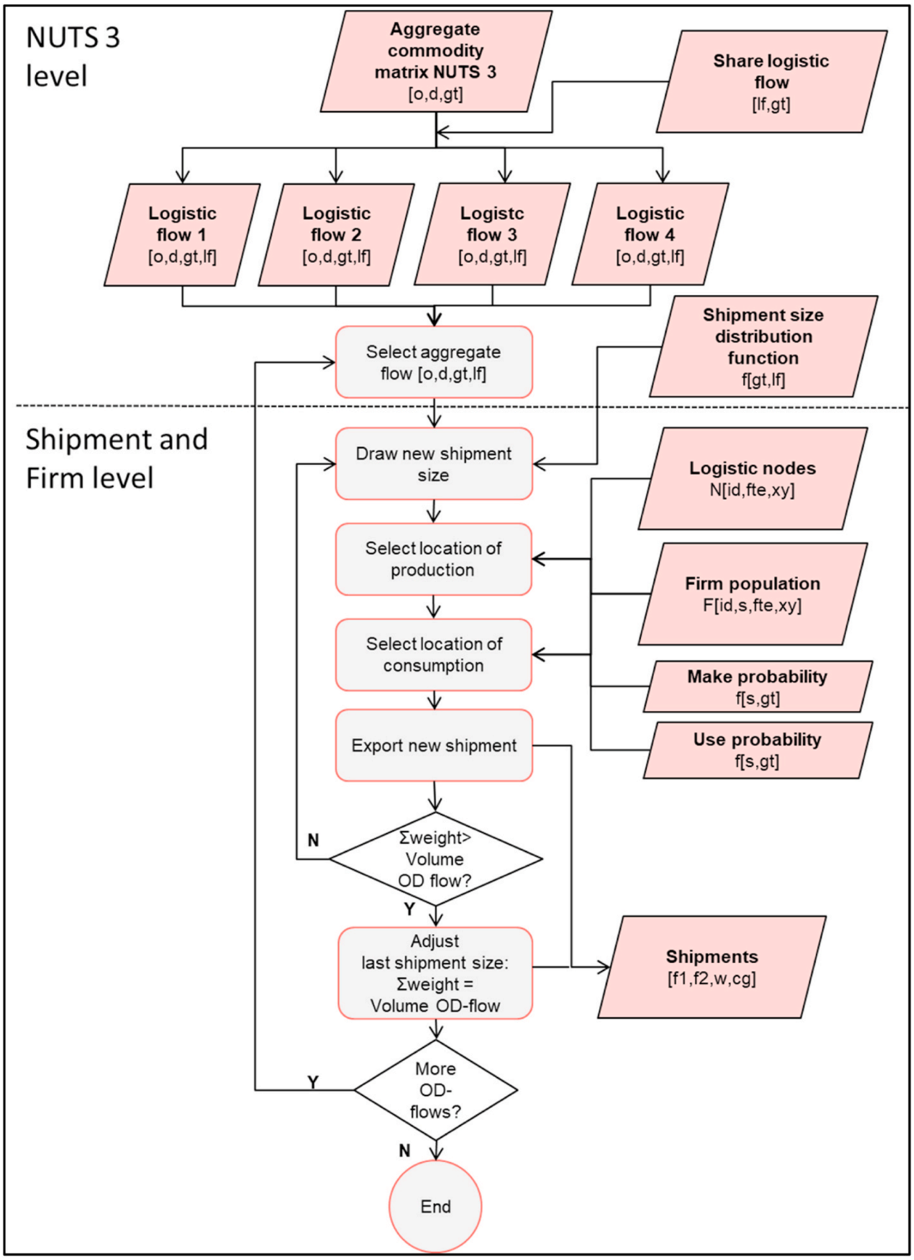

Fig. 3. Shipment synthesizer procedures in MASS-GT version 2.

formation of round tours from the synthetic shipments, based on behavioral choices and conditions. The tour formation model is shipment based and applies an estimated incremental logit model. The formation of round tours is an important aspect in urban freight transport, and many empirical examples of tour formation models exist in literature. Most the models are trip-based, such as Hunt and Stefan (2007), Kim and Park (2017) or Wang and Holguín-Veras, 2008. More behavioral models are shipment-based (Nuzzolo et al., 2012; Outwater et al., 2013). Because of this higher behavioral validity, and the possibilities with the available data, we estimated a shipment-based tour formation model. Vehicle type and time-of day are not yet simulated with a logistic choice model but simulated from observed market shares by goods type and monte-carlo simulation.

For a detailed specification, estimation and validation of the tour formation model see Thoen et al. (2020). The structure of the tour formation model will be described here shortly. The model comprises of two discrete choice models: first the decision to add a shipment to the tour, and second, to choose the shipment to add to the tour. The tour formation model is estimated on observed tour patterns. It considers several objectives and constraints that differentiate the tour formation process for different goods type, vehicle type, and type of (un)loading locations. Constraints that are taken into account include vehicle capacity, tour duration (i.e. maximum work shift), and availability of shipments that can be consolidated. The utility function includes attributes for transportation costs, goods types, vehicle type and location type.

For example, shipments to and from multimodal terminals (e.g. ports) are observed to be transported in direct tours, while tours starting at a distribution center tend to have more stops, which the model is able to capture. Such logistic choice models enable to simulate the impact of changes in distribution channels on tactical choices in tour formation. We will analyze this in the case study with urban consolidation centers.

5.4. Network assignment

The last level in the framework is the network level, where we simulate route choices on congested networks. The simulated tour patterns are translated into vehicle trip matrices and assigned to a congested network, using a simple all-or-nothing assignment to determine the shortest path in generalized transportation costs using congested travel times. The freight traffic assignment results are stored by vehicle type and commodity type, to allow the derivation of network indicators for specific freight segments.

5.5. Output

The model produces output at different levels. Fig. 4 visualizes the generated shipments: at the top left a selection of shipments transported between distribution centers. At the top right we made a comparison between the predicted weight of all simulated shipments to the total observed freight volume from available data. For this purpose we used the Basisbestand Goederenvervoer from the CBS that is available at more aggregate level: Transportation Analysis Zones (TAZ) of the Dutch Freight Transport Model. As output we also visualize the simulated round tours for one carrier (bottom-left) and results from the network assignment of the freight trips (bottom-right).

From the comparison in the scatterplot we conclude that the second version of the model predicts the zones generating most of the freight transportation demand effectively. The terminals in the port of Rotterdam typical generate large traffic volumes, and this pattern seems to be well predicted. This is mainly explained by the segmentation of the total transportation volumes to distribution channels. As discussed in the previous section, the model is developed following an incremental development strategy. In next increments the validity will be further improved by implementing new empirical models. A first step will be the implementation of vehicle and shipments size choice model (Mohammed et al., 2019). Another possible improvement will be to include firm level freight demand regression models, as a predictor for sender and receiver probabilities. An overview of effective methodologies is provided in Transportation Research Board (2012).

6. Case study: impacts of a zero emission zone

6.1. Background

To explore the possibilities of the model we applied it in a case study of a zero-emission zone with urban consolidation centers in Rotterdam. Zero-emission zones (ZEZ) are currently considered by many large cities

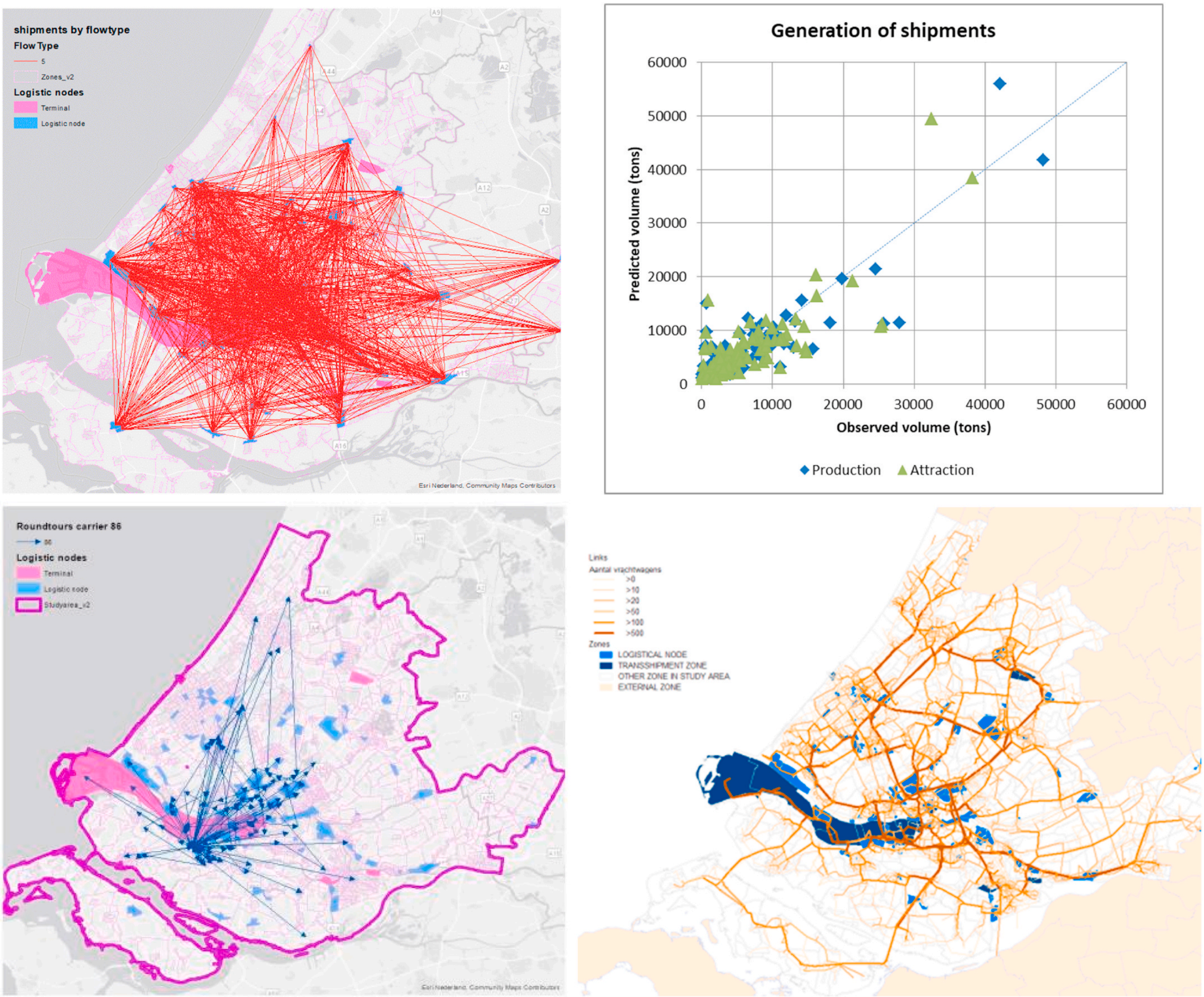

Fig. 4. Simulated shipments between distribution centers (top-left); comparison of total weight predicted and observed at level of Transportation Analysis Zones (top-right); simulated round tours for one carrier (bottom-left) and results from the network assignment of the freight trips (bottom-right).

in The Netherlands to reduce emissions by city logistics within the city borders (Connekt, 2018). In our case study we assume that the implementation of a zero emission zone is to be combined with urban consolidation centers (UCCs) from which the shipments in the ZEZ will be distributed or collected. van Duin et al. (2012) discuss a feasibility study for analyzing urban distribution centers. They confirm the observation that existing modeling approaches are not able to predict impacts of urban distribution centers well. They propose a multi-agent approach to effectively analyze impacts of UCCs. An advantage of simulation models is the possibility to analyze a combination of potentially supportive policies, such as toll, road pricing, time windows, zero emission zones (Duin et al., 2012). In this article we want to illustrate how such empirical models can be used for policy analysis by analyzing the impacts using the presented empirical model. First we discuss the assumptions in the case study.

Urban consolidation centers exist in different formats and many definitions exist (Browne et al., 2005). We reformulate the general definition in Browne et al. (2005) to our specific case study as: a UCC is best described as a logistics facility that is situated in relatively close proximity to the zero-emission zone, from which consolidated deliveries are carried out within that area. The use of UCC effectively means adding a stage to existing supply chains (Marcucci and Danielis, 2008).

In our explorative analysis we implement a rigorous scenario: the zero-emission zone imposes all shipments in the ZEZ to be distributed or collected through the urban consolidation center. Only ZE-vehicles are allowed in the city center and we consider ZE-vehicles to have a marginal share in the existing fleet. The transportation takes place using ZE-vehicles operated by the UCC. We assume the shippers are compensated for the cost difference so we do not consider impacts on storage decisions or firm relocation.

Fig. 5 shows the zero-emission zone (ZEZ), that more or less follows the boundaries of the existing low emission zone in Rotterdam. Over 5 thousand shipments are distributed within the zone (pick-up or delivery).

6.2. Results

Table 2 presents the simulation results for a reference case, and a run with the Zero Emission scenario for Rotterdam. Given the scope of this version of the MASS-GT model we can analyze the impact of the ZEZ on the tactical logistical decisions: redirecting the shipments affected, and the impacts on tour formation.

First of all we measure an increase in vehicle kilometers travelled (VKT) in the zero emission scenario. This is an unexpected, but realistic finding and can be explained by the extra leg that was added to the transportation chains to and from the LEZ. Of course, the planned UCCs in the scenario can be extended with UCCs at other main access routes into the LEZ. The increase in VKT is partly absorbed by an increase in logistical efficiency: we observe more weight distributed per tour, and a decrease in the number of empty trips running. This is the result of consolidating the shipments at the UCC: this makes it possible to combine more shipments into a round tour. Studies that do not consider consolidation in the formation of round tours, are likely to overestimate the increase of VKT in scenarios with more UCCs. We also observe that the number of shipments per goods type can change. This is explained by the tour formation model: smaller shipments of goods type A, that are carried in a tour with a larger shipment B, are labelled as a tour of goods type B. In the UCC scenario, more smaller shipments are combined in mixed tours.

This case study shows that the impact of UCCs is not trivial: emissions within the ZEZ are reduced (because all transportation takes place with ZE-vehicles) but we can see an increase in vehicle kilometers

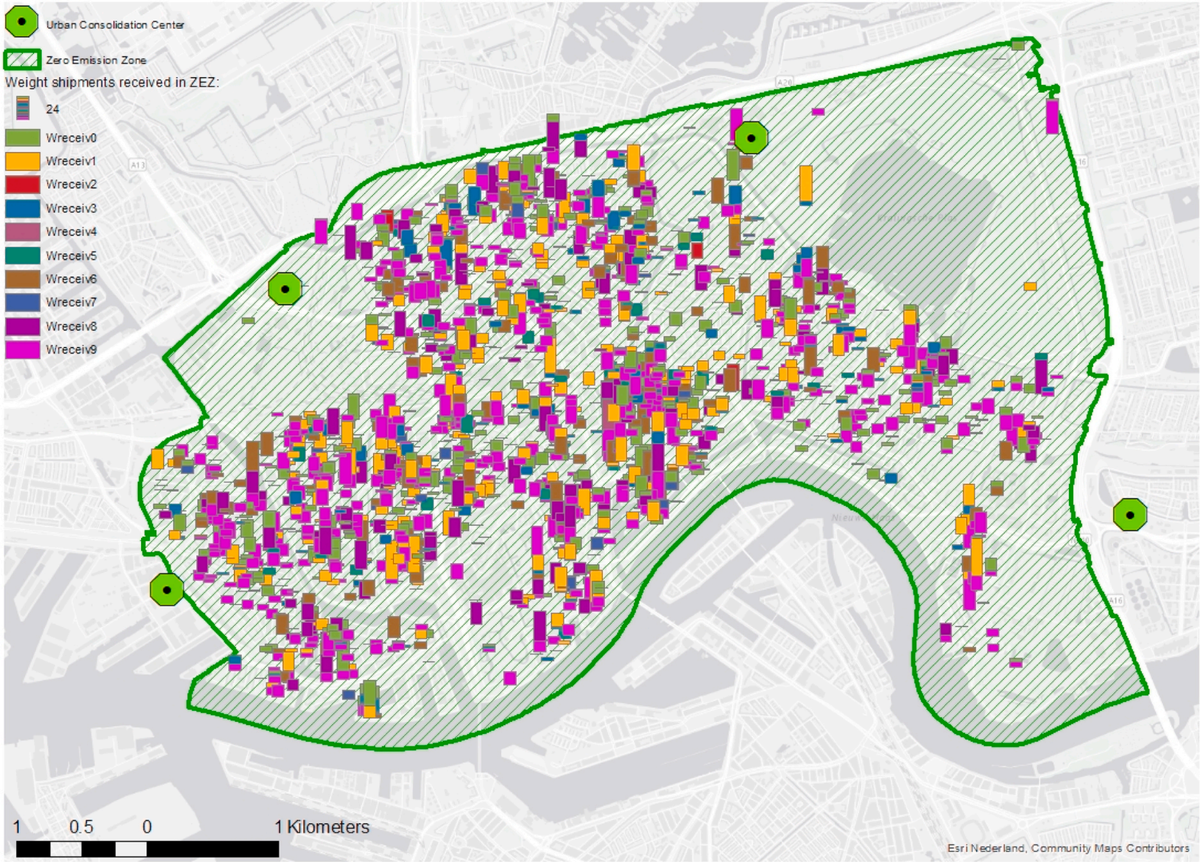

Fig. 5. Urban Consolidation Centers and shipments in the Zero Emission Zone.

Table 2
Logistical indicators of transported shipments to and from the ZEZ.

	Agricultural products and live animals	Foodstuffs and animal fodder	Solid mineral fuels	Petroleum products	Ores and metal waste	Metal products	Minerals and building materials	Fertilizers	Chemicals	Manufactured and miscellaneous articles	Empty vehicles	Total
NST/R	0	1	2	3	4	5	6	7	8	9		
Reference scenario:												
Shipments [#]	934	848	11	362	4	111	402	38	443	1936		5089
Weight [ton]	4689	6187	124	1227	76	565	3247	334	4653	10491		31592
Tours [tour]	449	406	5	251	4	52	219	35	242	797		2460
Load/tour [ton/tour]	10.4	15.2	24.7	4.9	18.9	10.9	14.8	9.6	19.2	13.2		12.8
Trips [#]	1285	1160	17	415	4	162	521	40	588	2670	2380	9242
Vehicle kms [vkms]	22366	20795	346	8036	124	2783	9769	979	10562	45952	60118	181830
ZEZ scenario:												
Shipments [#]	917	899	6	343	6	97	437	50	401	1933		5089
Weight [ton]	4566	6314	124	1192	91	575	3385	382	4588	10376		31592
Tours [tour]	404	349	5	215	4	46	230	29	254	695		2231
Load/tour [ton/tour]	11.3	18.1	24.7	5.5	22.7	12.5	14.7	13.2	18.1	14.9		14.2
Trips [#]	1009	987	6	359	7	107	483	53	435	2119	2150	7715
Vehicle kms [vkms]	22360	22957	261	8496	184	2966	11320	1274	10069	49092	58174	187154

travelled (VKT) outside the ZEZ. However, logistic efficiency can be increased as a result of improved consolidation possibilities, which absorbs the increase in VKT. Policy makers can use these detailed simulations to optimize the location of planned consolidation centers to minimize the additional VKT.

The level of detail in the multi-agent model also allows the implementation of different impacts on specific segments in urban freight transportation, to better account for heterogeneity in preferences of different actors. Marcucci and Danielis (2008) found evidence that some sectors are more likely to use UCCs: retail stores are more receptive because they have lower delivery frequencies and are less time critical. Food shops and restaurants have higher delivery frequencies and are more time critical and therefore less likely to accept an additional transportation leg in their supply chain. With the level of detail in the presented model it is possible to analyze alternative scenario assumptions for specific segments, for example: small shipments to restaurants are likely to be delivered directly to the restaurants by a zero emission van operated by the shipper of the goods. In this way the response to the introduction of a ZEZ and the impact on the transportation and logistic infrastructure can be simulated in a more accurate manner.

7. Conclusion and further research

Simulation models should be able to effectively simulate the impacts of policy measures on logistic decision making and the heterogeneity behind freight transportation demand. The presented MASS-GT model is an empirical large-scale simulation model of logistic decision making behind the transportation of shipments. The stakeholders in the model are policy makers, firms as producers and consumers of goods, and logistic nodes (distribution centers and multimodal terminals). The presented model is calibrated using a very large dataset with carrier truck trip diaries that was sampled across the study area but validation could be further improved using other data sources: for instance using local traffic counts, or with a comparison of deliveries and vehicle type use with a local establishment survey.

We showed an application of the model to a relevant policy strategy: the implementation of a zero-emission zone in combination with urban consolidation centers. The results provide relevant insights into the impacts of the ZEZ on freight trip patterns: emissions are reduced in the ZEZ, but the vehicle kilometers travelled (VKT) outside the ZEZ increase. At the same time logistic efficiency increases as a result of improved consolidation possibilities, which compensates for the higher VKT. These results illustrate how the simulated disaggregate logistical behavior impacts the outcomes of the tour formation process.

However, we also see three shortcomings in the presented implementation: the model does not provide emission calculations, it lacks the explicit simulation of more logistic trade-offs, and the presented zero-emission scenario lacks stakeholder specific transitions. Research is ongoing to incorporate disaggregate emission calculations, that consider the loaded shipments and efficiency of the vehicles. In addition, upcoming updates of the framework will include logistic choice models for simultaneous vehicle type and shipment size choice or distribution channel choice. The transitions in the zero emission scenarios are likely to vary by stakeholders: parcel delivery services are more likely to shift from vans to emission free electric light goods vehicles (LEVVs), while construction logistics will change the combustion type of tractors used from diesel to biofuel of hybrid power trains (City of Rotterdam, 2019). The detailed multi-agent approach presented here allows the implementation of detailed stakeholder specific scenarios.

The study is presented as an example of how extensive freight transportation data is used to develop large scale empirical multi-agent model for urban goods transportation for the analysis of urban freight transportation measures. In order to manage complexity, the MASS-GT model is being developed following an incremental development strategy to optimize the design of the multi-agent framework. During development effective prototypes can already be used to explore policy scenarios, such as the zero-emission case study presented in this article.

Author statement

Michiel de Bok: Conceptualization, Methodology, Software, Formal analysis, Investigation, Data Curation, Writing - Original Draft, Writing - Review & Editing, Visualization, Supervision; **Lórant Tavasszy**: Conceptualization, Methodology, Writing - Review & Editing, Supervision; **Sebastiaan Thoen**: Methodology, Software, Formal analysis, Writing - Review & Editing.

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