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Shipment-based urban freight emission calculation

Sebastiaan Thoen, Michiel de Bok, Lóránt Tavasszy

Abstract— In this paper we present a methodology to more accurately calculate emissions in regional freight transportation models by taking the loading rate of vehicles into account in the emission factors. This is done by incorporating the shipment-based demand data from a multi-agent simulation framework into the route assignment. In a case study we show that disregarding the vehicle loading rate can lead to underestimations of the amount of pollutant gasses. The application of this methodology in combination with a multi-agent simulation model allows to simulate impacts of changes in logistics behavior, such as vehicle type use or the scheduling of round tours, on emissions more accurately.

I. INTRODUCTION

Reducing emissions caused by urban freight transportation is an increasingly important policy objective for transportation planners around the world. For analyzing urban freight transportation policies there is a need for strategic approaches to design and review urban freight transportation measures [2]. 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. Multi-agent urban freight models have the potential to simulate the impacts on logistics decision-making and the heterogeneity behind freight transportation demand [11] [21].

Literature provides multiple examples of multi-agent freight transportation models that simulate the logistics choices of micro agents, such as [3], [6], [9], [14], [22], [24] and [27]. However, for different reasons these models have not been applied for urban freight policy studies or emission calculation: 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-based simulation models still need to be fully developed [21]. Since most of the operational logistics choices take place at the level of shipments, it is preferred to apply a shipment-based approach such as [3], [7], [12], [14], [19], [22], [23] and [27]. When freight transportation models are shipment-based, the loading rate of vehicles is simulated explicitly. This load is one of the influencing factors of vehicle

emissions. Therefore, shipment-based freight transportation models have the potential to more accurately calculate vehicle emissions, and secondly also the possibility to associate emissions to individual shipments, providing new possibilities for evaluating the carbon footprint of urban freight transportation demand.

Average-speed models are often used to calculate emissions based on traffic intensities forecasted with a freight transportation model. Here, emission factors, calculated based on a mean travelling speed, are multiplied by the vehicle kilometers in the network [20]. [16], for example, use vehicle-type specific emission factors and vehicle kilometers to calculate CO₂ emissions with an agent-based freight simulation model applied to urban food distribution in Berlin. In the literature we find different approaches that improve on this rather crude method for emission calculations, most of these approaches focus on incorporating traffic flow conditions, using continuous emission functions, or including more levels of segmentation in emission factors.

Traffic flow conditions influence the amount of pollutant gasses emitted per vehicle kilometer. For example, the emissions are much greater in stop-and-go conditions than in free flow conditions [26]. Hence, good estimates of traffic flow conditions provide better emission calculations. [26], for example, use different emission factors per traffic flow condition (free flow, heavy, congested, stop-and-go). They also propose a quasi-dynamic traffic assignment to arrive at better estimates of traffic flow conditions based on static model outputs. This method avoids the need for microscopic traffic modelling, which is usually computationally infeasible for regional/national transportation models. Another example is [1], who propose a method which uses link speed distributions instead of link mean speeds in order to consider traffic flow conditions more accurately in emission calculations.

Another approach to improve on the default average-speed model is incorporation of more levels of segmentation in the emission factors, or to use continuous emission functions. [10] and [15] provide detailed continuous emission functions including, amongst others truck type, payload and speed, and study their behavior for purposes of policy analysis. [5] use segmented emission factors for different average speed levels. [18] include average speed, Euro-norm, road type and vehicle loading rate in emission calculations. Because of the shipment-based nature of the model used by [18], it is possible to link emission functions to the flow data, using the loading rate of each individual trip instead of using average loading rates.

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Little is known about the influence of using detailed emission functions instead of rough averages on the total emissions predicted with a regional freight transportation model. To the best of the author's knowledge, there is no study yet which makes the different results explicit. In this paper, we use a shipment-based freight simulation model to analyze this. Section II presents the dimensions and overall structure of the freight simulation model, while Section III explains the method used for emission calculations in more detail. Section IV shows results for emissions calculations with different levels of detail. In Section V we formulate conclusions and recommendations for future research.

II. MULTI AGENT SIMULATION FRAMEWORK

The method that is presented in this article is part of a multi-agent simulation model, MASS-GT, that is being developed at TU Delft [7], [8]. This model aims at establishing a comprehensive multi-agent simulation model that simulates the logistics decision-making behind urban freight transportation demand. This simulation framework is the basis for the tactical freight simulator that is being developed in the multi-agent simulation framework called HARMONY. The analysis presented in this paper adds another building block to this framework: a route assignment for emission calculation, as part of the logistics behavior simulation.

A. Overall dimensions

The simulation framework is multi-agent, meaning it represents individual firms and individual freight shipments. In freight transportation, most logistics decision-making takes place at the level of shipments: therefore, the framework includes an explicit simulation of shipments. Since freight transportation demand involves a large variety of decision-makers, choices are simulated at level of individual firms. This gives more advanced possibilities to simulate behavioral decision-making and to account for costs and constraints that are in many cases agent-specific.

The study area of the current model is the Dutch Province of South Holland and all freight transportation that takes place within, to- and from this study area.

Since the simulation framework is to be used for policy evaluation, the validity of the behavioral simulation is important. Therefore, the framework is empirical, meaning the logistics decisions and processes in the model are simulated based on observed data. This data is available from a novel data collection of extremely high density transportation data: an automated collection of truck trip diaries among a sample of Dutch truck owners [7], [8], [25]. The data includes information on: the vehicle, the tours driven (load and stop locations), and shipment information during these tours (commodity type, size).

B. Main structure

The core of the tactical freight simulator consists of two logistics modules: the shipment synthesizer for long-term tactical choices and the scheduling module for short-term tactical choices (respectively modules 6.1 and 6.2 in Fig. 1).

The shipment synthesizer simulates long-term tactical choices. In a step-wise procedure different logistics choices or processes are simulated: allocation of freight transportation flows to distribution channels, selection of receiver and supplier, and shipment size and vehicle type decisions. Effectively, the shipment synthesizer builds a population of discretized shipments that are transported to, from and within the study area. The first step is to allocate total freight transportation demand to distribution channels: which share of each commodity is transported through distribution channels and/or multimodal transshipment terminals. The volume of freight through distribution channels of logistics transportation flows (direct, to DC, etc..) is calculated from observed market shares by commodity type from the transportation data. Next, the aggregate transportation flows are broken down into shipments by applying a discrete choice model for vehicle type and shipment size. Both choices are explained by a logistics cost function that includes transportation costs and inventory holding cost. The model is estimated on the available transportation data (see [17]). Next, the individual shipments are allocated to a receiver (demand size), that selects a supplier for the commodities. The allocation of a shipment to a receiver is based on I/O statistics: the receiver probability of a firm f of a shipment with commodity type gt depends on the firm size, and the 'use' probability for the industry sector [7]. Next the supplier of the shipment is selected on the same principle: the supplier probability of firm f belonging to sector s , being the supplier of a shipment with commodity type gt depends on the firm size and 'make' probability for the sector.

The scheduling module simulates short-term tactical choices and schedules truck round tours for the collection and delivery of all shipments in the study area. It builds tour patterns, in a step-wise procedure, simulating the logistics processes of tour formation in which carriers plan round tours with one or multiple stops, and delivery time choice. Tour formation is simulated with discrete choice models (similar to the approach of [13] but formulated for a shipment-based context). For a description of the model, see [25]. The model iteratively simulates how additional shipments can be added to a round tour. These decisions are based on a logistics utility function and constraints. Constraints include capacity of the vehicle, tour duration and transportation distances. The utility function includes generalized transportation costs, commodity types, vehicle type, and stop location attributes (urban density, logistics node). The results are planned round tours of freight vehicles.

An auxiliary network module is used to allocate vehicle movements to the network. This module simulates route choices for each vehicle between subsequent stops. This serves two purposes: first, it gives the vehicle intensities on the networks, which can be used to derive emissions or other local externalities. And secondly, the route choice module is also used to derive transportation time and distance in the network scenario: these are input to the logistics choices and processes in the shipment and scheduling modules. The indicator module is used to derive relevant output indicators from the previous

modules. Indicators include local demand indicators, transportation logistics indicators (e.g. vehicle type distribution, average load per vehicle, stops per tour, ...), network indicators, and externalities. This article focusses on the calculation of emissions in the network module.

Figure 1. The overall structure of the tactical freight simulator.

III. SHIPMENT-BASED NETWORK ASSIGNMENT WITH EMISSION CALCULATION

In the network module we assign all trips resulting from the scheduling module to the network. For the illustration in this paper we use a static All-Or-Nothing traffic assignment on a network with congested travel times resulting from a calibrated regional passenger transportation model (NRM-West).

Because the model works at the level of individual shipments and trips/tours instead of aggregate commodity flows, we have very detailed information on all trips that drive on each link (e.g. loading rate, type of goods transported). This has two main advantages for emission calculations. Firstly, we can use more detailed emission factors and, consequently, get more accurate emission calculations from the model. Secondly, in this approach where we are able to combine the shipment information from the freight demand model in the static traffic assignment, the detailed calculation of emissions at a regional level is feasible in a computational efficient way.

To calculate the emissions, we use an average-speed approach with emission factors segmented by vehicle type, road type (urban, highway, rural) and loading rate [4]. The emission factors are provided as g/km CO₂, SO₂, PM and NO_x for an empty vehicle and a full vehicle (see Table 1 for the CO₂ emission factors). Linear interpolation between the emission factor for an empty vehicle and for a full vehicle allows selecting the right emission factor for a given loading rate [4]. For each trip, we calculate the emissions on each visited link by multiplying the link distance with the according emission factor.

To analyze the impact of using these detailed emission factors, we compare the emissions as calculated with the described method (VRL in Table 2) with the emissions as calculated with two methods using less detailed emission factors (VR and V in Table 2). In method VR we use emission factors segmented by vehicle type and road type and we use the average loading rate per vehicle type (weighted by distance) resulting from the model. In method V we use emission factors segmented by vehicle type and we use the average loading rate and the road type shares per vehicle type (weighted by distance) resulting from the model.

Table 1. The emission factors used in this study (from [4]).

Vehicle type	CO ₂ (g/km)					
	Empty			Full		
	Urban	Rural	Highway	Urban	Rural	Highway
Van [$< 2 t$]	197	117	171	213	126	185
Van [$> 2 t$]	276	170	250	302	186	275
Truck [$< 10 t$]	419	281	253	472	316	286
Truck [$10-20 t$]	858	555	471	1009	653	554
Truck [$10-20 t$] + trailer	1023	658	559	1387	892	757
Truck [$> 20 t$]	1223	791	649	1501	871	796
Truck [$> 20 t$] + trailer	1321	838	700	1922	1220	1019
Tractor-trailer light	1189	768	619	1565	1011	814
Tractor-trailer heavy	1447	901	628	2258	1407	981
Longer Heavier Vehicle*	1954	1217	848	3048	1899	1324

* Max. 25.25 meters and 60 tons.

Table 2. The levels of segmentation used in the three methods.

Method	Segmentation of emission factors		
	Vehicle type	Road type	Loading rate
VRL	✓	✓	✓
VR	✓	✓	
V	✓		

IV. RESULTS

First, we compare method VR with method V, i.e. the influence of segmenting the emission factors by road type. Next, we compare method VRL with method VR, i.e. the influence of including the loading rate in the emission factors. In this paper we present the CO₂-emissions, the results are similar for SO₂, PM and NO_x.

In Fig. 2a and Fig. 2b the differences between the calculated CO₂ emissions with method VR and V are visualized per link, respectively in the form of a histogram and a GIS map. In Fig. 2a, as can be expected from the emission factors by road type

in Table 1, we can identify three clusters: from left to right these clusters consist of the highway links, the rural links and the urban links in the network. From this we can conclude that in this case study the exclusion of segmentation by road type in the emission calculation leads to an average underestimation of around 100% for urban links, an average underestimation of approximately 25% for rural links and an average overestimation of roughly 5% for highway links. Please note that the largest share of emissions is produced on highway links as a result of larger vehicle mileage and average speed on these links. This explains the relatively larger error for urban links: these links count for a small proportion in total emission and are highly biased when all links are averaged out. In Fig. 2a these three clusters are clear too: urban links, rural links and highway links show up as dark red, bright red and light blue respectively.

Figure 2a. VRL / VR - Differences between calculated CO_2 emissions per link.

Figure 2c. VRL / VR - Differences between calculated CO_2 emissions per link.

This shows us that disregarding road type in emission calculations and taking an average emission factor leads to large errors on individual links, most notably in the city centers. Given that cities are more densely populated, it is especially important to include road type in the emission calculation when the number of people exposed to different levels of air pollution is relevant in evaluating a project.

In Fig. 2c and Fig. 2d the differences between the calculated CO_2 emissions using method VRL and VR are shown. When we compare Fig. 2c to Fig. 2a, we see that error induced by disregarding the loading rate is much smaller than the error induced by disregarding the road type. However, we still see that the over/underestimation induced by disregarding loading rate is larger than 1% for most links.

Figure 2b. VRL / VR - Network plot South Holland. Differences between calculated CO_2 emissions per link.

Figure 2d. VRL / VR - Network plot South Holland. Differences between calculated CO_2 emissions per link.

In general, an underestimation of emissions takes place on links with a higher average vehicle loading rate than the average vehicle loading rate in the whole network. One of the places where we see this is in the city centers (for example in The Hague, C5 in Fig. 2d). The scheduling module predicts more often multiple-stop tours in the city centers because the high density of pick-up/delivery locations allows more efficient combination of multiple locations [25]. This leads to an average loading rate that is higher than in locations where more often direct tours (one pick-up location, one delivery location) are predicted.

Fig. 2d also shows significant differences on particular transportation corridors: these differences reveal a variation in loading rate on these corridors, which can be explained by a higher share of vehicles with higher average loads carrying bulky commodities.

V. CONCLUSIONS AND DISCUSSION

In this paper we use a shipment-based freight simulation model to improve emission calculations. Working at the level of shipments and unique trips/tours allows considering more aspects in emission calculations, such as the vehicle loading rate.

We quantify the influence of including a segmentation by road type and by vehicle loading rate on the calculated amount of emissions. Here we show that disregarding road type in emission calculations can lead to large errors (about 100%) on individual links. Disregarding the vehicle loading rate also induces errors, although to a lesser extent. Especially for links located in a city, the exclusion of road type and vehicle loading rate leads to underestimations of the amount of pollutant gasses in this case study.

The application of this methodology in combination with a multi-agent simulation framework for urban freight transportation demand allows to simulate impacts of changes in logistics behavior, such as vehicle type use or the scheduling of round tours, on emissions more accurately.

In this study we assume that emission factors that do not feature a segmentation by road type or vehicle loading rate are based on the same average vehicle loading rate and share of road types as the model results. However, if the average loading rate and share of road types used in the data for determining the emission factors is different from the average loading rate and share of road types in the model (for example if the model has a different scope than the calculated emission factors), then this will cause an additional error. In that case, not only the distribution of emissions over links will be off, but also the total amount of emissions in the network. The size of this error is dependent on the discrepancy between the two averages. This is a subject for future research.

Another subject for future research is analysis of the impact of using continuous emission functions instead of segmented emission factors in a freight simulation model. For this purpose, the emission functions of [10] and [15] may be applied.

Finally, emission factors segmented by traffic flow conditions (e.g. [26]) may be used to quantify the impacts of congestion on emissions.

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