# Modelling urban freight transport in the context of decarbonising transport in Europe

## A case study of the Groot-Rijnmond urban area with possibilities for model transferability

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TUDelft
International Transport Forum

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by

M.S. ter Laag

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# Preface

This report is the final product of my TIL MSc Thesis, which forms part of the master programme in Transport, Infrastructure and Logistics at Delft University of Technology. This project has been conducted in collaboration with the International Transport Forum, and is part of the EU-funded Decarbonising Transport initiative. The aim of this project was to provide a first insight and advice for a EU-wide model for urban logistics. I hope the results of my work will be of use to the ITF and to the transportation sector in general.

When I heard about the opportunity to conduct my research at the ITF in Paris, I thought: YES! I knew that this would be the perfect way to combine my interest in modelling, environment, and society. Urban logistics was a new and challenging topic for me, especially since the assignment from the ITF was quite broad. I created a full model, but looking back, this has forced me to make some quick decisions that were not always the right decisions. I hope that the recommendations that I have made will be of use to the necessary improvements of the model. In the end, I am proud of the comprehensive work that I have done, and I have started to love urban logistics! Moreover, I have learned a lot about data analysis, writing code, how to communicate, about the transport sector in general, and about myself.

There are some people that I would like to thank. First of all, thanks to Lóri and Jari for giving me the opportunity to be the first Master student from TU Delft at the ITF. I hope many students will follow. Furthermore, thanks to the CBS for their quick answers to my questions. Another thank you to Eurostat, whose expertise helped me to establish a transferability framework. Jan-Robbert Albrechts, thank you for taking time for an interview, it was very useful to see the context of my work. Of course I want to give a huge thank you to my dear colleagues at the ITF. I enjoyed all our coffee breaks, lunches and discussions about how things work in different countries. Special thanks to Olga, Dimitrios and Francisco: without your help I would probably still be working on my model right now.

Many thanks to my committee: Lóri, Michiel, Gonçalo, Ron and Luis. Lóri, I truly value your personal interest in your students' lives, considering your busy schedule. Gonçalo, thank you for being critical and asking the right questions. You made me think about my own research from a different perspective. Thank you, Ron for kickstarting my research with a few incredibly useful tips: your suggestions sparked my interest in urban logistics, which was a huge motivation boost. Michiel, our weekly meetings were very useful and helped me keep my motivation. Your knowledge of modelling and the microdata, and your support with some important decisions helped me a lot. And: thank you for always adding a positive note! Luis, a huge thank you for everything. You were there for me both professionally and personally, helping me through some tough times. I learned a lot from you, and I enjoyed our discussions about politics, linguistics etc. It was an honour to work with you.

Finally, I want to thank my friends and family, because their support has helped me reach this point in my life. Special thanks to: Mam, for all the support and, of course, for checking my written English. Pap, thank you for giving me confidence and trust in everything that I do. Sjoerd, without you I would not be the person I am today. Thank you for challenging me and always being there for me at times I needed it most.

I would like to end with the following: no matter how interesting the topic, how tough the journey, it is the people around you that help you be the person to accomplish your goals.

*Maya Sarah ter Laag*
*Delft, September 2019*

# Summary

Urban freight transport is a significant cause of $CO_2$ emissions. This creates the need to implement $CO_2$ mitigation measures for freight transport in cities. The International Transport Forum (ITF) is currently working on an EU-funded programme, the Decarbonising Transport initiative, to assess $CO_2$ mitigation measures. However, there is no model yet that is suitable to analyse urban freight transport on a European level. Therefore, the research question of this thesis is:

*How can a model for urban freight transport in the urban region of Rotterdam (Groot-Rijnmond) be created, that allows for estimation of $CO_2$ impacts of policy measures for decarbonisation and that can be transferred to other European urban areas?*

To answer this question, a literature study has been done to set the context of the project. This was followed by an identification of available data sources for European freight transport and the creation of a transferable modelling methodology. Based on the data and the established methodology, a model has been estimated. With this model, seven policy scenarios have been tested.

**Literature study**
A literature review of policy measures for decarbonisation and existing urban freight models to assess these measures has been done. The identified measures and trends for decarbonisation are:

- Zero/low emissions vehicles
- Restricted access to zones (restriction can be based on different characteristics)
- Pricing measures (on time or location)
- Urban consolidation centres
- Intelligent Transport Systems

Following this identification, a literature review of existing urban freight models has been conducted. The main finding was that there is currently no model for urban freight with an underlying data structure and methodology that can easily be applied to all urban areas in Europe and be used to assess policy scenarios.

**Methodology**
Using the knowledge from the literature study, it was decided to create a commodity-based adjusted four-step model. This modelling method was found to be the best approach to create a transferable model that also allows for assessment of policy scenarios. The modelling structure consists of four parts. The first part is freight generation, in which freight production and consumption in a zone are estimated with a generalised linear model (GLM) based on spatial characteristics. The second step is freight distribution. In this step, freight production and consumption are converted into freight flows between zones, based on an OD-matrix with generalised transport costs and commodity-specific sensitivity parameters. In the third step, these flows are converted into trips. First, shipments are created using an iterative procedure, after which vehicle types are assigned to these shipments. Then, these shipments are grouped into trips based on a probability function and the capacity of the vehicle. Once trips are created, the last step of the model can be executed: the tank-to-wheel emissions of each trip are calculated based on the tonne-kilometres of the trip.

An important part of this modelling methodology is its transferability framework. This framework requires the input data of the model to be available for all urban NUTS3 areas in Europe. Moreover, the model has to use a uniform spatial structure. The modelling methodology that has been designed during this study complies to the transferability framework, as it uses only input data that are available from European data sources. However, re-estimation of parameters in the generation and distribution steps may be needed when applying the model to other urban areas.

**Available data and data structuring**
Six different data sources from three different organisations have been brought together for the creation of this model: XML shipments microdata from Statistics Netherlands (CBS), commercial services data, regional freight data and population/GDP data from the ITF/OECD, and land use data and road freight data from the EU. The first, the CBS microdata, were used to make estimations of the freight generation model and the sensitivity parameters of the distribution model. The other sources were used either as independent variables, or as empirical data to create e.g. vehicle choice distributions.

Before using these data sources, they had to be converted to the same spatial structure. This was done using overlap of geographical surface, with which a uniform grid of zones of 1 by 1 kilometre was created. This way, these data have the same structure for all of Europe and can thus easily be used to estimate models for other cities using the same methodology. Moreover, only shipments with their origin or destination in the Groot-Rijnmond region were selected from the CBS microdata. Subsequently, the volumes of these shipments were linked to the 1 by 1 kilometre grid as freight production or consumption of the zone. Another data conversion that was applied, is the creation of ten commodity types that describe the goods types in the XML data and have some city-specific goods types as well, such as parcels and waste.

**The estimated model**
Using the structured data and the established methodology, a model for the Groot-Rijnmond region has been estimated. An ordinary least squares (OLS) model proved to be the most suitable fit. The $R^2$s of the generation models of the ten commodities are quite low, but are comparable to those of existing models for urban freight. For the distribution model, parameters have been estimated that express the sensitivity of the commodities to generalised transportation costs (based on distance and travel time). This was done based on total tonne-kilometres in the region. Most commodities have comparable sensitivities, except for climate-controlled goods and transportation equipment that are not as sensitive to transport costs, and paper and wood that are more sensitive to transportation costs.

After the application of the trips creation procedure, a final estimation of $CO_2$ emissions was made. The model predicted total tank-to-wheel emissions of 515.8 ktonnes of $CO_2$ by road freight transport in the region, which equals 6.1 percent of the total road freight transport $CO_2$ emissions in the Netherlands. This outcome seems plausible. It is larger than 1/40 of total road freight transport $CO_2$ emissions (the Netherlands has forty NUTS3 regions), but this is explained by the fact that 20.6 percent of the total transported goods volume in the Netherlands originates or ends its journey in Groot-Rijnmond.

**Assessment of policy scenarios**
Seven policy scenarios have been assessed with the model. These scenarios are based on three different implementations of zero-emissions vehicles and the implementation of a low emission zone based on road pricing in Rotterdam:

1. Zero-emissions vehicles
   (a) Electrify all vans (applies only to construction materials and parcels)
   (b) Electrify all trips with a load <1.5 tonnes
   (c) Electrify all trips with a load <3.5 tonnes
2. Low emission zone with pricing: 10 euros for passing entry and exit points of the low emission zone, no differentiation made between vehicle types or time of day

A summary of the conducted experiments and the outcomes is given in table 1. The results indicate that the introduction of electric vehicles causes a reduction in $CO_2$ emissions. The change in $CO_2$ emissions between only electrifying vans, or electrifying all trips with a load of fewer than 3.5 tonnes is not statistically significant. The implementation of a low emission zone based on pricing does not cause a statistically significant change compared to the base scenario, due to the current mechanics of the distribution model.

Table 1: Policy scenarios summary

| | Zero-emissions vehicles | | | Pricing | $CO_2$ change |
|---|---|---|---|---|---|
| | Electrify vans | Electrify trips <1.5t | Electrify trips <3.5t | | |
| Base scenario | 0 | 0 | 0 | 0 | |
| Scenario 1 | 1 | 0 | 0 | 0 | -3.86% |
| Scenario 2 | 0 | 1 | 0 | 0 | 0.12% |
| Scenario 3 | 0 | 0 | 1 | 0 | -3.77% |
| Scenario 4 | 0 | 0 | 0 | 1 | -0.26% |
| Scenario 5 | 1 | 0 | 0 | 1 | -3.58% |
| Scenario 6 | 0 | 1 | 0 | 1 | -0.42% |
| Scenario 7 | 0 | 0 | 1 | 1 | -4.06% |

**Main recommendations**
Two main recommendations can be done to improve the current model. The first recommendation is to improve the distribution model. It currently calculates an excessive amount of minuscule OD-flows, which leads to an overestimation of the number of trips. A constraint could be included that sets a maximum to the number of very small OD-flows. Additionally, the distribution model can be improved by basing it not only on generalised transportation cost, but also on GDP and population in the destination zone and logistics hubs.

The second recommendation is to improve the vehicle choice model. Currently, vehicle choice is based on a commodity-specific empirical distribution for seven shipment size clusters. However, this makes that changes in vehicle choice cannot be influenced by pricing measures. It would be beneficial to create a vehicle choice model that is dependent on a deterrence function.

# Contents

# List of Figures



# List of Tables

# 1
# Introduction

Climate change affects the entire world population. Therefore the European Commission has introduced Horizon 2020: a research and innovation programme with which a sustainable future of Europe is promoted (European Commission, nd). The ITF (International Transport Forum) takes part in Horizon 2020 with its Decarbonising Transport initiative. The initiative aims to promote carbon-neutral mobility, by providing advice on $CO_2$ mitigation measures (International Transport Forum, 2019a). To be able to select the right policy measures for decarbonisation, assessing the effectiveness of the measures before implementation is essential (Comi et al., 2012). Thus, the ITF uses models to map transport patterns, and it aims at assessing how changes in mobility patterns, caused by implementation of decarbonisation measures, will affect $CO_2$ emissions.

When looking at $CO_2$ emissions from transport, freight transport is essential, because it emits significantly more $CO_2$ compared to passenger transport (Coulombel et al., 2018). This is due to the fact that in Europe most inland freight transport is conducted by road (Jonkeren et al., 2019), and vans and heavy goods vehicles (HGVs) are the largest emitters in terms of $CO_2$ per tonne-km (McKinnon, 2007). This emphasises the need for models for freight transport to support assessment of decarbonisation measures.

To assess the effects of $CO_2$ mitigation measures, the ITF uses its modelling framework, which includes models for freight, urban passenger mobility and non-urban passenger mobility. Although all aspects of the framework should be updated to fit the Decarbonising Transport initiative, one aspect is missing entirely: urban freight transport (or city logistics). This aspect is crucial since over 70 percent of the European population lives in urban areas. With the urban population only expected to grow (Eurostat, 2016), impacts of freight transport on the sustainability of urban establishments are important to evaluate (Aditjandra et al., 2016; Comi et al., 2014). While some case studies of urban freight transport models have been conducted, there is no spatially transferable model for urban freight transport in Europe. This is a gap that can be observed in literature (for a more extensive literature review of existing models for urban freight transport, see chapter 2).

## 1.1. Problem statement

With a focus on decarbonising transport in the near future, there is a need for generally applicable modelling tools that allow assessment of implications of transport policy measures that are aimed at decarbonisation. The ITF modelling framework currently has tools available for international freight, domestic surface freight, international passenger aviation, urban passenger mobility and non-urban passenger mobility. However, there is a lack of urban freight models that are generally applicable. Studies on urban freight modelling have been done in the past, but these mostly focused on specific case studies. A reason for this is that there are problems with data availability for urban logistics (Comi et al., 2012), and that there is no general framework that indicates which data to use in urban freight modelling. Therefore, it is important to establish a modelling tool for urban logistics, which can be extrapolated to major European urban areas, to be able to analyse the effects of $CO_2$ mitigation policies on city logistics in Europe.

## 1.2. Research objectives

The objective of this study is to partly close the gap that was mentioned earlier in this chapter: there is no generally transferable model for urban freight transport in Europe. The first step towards closing this gap is taken by creating an exemplary model for urban freight transport for the case of Groot-Rijnmond (the urban area around Rotterdam), which is suitable to assess effects of policy measures in different scenarios. To enable a smooth transition to the further process of closing the knowledge gap, this model should take into account transferability to other urban areas in Europe. The transferability requirements are based on data availability for these areas. This study contains two main deliverables:

- The theoretical deliverable of this study is to provide a methodology for creating a demand model for urban freight transport that can be transferred to other urban areas in Europe, even though this project only comprises one case study. For other urban areas, it should be possible to use the same modelling structure and underlying data, but parameters possibly have to be adjusted for different country or city characteristics.
- The practical deliverable is a model that is written in R, to support possible later integration with the other modelling tools of the ITF. The model is estimated on a zonal level, with zones measuring 1 by 1 kilometre. The model should be able to estimate OD matrices with commodity flows, from which trips are created that can be used to calculate tank-to-wheel emissions.

## 1.3. Scope

The Horizon 2020 part of the Decarbonising Transport initiative of the ITF is funded by the European Commission. Consequently, this project focuses on urban freight transport in the European Union. This focus will be the context for the literature review in chapter 2 and the modelling work that is conducted in the rest of the project. Due to the limited time available for conducting both a literature review and the creation of a model within the scope of this thesis report, a full urban logistics model on the scale of Europe was not considered feasible. The scope has therefore been limited to a case study, to be able to estimate a complete model and give an example of the assessment of the effects of measures for decarbonising transport with this model.

Additionally, since the ITF plans to create a model for urban freight that can be applied to regions that are considered urban on the NUTS3-level, the case that is selected should be a NUTS3 region. The case study that has been chosen for this project is the urban NUTS3 region in which the city of Rotterdam is located: Groot-Rijnmond. An image of this region and its location within the Netherlands can be seen in figure 1.1. This region has been chosen first of all since Rotterdam is a European freight hub, but also because of the extensive road freight survey microdata that are available for this area. The dataset includes detailed data about freight trip patterns. It should be noted that the level of detail present in the dataset is not available for all urban regions in Europe, which has to be accounted for in further modelling. During this project, there is a constant emphasis on the transferability of the model. The model has to be an aggregate one and should be estimated based on a standardised zonal system, as explained in section 1.2. Finally, it should be noted that while in the end, the model should be able to take into account various exogenous future scenarios (e.g. changes in land use, population or economy) these scenarios will not be part of this research.

Figure 1.1: Location of the case study (yellow area)

Considering the policy measures that will be assessed with the model, it is important to realise that there are two main sources of urban freight flows. The first source consists of freight that has both origin and destination within the city, or freight that has either its origin or destination within the city. This includes ports and airports that are located within the urban area: they are not considered flows from outside. The second source is freight that is passing through the city, so it has both its origin and destination outside of the city. The second source will not be considered, as it is already accounted for in the regional models. A visualisation of the sources of freight, and which will and will not be included, can be found in figure 1.2. Another decision that is made with regards to the assessment of policy measures is that only tank-to-wheel emissions will be considered.

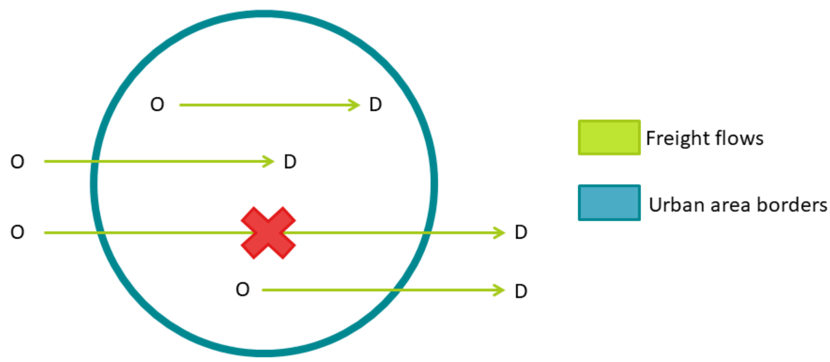



Figure 1.2: Definition of urban freight transport in this project (O = origin, D = destination)

## 1.4. Research questions

Resulting from the problem statement and research objectives as explained in sections 1.1 and 1.2, the main research question and sub research questions can be defined. The main research question is:

*How can a model for urban freight transport in the urban region of Rotterdam (Groot-Rijnmond) be created, that allows for estimation of $CO_2$ impacts of policy measures for decarbonisation and that can be transferred to other European urban areas?*

This research question should lead to a transport model for the agglomeration of Rotterdam (Groot-Rijnmond), using a data structure that allows the model to be transferred to other European urban areas. The model should enable a connection to the model for regional freight that already exists in the ITF modelling framework (International Transport Forum, 2019b). Moreover, every module of the model should allow for implementation of decarbonisation measures of which the effects can easily be analysed. To be able to answer the main research question, several subquestions are defined, that can be divided into four research phases: context study, model transferability, modelling phase, and model application.

**Context study**

1. Which existing urban freight models can be taken as a starting point, and what are the lessons that can be learned from these models?
2. Which policy measures should be implemented in the model?

**Transferability**

3. Which factors should be taken into account when applying the model to other urban areas in Europe?
4. How can limited data availability in other urban areas be dealt with?
5. How can interoperability with other models in the ITF modelling framework be ensured?

**Modelling phase**

6. Which types of commodities should be considered in a European model for urban freight transport?
7. Generation: How can the volume of freight that is generated in a certain zone be estimated?
8. Distribution: How can freight flows on a regional level be transferred to freight flows on a zonal level?
9. Vehicle trips: How can vehicle split and the creation of vehicle trips be modelled?

**Model application**

10. How can the policy measures that were defined in the context study be implemented?
11. What are the impacts of these policy measures on the expected tank-to-wheel $CO_2$ emissions?

## 1.5. Research approach

The research approach in figure 1.3 is used to answer the research questions. The research starts with simultaneous literature research and data collection. The literature study is conducted to identify policy measures for decarbonisation and existing models for urban logistics. The data that are collected, are European data on road freight transport from Eurostat and the ITF/OECD, which set the constraints for the creation of a modelling methodology. Moreover, XML microdata from Netherlands Statistics (CBS) are collected to estimate a proof-of-concept model for the Groot-Rijnmond region. After data collection, the data are analysed and structured to create a useful base for model estimation. Subsequently, with more knowledge of the data and the possibilities that they offer, a modelling methodology can be created. This modelling methodology has possibilities to be transferred to other urban areas in Europe. Using this methodology and the structured data, a model is created. This is done in an iterative process of model development, model estimation and model validation. After the last validation, the model is used for application in several policy scenarios, from which conclusions can be drawn.

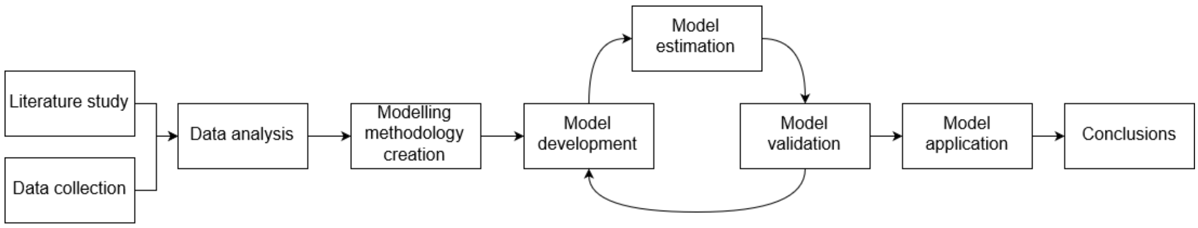



Figure 1.3: Research approach

## 1.6. Contribution to science and practice

The modelling methodology that is created in this study is built from existing methods in transportation modelling. However, it is positioned in the scientific gap that has been found, that is: there is no existing model for urban freight transport that is easily spatially transferable and that has possibilities for assessment of policy scenarios. The modelling methodology is novel in the way that the main requirement is the ease of datasets from different cities to be used as input. This is established by using a uniform spatial structure, and by only using input data that are available for all urban areas in Europe. The modelling structure is easily usable: the only input data needed to use the model are a file with spatial characteristics and additional data from Eurostat.

Concluding: the modelling methodology that is established in this research is innovative because it uses only input data that is available for all European urban areas, and because of its uniform spatial structure. This way, a first step towards a useful tool to give guidance in the effectiveness of certain measures for European urban areas is provided.

## 1.7. Report outline

This report starts with a literature review in chapter 2. In this chapter, the two literature reviews of $CO_2$ mitigation measures and existing models for urban freight are elaborated, followed by a connection of the reviews. In chapter 3, the establishment of the modelling methodology is explained. This is followed by a chapter about the available data and their characteristics (chapter 4). Combining these data and the methodology, an empirical model for urban freight transport is created, which is described in chapter 5. Subsequently, the results of the application of two $CO_2$ mitigation measures are discussed in chapter 6. The report ends with a conclusion that answers all research questions from this introduction in chapter 7. In that chapter, recommendations for future research and future updates of the model are done as well.

# 2

# An analysis of decarbonisation measures and urban logistics models

The literature review in this chapter aims to give an insight in decarbonisation measures for urban logistics and how these can be assessed by using transport models. First, an identification of relevant policy measures for decarbonising urban freight transport is given in section 2.1. Subsequently, conventional modelling techniques for urban logistics and a definition of transferability of models are explained in sections 2.2 and 2.3. This is followed by an impression of the state of the art of urban logistics models in section 2.4. This review of models is aimed at identifying how these models can be used for this study and where knowledge gaps exist. A summary of the scientific gap is given in section 2.6.

## 2.1. Identification of $CO_2$ mitigation measures for urban logistics

To make a selection of $CO_2$ mitigation measures that should be assessed, a literature review has been done of mitigation measures in literature and existing models. These also include current trends to decarbonise transport, which are not necessarily initiated by the local authority. This review has been validated in an interview with the municipality of Rotterdam (see appendix A).

### 2.1.1. Mitigation measures in literature

A literature study has been done on articles and reports that discuss urban logistics measures. Few sources specifically focus on urban freight transport, but rather focus on road freight in general, or urban passenger mobility. However, after studying the few useful articles that were found on urban freight, and after consulting experts on the topic, fifteen sources were found. Of these fifteen, twelve specifically focus on urban freight transport, one on road freight, and two on urban mobility (passenger and freight). Among these sources, there are reports from the European initiatives CIVITAS, a network of cities that aims for better transport in cities (CIVITAS, 2013), and BESTUFS, which is an initiative for collaboration in the field of urban logistics (BESTUFS, nd).

Table 2.1 gives a summary of the measures that were found in different sources. It should be noted that the measures that are included are the ones that aim for decarbonisation. However, they could have other impacts as well, caused by the fact that most articles focus on urban logistics in general. Consequently, they give measures that can have an impact on several characteristics of urban freight, including efficiency and emissions. Another remark is that some sources do not clearly explain the measures that they mention. In these cases, assumptions were made to allocate them to a certain category. Furthermore, two sources on the CIVITAS project were studied (Bosetti et al. (2014) and Van Rooijen and Quak (2014)), since they both mention different measures.

It is clear that some measures are mentioned much more often than others. Zero/low emissions vehicles, restricted access to zones and urban consolidation centres are among the measures that are mentioned most often. All measures are explained briefly in the remainder of this section.

Table 2.1: Overview of policies discussed in literature

| | Aljohani and Thompson (2016) | Allen et al. (2007) | Den Boer et al. (2017) | Bosetti et al. (2014), Van Rooijen and Quak (2014) | Coulombel et al. (2018) | Crainic et al. (2004) | DG MOVE (2012) | International Transport Forum (2018) | Goldman and Gorham (2006) | Holguín-Veras et al. (2017) | Oliveira et al. (2017) | Muñuzuri et al. (2005) | Russo and Comi (2016) | Yannis et al. (2006) | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Zero/low emissions vehicles | | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | | ✓ | ✓ | ✓ | ✓ | 10 |
| Restricted access to zones | | ✓ | | ✓ | | ✓ | | | | | | | | | 3 |
| *- Time windows* | | ✓ | ✓ | | ✓ | | ✓ | ✓ | | ✓ | | ✓ | ✓ | ✓ | 9 |
| *- Weight and size* | | ✓ | | | | ✓ | ✓ | | ✓ | | | ✓ | ✓ | ✓ | 7 |
| *- Emissions* | | | ✓ | ✓ | ✓ | | ✓ | ✓ | ✓ | | | | ✓ | | 7 |
| *- Load factor* | | | | | | | | | ✓ | | | ✓ | | | 2 |
| Pricing measures | | | | | | | | ✓ | | | | | | | 1 |
| *- Congestion charging* | | | | ✓ | | | ✓ | | ✓ | ✓ | | | | | 4 |
| *- Road/zone tolls* | | ✓ | | ✓ | ✓ | | | | ✓ | | | ✓ | ✓ | | 6 |
| Urban consolidation centres | ✓ | ✓ | ✓ | ✓ | | ✓ | ✓ | ✓ | ✓ | | | ✓ | ✓ | ✓ | 11 |
| *- Use of "human" modes* | | | | | | | | | | | ✓ | ✓ | | | 2 |
| *- Pick-up consolidation* | | ✓ | | | | | | | ✓ | | | ✓ | ✓ | | 4 |
| Intelligent Transport Systems | | ✓ | | | | ✓ | ✓ | ✓ | ✓ | | | | ✓ | | 5 |
| *- More efficient routing* | | ✓ | | ✓ | | | ✓ | ✓ | | | | | | | 4 |
| *- Eco-driving* | | | | ✓ | | | | ✓ | | | | ✓ | | | 3 |

**Zero/low emissions vehicles**
Zero/low emissions vehicles is a bundling term for electric vehicles and vehicles that use alternative fuels, such as hydrogen and natural gas (DG MOVE, 2012). These are all bundled because when viewed from a tank-to-wheel modelling perspective, their effect is the same. A wider use of these vehicles reduces $CO_2$ emissions, but the magnitude of this reduction depends on the type of vehicle and the energy source that is used.

There are two issues that should be taken into account when promoting the use of zero/low emissions vehicles. The first is that the source of energy should be considered. Only one of the fifteen reviewed documents mentions this consideration. This report (International Transport Forum, 2018) states that there should be sufficient capacity to produce the fuel that is needed. The second issue is that not all vehicle types are suitable to use certain fuel types. For example, full-electric vehicles are more suitable for short trips and lighter vehicle types because of their limited range and battery power (International Transport Forum, 2018), whereas it could be difficult to electrify HGVs. Van Duin et al. (2013) already showed six years ago, using a vehicle routing problem, that with the available technology at the time, electric vehicles could reduce $CO_2$ emissions in the centre of Amsterdam by 90 percent. They did remark that a high load factor is essential to an economically feasible scenario.

**Restricted access to zones**
Restricted access to zones is predominantly meant to reduce congestion and local pollutant issues, but it has other beneficial environmental effects as well (Muñuzuri et al., 2005). As can be seen in table 2.1, different implementations for restricted access to zones are possible, the main ones being based on time windows, weight and size of vehicles, and vehicle emissions. Since restrictions based on load factor are only mentioned by Goldman and Gorham (2006) and Muñuzuri et al. (2005), and they do not clearly explain how these would be executed, this measure is not considered any further. A brief explanation of the other measures is as follows:

- Time windows: this measure is mentioned in many different ways, but includes fixed time windows during which certain vehicle types are allowed to enter the zone, allowance of night-time deliveries in zones, and off-peak deliveries. The general idea behind this measure is that a vehicle is only allowed into a zone for a limited period during the day.
- Weight and size: this measure bans vehicles from entering certain zones, based on their weight and size.
- Emissions: this measure bans vehicles from entering certain zones, based on their emission standard. This is often closely related to the weight and size of the vehicles.

Naturally, a combination of these three measures is possible as well. Moreover, access restrictions based on weight, size and emissions are closely related to one another. One could also ban certain vehicle types, such as all non-electric vehicles, from a zone for a certain time during the day.

There are several examples of successful and unsuccessful implementation of restricted access zones. Between 2008 and 2013, a low emission zone was installed in the city of Aalborg (DK), where only trucks complying with the latest environmental performance standards were allowed. This caused an increase in trucks complying with Euro IV standards from 28 to 54 percent, and a reduction in trucks with engine standard Euro II or lower from 26 percent to 15 percent. During the same period, similar results were found in the city of Utrecht (NL), when a low emission zone combined with an urban consolidation centre was introduced. This caused a 73 percent decrease in $CO_2$ emissions. However, a similar project in Zagreb (HR) failed (Van Rooijen and Quak, 2014). In Gothenburg (SE), a low emission zone was installed as early as 1997, requiring HGVs to meet Euro IV emissions standards. In 2012, 96 percent of HGVs operating in the city complied to Euro IV emissions standards (DG MOVE, 2012).

Restricted access to zones may seem similar to pricing measures, especially road and zone tolls, since these also limit access to certain areas of the city. The distinction that is made in this report is that restricted access to zones refers to a physical barrier, which makes it physically impossible to enter a certain area, while road and zone tolls simply discourage entering an area but do not make it impossible.

**Pricing measures**
Pricing measures, similar to restricted access to zones, come with different implementations. The implementations that are mentioned most often can be divided into two categories:

- Congestion charging: charging vehicles for transporting goods during peak hours.
- Zone charging: also called road tolls, zone tolls or road charging. This means that vehicles are charged when they enter certain zones or roads.

The direct impact of these measures is that they reduce congestion, but indirectly they also reduce emissions. Moreover, carriers are forced to improve their efficiency and reduce their logistics costs to make up for the higher prices. However, the initial effect of pricing measures on carrier operations is questionable, as carriers would be able to pass the higher logistics costs on to the receivers (Quak and Van Duin, 2010).

Empirical examples of pricing measures are found in Trondheim and London. In Trondheim, 21 toll stations have been set up, with rates differentiating between different vehicle sizes and peak hours (Miljøpakken Trondheim, nd). No documentation of the effects of this tolling system can be found. Another example is London, where the introduction of a congestion charging system caused an 18 percent reduction in traffic volume and a reduction in delays of 30 percent, indirectly decreasing $CO_2$ emissions (Allen et al., 2007). More recent plans in London are to implement an ultra-low emission zone (Miles, 2019): starting in October 2021, only fully electric vehicles will be able to enter the zone free of charge.

**Urban consolidation centres**

Urban consolidation centres (UCCs), also called urban distribution centres or logistics hubs, are locations close to the border of the city (centre), to which goods can be transported, and from which shipments can be consolidated and transported into the inner city in lighter vehicles. Their main purpose is to avoid not fully loaded trucks delivering goods in urban centres (Browne et al., 2005). This makes them very suitable to be combined with measures to promote the use of zero/low emissions vehicles. The combination of increased vehicle load factors and the use of zero-emissions vehicles leads to environmental and social benefits in urban areas (Browne et al., 2005). Van Duin et al. (2010) discovered that the use of electric vehicles can be a success factor, although only if well-adjusted to the area.

There are several other context variables that improve the success of UCCs, according to Browne et al. (2005): availability of funding, strong public sector involvement, existing congestion/pollution problems in the area, bottom-up pressure from local interests, and UCCs with a single manager. They also state that the main focus of a UCC should be on improving vehicle capacity utilisation, as opposed to the traditional view of just transferring loads into smaller vehicles. Additionally, Van Duin et al. (2010) mention that for the business case of a UCC to work, the municipality should actively help to bring costs and benefits together.

The implementation of UCCs has several issues that require attention. First of all, traffic conditions around the UCCs can deteriorate (Van Binsbergen, 2018). Secondly, implementation creates difficulties at the side of logistics service providers (Van Duin et al., 2010), who have to deal with the costs of additional handling (Browne et al., 2005) and changes in tradition and contract forms (Van Binsbergen, 2018). The logistics providers often already have efficient distribution structures in place and are not keen on changing those. Another issue that should be considered is brought up by Aljohani and Thompson (2016), who warn for urban sprawl (the relocation of UCCs to areas outside of the city centre), which could cause larger distances to be travelled by vehicles and all the environmental impacts concerned. This is confirmed by Dablanc and Rakotonarivo (2010), who conducted a study on the $CO_2$ impacts of logistics sprawl in the Paris urban area. They conclude that due to urban sprawl since the 1970s, annually 15,000 tonnes of $CO_2$ had been generated. They also state that this could be mitigated by using zero-emission vehicles for inner-city transport.

Two variants of UCCs are the use of ”human” modes and pick-up consolidation. The use of ”human” modes implies the use of parking spaces or UCCs as a temporary parking space for a vehicle, while the last mile is covered on foot or by bicycle. The feasibility of this option depends on the commodity type and the shipment size. The idea behind pick-up consolidation is to not bring goods to the customer, but to let the customer pick up the goods themselves from e.g. lockers. This measure is aimed towards deliveries to the end-consumer and becomes more relevant with the growth of e-commerce. Instead of making multiple stops for all the receivers, the vehicle would just have to make one stop for delivering the goods to the storage facility (Muñuzuri et al., 2005). In terms of modelling, this measure is quite similar to the use of ”human” modes, as is explained in chapter 3.

There are numerous examples of the implementation of UCCs. As mentioned before, the city of Utrecht saw a 73 percent reduction in $CO_2$ emissions (5.8 tonnes) after implementing a low emission zone combined with a UCC and delivery by an electric train (Van Rooijen and Quak, 2014). An experiment in Paris with delivery with electric tricycles saved 112 tonnes of $CO_2$ (Allen et al., 2007). Another example in which tricycles were used, with the addition of electric vans and one diesel truck, is London. The introduction of a micro consolidation centre caused a 54 percent $CO_2$ reduction in the entire system (Browne et al., 2011). In Bristol, two Euro III vehicles were used for deliveries from a UCC, which saved 5.29 tonnes of $CO_2$ (Allen et al., 2007).

**Intelligent Transport Systems**
Five sources mention Intelligent Transport Systems (ITS) as a policy measure. Goldman and Gorham (2006) even discuss it as one of the main directions of innovations in urban transport. However, it is not clear how ITS themselves are a measure to cause a reduction in emissions. The International Transport Forum (2018) and Goldman and Gorham (2006) explain how ITS can be used in the implementation of other measures, but only the International Transport Forum (2018) explains how this can contribute to a reduction in emissions. Since ITS are thus mainly used to aid in the implementation of some of the other measures that are mentioned in this section, they are not further considered for assessment with the model.

Two examples of specific measures related to ITS are more efficient routing and eco-driving. First of all, more efficient routing can help truck drivers to avoid congested areas, use major roads for longer distances and avoid steep ramps or junctions (Allen et al., 2007; International Transport Forum, 2018). Again, only the International Transport Forum (2018) explains how this leads to a reduction in emissions, by optimising fuel consumption. The four sources that mention this measure give conflicting statements about its effectiveness and its effects. The International Transport Forum (2018) mentions it as one of the main options to make urban freight transport more sustainable, while Bosetti et al. (2014) express doubts about the ease of implementation. Moreover, Allen et al. (2007) state that more efficient routing could lead to journey time savings, but the International Transport Forum (2018) contradicts this, stating that the optimisation of fuel consumption could lead to longer trips. The other measure: eco-driving/driver training/eco-driving training, refers to changing the behaviour of truck drivers to a driving style that would be less polluting, by reducing speed and smoother driving - it could cause a reduction in fuel use and therefore a reduction in $CO_2$ emissions. According to the International Transport Forum (2018), it could be very effective to reduce emissions, and has already shown to be a proven concept.

### 2.1.2. Mitigation measures from the perspective of the local authority

To validate whether the findings in section 2.1.1 correspond with reality, an interview with the municipality of Rotterdam was conducted (see appendix A). This interview confirmed the findings of the literature review. The municipality has already worked on stimulating zero-emissions vehicles and reducing emissions of vehicles by promoting eco-driving and more efficient routing during the last few years. In the next few years, they plan to implement a zero-emission zone. In this zone, heavy freight vehicles will not be allowed. The size and location of the zone are still subject to discussion.

Furthermore, the municipality expects that the introduction of a zero-emission zone will stimulate the logistics sector to start using UCCs, even though Van Duin et al. (2010) analysed that the influence of accompanying measures on the success of UCCs is unclear. The municipality stresses that the implementation of UCCs by the government is usually unsuccessful, so they leave the introduction of this measure up to the logistics sector. This is contradictory to Browne et al. (2005), who state that there should be strong public sector involvement to make UCCs successful, while Van Duin et al. (2010) state that there is no clear indication that the actor who started the UCC determines whether it will be successful or fail (although private organisation of the UCC is more often successful). An example of a UCC in Nijmegen (NL) showed that the UCC failed when it was organised top-down, but with a later bottom-up organisation that was driven by the private sector, the UCC managed to be successful (Van Duin et al., 2016). The municipality and Browne et al. (2005) do agree, however, that for some logistics segments, consolidation already exists and therefore UCCs have limited beneficial effects for the carriers in these segments.

The municipality has some doubts about the impacts of some other measures. They expect that congestion charging, for example, will mainly be successful to improve general traffic conditions and accessibility in the city. It will likely also impact emissions, but the question remains on what scale. Another example is eco-driving: for different types of vehicles, different types of driving are more effective for reducing emissions. The fact that the municipality has doubts about the effectiveness of some measures stresses even more that there is a need for urban logistics models that provide ex-ante assessment of policy measures.

## 2.2. Approaches in modelling urban freight transport

Now that it is clear which mitigation measures can be assessed, an analysis can be done of how to review these measures with the help of transport models. Two categorisations of approaches in modelling urban logistics were found. The first is given by Comi et al. (2012), who differentiate four approaches for city logistics demand modelling. All approaches use different modelling structures because they are based on different reference units, but their output (vehicle OD matrices) is the same. The approaches are:

- Truck-based: makes use of freight vehicles trips, and can estimate vehicle OD matrices in a limited number of steps. However, case studies show problems with transferability in the generation step. Additionally, applying a truck-based model in forecasting analysis proves to be difficult.
- Commodity-based: makes use of commodity quantities. There are some issues with data availability for commodity flows, and the conversion of commodity flows into vehicle tours is not easy. Moreover, there is a lack of a complete modelling framework.
- Delivery-based: uses deliveries between generators and transport operators as a reference unit. There are some good examples of transferable models. However, there are problems with using these types of models for forecasting analysis to asses policy measures.
- Mixed: makes use of a mix of commodity-based models and delivery-based models.

The second categorisation is based on the structure of the model, and is given by González-Feliu et al. (2014). They identify four modelling structures:

- Classical four-step models: following the logic that is also used in modelling urban passenger transport. The consecutive steps are: trip generation (resulting in the number of vehicle trips), trip distribution (resulting in OD pairs), mode choice (resulting in vehicle choice), and traffic assignment. A disadvantage of these models is that they do not take into account the type of goods.
- Adapted four-step models: adapt the structure of the classical four-step model to fit freight transport. The consecutive steps are: generation of the need for goods, estimation of a goods OD matrix, estimation of trips, estimation of a trips OD matrix and traffic assignment. However, the amount of data that are needed is quite large, which could be problematic in the case of limited data availability.
- Combined models: use a combination of modelling approaches. A typical way of describing these models is not given, as they differ from one another quite a lot.
- Category class models: in this classification of models the firms are divided into classes upon which freight generation is based.

The conclusion from both categorisations of models is that all models for urban logistics start with a demand generation step, and have an output of vehicle OD matrices that can be assigned to the road network. The steps that are taken in between differ, and all have their advantages and weaknesses. The choice for a modelling approach in this study is based on three requirements: the needs of the ITF, the goal for which the model is used (assessment of decarbonisation measures) and a limited need of data. This implies that the modelling approach that is most suitable will likely be a combination of a commodity-based and a four-step model with some adaptations.

## 2.3. Definition of model transferability

Since this project is conducted in the context of the European Commission, the created model for the case study must have the possibility to be transferred to other urban areas in Europe. If this is accomplished, this leads to a reduction in data requirements, and to a reduction in model development effort for the models that are based on the original model (Ibeas et al., 2012). Thus, transferability is key during this project, and it is of great value to study earlier models that take transferability into account. Now, the question arises what model transferability actually entails. Several viewpoints should be explained regarding this topic.

When discussing transferability, the notion of spatial extrapolation is the one used most often. Spatial transferability implies that a model for a certain region is suitable for modelling freight patterns in other regions. Holguín-Veras et al. (2013) discuss extrapolation of three urban freight trip generation models on the establishment level from their original region (New York City) to other regions (Midwest and Seattle). This study shows that only for furniture stores in Michigan there is a significant difference in modelling freight trip attraction; the other models are transferable. Furthermore, they show that the Project 25 models of the National Cooperative Freight Research Program (NCFRP) are quite suitable to be applied to other regions. Finally, they introduce a synthetic correction procedure to improve freight trip generation predictions for establishments. They show that using a regression model instead of a constant freight trip generation rate causes major improvements in the accuracy of the predictions.

Another example of spatial transferability is given by Koning et al. (2018). They show that shipment size choice parameters can be transferred between France and Germany. This supports the idea that shipment size choice should be at least the same within a country, and possibly even within Europe. It must be noted that the authors were fortunate enough to have two comparable datasets to base their estimations on, which stresses the need for appropriate data to conduct transferability studies. This statement is supported by Moeckel and Donnelly (2016), who note that when extrapolating a distribution model, the gravity models were not transferable due to differences in zone sizes. They also criticise the general methodology of freight demand models in the United States, as these simply take parameters from the Quick Response Freight Manual by Beagan et al. (2007). Moeckel and Donnelly (2016) conclude that simply transferring these parameters to another region leads to underperforming models. An important remark is made by Giuliano et al. (2010), namely that commodity-based models could be more appropriate for spatial transferability than vehicle-based models, because they include the underlying indicators for freight demand.

In addition to spatial transferability, there is the notion of temporal transferability. This refers to the transfer of parameters in time, e.g. using model parameters that were derived from a survey for 2014 to estimate freight demand in 2017. Temporal transferability was examined by Shibasaki et al. (2005), who transferred a model for container freight in East Asia from 1993 to 1998. The authors show similarity between both years, but it should be taken into account that international container transport between ports is very different from urban freight patterns. Similar to spatial transferability, Moeckel and Donnelly (2016) state that transferring parameters in time leads to performance problems in models.

Finally, there is the notion of the possibility to transfer model parameters between commodities. An example is a study by Rich et al. (2009), who use the same parameters for different commodity groups in case of difficulties with parameter estimations. However, the general opinion in literature is that differentiation between commodity groups (also called supply chains) is of great importance, because of the difference in demand models and the different transportation structures and modes (Alho and De Abreu e Silva, 2014; Boerkamps and Van Binsbergen, 1999; Gentile and Vigo, 2013; Lawson et al., 2012). In the previously mentioned transferability study by Holguín-Veras et al. (2013), a differentiation between freight production for different sectors was made, which indicates a differentiation between establishment types, possibly because different establishment types form part of different supply chains. In general, it can be concluded that transferability from one commodity group to another is not needed, primarily because it is not wanted.

In the continuation of this thesis, when the term ”transferability” is used, it is used to refer to spatial transferability. This is the case because the main issue is the suitability of transferring the model from Groot-Rijnmond to other urban areas in Europe. The assumption is made that temporal transferability can be accounted for by the use of growth factors and adjusted aggregated data as input for the demand model, and that supply chain/commodity transferability is unnecessary. In terms of spatial transferability, a re-estimation of several parameters for the demand model may be needed, but it is the goal to keep the general modelling methodology the same for all regions. It is especially important to review the ease of implementation of a modelling methodology for a large number of urban areas, since the goal is to assess effects of mitigation measures in a large number of urban areas in Europe. Further assumptions and choices that are made to enhance the transferability of the model that is created in this study are clarified in the explanation of the methodology in chapter 3.

## 2.4. An overview of existing models

This section gives a short and non-exhaustive impression of existing models for urban freight transport. The goal is to identify what kinds of models already exist that can serve as an example, and more importantly: to identify what has not been done yet, mainly in terms of transferability (based on underlying data) and the implementation of policy measures. The results of this literature review are summarised in table 2.2. In addition to an investigation of the abovementioned two characteristics, the models are identified based on their focus, the category of models according to Comi et al. (2012) and the modelling structure according to González-Feliu et al. (2014).

The next three subsections discuss the different models. Their grouping is based on their data requirements, since data availability is still a constraining factor in modelling urban freight transport (Coulombel et al., 2018). Two main categories of models can be distinguished from the transferability viewpoint: models that are based on socio-economic data, and models that are built on establishment data. The statements made about the models are based on the literature that was found, and could, therefore, contain inaccuracies about the actual performance of the model. Furthermore, only models with a strategic focus, thus from the view of the local/regional administrators were reviewed, as these are most relevant for the final purpose of this study: policy analysis.

### 2.4.1. Models based on socio-economic data

Models based on socio-economic data are using land-use data, economic data and spatial data as input for model estimation. This can either be for freight demand estimation, or the estimation of the network and its characteristics. An advantage of these models is that the data that they use are often publicly available. As can be seen in table 2.2, a limited number of models is based on only socio-economic data, with the latest dated 2012.

The first model that uses socio-economic data as an input is that by Yannis et al. (2006), which was established to assess the effects of delivery restrictions (based on time windows, see section 2.5 for more details) on traffic conditions and emissions in the city of Athens. The authors state that the methodology that is applied could be transferred to other cities, but the model itself could not. They use traffic characteristics and land use patterns to generate a network, but from the article, it seems that they did not estimate a demand model. Instead, they used readily available OD matrices based on traffic measurements. Thus the policy analysis is only applicable to the network assignment, and does not include effects on the demand level.

Kanaroglou and Buliung (2008) also focus on the environment with their model for the city of Hamilton. They use integrated land use and transport modelling to estimate emissions from urban freight transport. Their methodology only needs limited data, which enhances transferability to other urban areas. However, no examples of transferring this model are given, and the authors themselves state that freight is sensitive to the unique characteristics of specific urban areas. This complicates transferability. Moreover, similar to Yannis et al. (2006), only traffic assignment and an emissions model were applied, using existing OD matrices based on traffic surveys and passenger car equivalents. The focus is on the conversion of traffic patterns to emissions, but no assessment of policy measures is discussed in the article.

The most recent example that has been found, is the CMAP model for Chicago (Urban et al., 2012). While this is an agent-based model and is based on interactions between establishments, the model uses an establishment generation step to generate a synthetic establishment population. Consequently, it does not need detailed data. The model is suitable to asses policy measures, and the report gives an elaborate list of potential policy scenarios. Unfortunately, more recent literature about this model and its application has not been found.

### 2.4.2. Models based on establishment data

The models described in this section are based on detailed establishment characteristics, often from national databases such as the French SIRENE database that is used in Freturb (Routhier and Toilier, 2007; Coulombel et al., 2018). Data characteristics include information about location, the number of employees and the floor space of an establishment. A disadvantage of the use of these types of data is that they are often protected and thus not easily accessible to any person or organisation.

The earliest model that is discussed in this review is a model for the city of Delft (NL) by Visser and Maat (1996). They use data on establishment type and location from the Dutch Chamber of Commerce (KvK). The number and type of establishments in a zone are used to estimate the number of deliveries, which, after several modelling steps, lead to an ”environmental scan” which outputs emissions and noise. However, the model is not validated, and although the authors speak of ”plausible and promising” results, more literature about a continuation of the model has not been found.

Another model that is based on establishment data is VISEVA/WIVER. This model is mentioned by many articles about urban logistics modelling, but there is barely any literature to be found that discusses the model. The model has been applied to several German cities, but the article about the model that was found (Friedrich et al., 2003) does not elaborate on how this transferability was established. Moreover, it does not discuss possibilities for assessing any policy measures.

From around the same time, there is a microsimulation model for the city of Tokyo that explicitly considers choices of firms (Hosoya et al., 2003; Wisetjindawat and Sano, 2003). The article by Hosoya et al. (2003) gives an interesting perspective because it considers emissions. Moreover, the assessment of three emissions mitigation measures is described: large-size truck bans, road pricing and the construction of an urban consolidation centre (see section 2.5 for a description of the outcomes of the assessment). However, in the available literature, it is unclear if the model can be transferred. The model uses location-specific firm behaviour characteristics and detailed establishment data to generate the demand model. This indicates that transferability to other areas may be difficult. Moreover, Tokyo is a mega-city and is therefore not suitable to be compared to European cities (Aditjandra et al., 2016).

Another case that suffers from incomparability with European cities because of the size and structure of the modelled city, is the TLUMIP model. This model was initially designed for the state of Oregon, but has since been applied to other states and cities in the United States (Donnelly et al., 2010). It is an agent-based model that uses detailed firm characteristics and the decision-making is based on traffic surveys. According to the authors, the model can be used for policy assessment. However, no additional literature has been found that discusses how policies were implemented, or even which policies were considered.

The Freturb model (Routhier and Toilier, 2007; Toilier et al., 2018) is the most appropriate existing model that has been found. It comprises a large number of urban areas in France, Belgium and Switzerland. It is a delivery-based model, and the only input that is needed is a detailed file of the establishments that are located in the city. Moreover, it has already proven to be suitable to analyse the effects of policy measures and to assess emissions caused by urban freight transport. Coulombel et al. (2018), for example, used Freturb in a case study of Paris in which they estimated the environmental cost of urban road freight. However, the authors state that the availability of rich national statistics is essential. Moreover, while the authors state that policy measures can be assessed, no explanation is given on how this is done, which measures are assessed or what their effects are.

Muñuzuri et al. (2009, 2010, 2011) created a model for the city of Seville, and state that their approach requires fewer data than other models. However, the model is based on establishment data, and the demand model is estimated based on surveys and vehicle counts. Thus, the authors fail to clarify how exactly they use limited data, or what they consider to be limited data. Furthermore, the authors mention that the transferability of the model should be investigated, but no later application of a transferred version of the model has been found.

A model that has, on the other hand, successfully been transferred is a model for Rome by Nuzzolo et al. (2012). It is a delivery-based model that uses data on the number of retailers and the number of employees to estimate freight demand. The model was successfully transferred to the city of Santander, but that did require an additional traffic survey to estimate new model parameters.

The CityGoods model by Gentile and Vigo (2013) is delivery-based as well. One of their most important findings is that the use of supply chains that are specific to urban goods transport is essential. They use a category index model to establish the supply chain categories. Furthermore, they briefly discuss transferability of the model, but it remains unclear whether this is a possibility. No examples of application of this model in other regions have been found. Moreover, since the model has a disaggregate approach and estimates freight demand on the establishment level, detailed establishment data are needed. This could be hampering spatial transferability to regions where these data are not available. The authors do, however, show that a more aggregated model is not necessarily performing much worse than a very disaggregated model.

There is one paper that discusses the effects of policy measures in great detail, by Aditjandra et al. (2016). They write about their model of the university district of Newcastle. The results of their policy assessment of a truck ban in the university district are well-described and could be of help to future modellers. However, the model in general is not useful to serve as an example for this study because its scale is so small.

Anand et al. (2014) propose an agent-based modelling approach that focuses on interactions between actors. They model the whole movement of goods from the viewpoint of the stakeholder, effectively modelling the whole process from goods demand by city inhabitants to the transportation of goods by carriers from shippers to shops, and management of infrastructure by the administrator. The methodology is applied to the road network of Rotterdam, but uses a synthetic set of agents (the authors define this as a ”toy model”). Variables that are used on the establishment level are for example floor area, service level and profit margin. Based on shop characteristics, consumers decide on a shopping destination, inducing goods demand. Because of the level of detail of the methodology and the possible difference between decision-making structures of agents in different countries, transferring this model to different European cities would be difficult. In terms of policy analysis, no measures regarding emissions reduction have been assessed. The authors do however describe an experimental scenario in which cooperation between stakeholders is promoted. In terms of environmental effects, this scenario shows a reduction in the total truck distance.

The last and most recent model that is discussed here is MASS-GT: an agent-based model which is currently being developed for the province of South-Holland in the Netherlands (De Bok and Tavasszy, 2018). It uses a rich dataset, with which an urban freight transport model that describes shipments on the firm level can be created. The article does not discuss transferability of the model, but because of its modular approach, different parts of the model and their methodology can possibly be used for other applications. However, the level of detail in the data makes transferability difficult. The authors mention that the model is built with the aim of testing policies, of which the implementation and results are discussed in De Bok et al. (2020) and De Bok et al. (2019). These results are further elaborated in section 2.5.

### 2.4.3. Models based on combined socio-economic and establishment data

The models that this section comprises, use a combination of socio-economic and establishment data. The earliest model that has been found, is the GoodTrip model by Boerkamps and Van Binsbergen (1999), which was applied to the city of Groningen (NL). Since the authors argue that the structure of a supply chain is essential for trip patterns, the model focuses on two supply chains: bookstores and food retail. The model is based on interactions between spatial organisation, infrastructure, goods flows and traffic flows. It uses data on spatial organisation as a driver for goods demand, but for their case study, the authors use detailed data of average consumer expenditure in all supermarkets in the city. If this data collection were needed for every city, transferability would be an issue. Being one of the earlier attempts to modelling urban freight transport, it is remarkable that they managed to assess two policies with this model, to review the environmental impacts of these policies. The two policies that have been assessed are urban consolidation centres and underground tubes for goods distribution (see section 2.5 for more details).

Another early example is a methodology by Russo and Comi (2002), who base freight generation on the number of families in a zone. With coefficients that they found in literature, they calculate shopping trips for durable and non-durable goods. This shows that their model is focused on last-mile delivery of consumer products. They use a distribution model that is based on the travel costs between zones and the attractiveness of a zone, based on the number of employees, the number of shops, retail floor space and others. The article explains the methodology, and although it is stated that the model is calibrated to the region of Calabria, no detailed application to an urban area is given. This means that no policies have been assessed, and the question if this methodology could be easily applied to different urban areas is not answered in the paper. Since the freight generation coefficients that are used originate in Italian literature, transferability of the demand model to areas outside of Italy is questionable.

A continuation of the application of the above-mentioned methodology can be found in a model for Calabria, which was established years later by the same authors (Russo and Comi, 2010). This model is suitable for policy analysis, and it is a multi-step disaggregate delivery-based model (instead of the earlier commodity-based model). Freight movements are driven by freight demand of consumers, and there is a differentiation by consumer trips and logistics trips. The model is calibrated on a consumer-focused survey including detailed household data, and a logistics-focused survey including detailed establishment data such as location, size, types of goods sold, number of employees, average number of customers per day/week and storage availability. In general, the methodology is clearly described and structured, but the amount of data needed for the model would be too large to create a model that is easily applicable to a large number of urban areas. Furthermore, despite the model being created with ex-ante policy assessment in mind, no application for policy assessment has been discussed in literature regarding the model.

Two more examples that, just as the models for Tokyo and Chicago, are not comparable to European cities because of the size and nature of the cities, are the LAMTA model for the Los Angeles region (Beagan et al., 2007) and a model for New York city by Lawson et al. (2012). LAMTA consists of an urban as well as a regional component. What makes this model very interesting is that it includes logistics hubs in which different shipments are chained. These hubs are only used in the regional component of the model, but could serve as an example for the inclusion of consolidation centres in urban freight models. The LAMTA model has elaborate data requirements and is based on network data and detailed socioeconomic data including employment in different sectors. The documentation in the report by Beagan et al. (2007) does not elaborate on further options for transferability or policy analysis, but with regards to transferability, it can be assumed that this would be difficult because of the highly location-specific data requirements. The model for New York by Lawson et al. (2012) only considers freight trip generation, which is estimated using land use classifications, goods reception surveys, and the number of employees per establishment. The authors themselves state that the use of this dataset is limited exclusively to New York.

Another model that aims at estimating freight trip generation was created by Alho and De Abreu e Silva (2014). They make use of logistics profiles based on spatial data, and predict the number of weekly deliveries to establishments with a regression model based on the number of employees. They also had datasets available for the floor space of the establishment, but these proved not to be a good predictor. An important conclusion from these modelling efforts is that differentiation for different supply chains improves the performance of the model, although in the end the predictive qualities of the model were deemed insufficient.

Hunt and Stefan (2007) give an elaborate description of their model for Calgary (CA), which is very useful in terms of methodology. Moreover, this model has, with some adaptations, been transferred to other urban areas. However, the data on which the model has been built are very detailed (based on interviews on firm-level), which hinders transferability to areas that do not have these data available. Moreover, the model is truck-based, not commodity-based. Taking into account the suitability of the model for policy analysis, a model that translates commodity flow into shipment size into vehicle allocation would be more appropriate for this purpose (see section 2.2 for an explanation). The model that was created by Hunt and Stefan (2007) was successfully transferred to the Greater Toronto and Hamilton Area by Ferguson et al. (2012), although they had some challenges with the re-estimation of location-specific model parameters. Furthermore, they do not mention any implementation of policy measures.

Table 2.2: Existing models for urban freight transport

| **Reference** | **Urban area(s)** | **Focus** | **Category** | **Modelling structure** | **Underlying data** | **Policies tested** | **Easy spatial transferability?** |
|---|---|---|---|---|---|---|---|
| Visser and Maat (1996) | Delft (NL) | Environment | Vehicle | Combined | Establishment | N | N |
| Boerkamps and Van Binsbergen (1999) | Groningen (NL) | Environment | Commodity | Adapted four-step | Socio-economic, establishment | Y | N |
| Russo and Comi (2002) | Calabria (IT) | Policy | Commodity | Adapted four-step | Socio-economic, establishment | N | N |
| Friedrich et al. (2003) | DE cities | Unclear | Vehicle | Classical four-step | Establishment | N | Y |
| Hosoya et al. (2003); Wisetjindawat and Sano (2003); Wisetjindawat et al. (2007) | Tokyo (JP) | Emissions | Commodity | Adapted four-step | Establishment | Y | N |
| Yannis et al. (2006) | Athens (GR) | Policy, Environment | Vehicle | Combined | Socio-economic | Y | N |
| Beagan et al. (2007) | Los Angeles (US) | Policy | Vehicle, commodity | Adapted four-step | Socio-economic, establishment | Y | N |
| Beagan et al. (2007); Donnelly et al. (2010) | US cities | Policy | Commodity | Combined | Establishment | Y | Y |
| Hunt and Stefan (2007) | Calgary (CA) | Policy | Commodity | Combined | Socio-economic, establishment | Y | Y |
| Routhier and Toilier (2007), Toilier et al. (2018) | FR cities | Policy | Delivery | Combined | Establishment | Y | Y |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Kanaroglou and Buliung (2008) | Hamilton (CA) | Emissions | Vehicle | Combined | Socio-economic | N | Y |
| Muñuzuri et al. (2009, 2010, 2011) | Seville (ES) | Policy | Delivery | Adapted four-step | Establishment | N | N |
| Russo and Comi (2010) | Calabria, Palermo (IT) | Policy | Delivery | Adapted four-step | Socio-economic, establishment | N | N |
| Urban et al. (2012) | Chicago (US) | Policy | Commodity | Combined | Socio-economic | N | N |
| Ferguson et al. (2012) | Toronto (CA) | Policy | Commodity | Adapted four-step | Socio-economic, establishment | N | N |
| Lawson et al. (2012) | New York (US) | Unclear | Vehicle | Classical four-step | Socio-economic, establishment | N | N |
| Nuzzolo et al. (2012); Nuzzolo and Comi (2014); Nuzzolo et al. (2016) | Rome (IT) | Policy | Mixed: vehicle, commodity, delivery | Adapted four-step | Establishment | N | Y |
| Gentile and Vigo (2013) | Emilia-Romagna (UT) | Policy | Delivery | Adapted four-step | Establishment | N | N |
| Alho and De Abreu e Silva (2014) | Lisbon (PT) | Unclear | Delivery | Combined | Socio-economic, establishment | N | N |
| Aditjandra et al. (2016) | Newcastle (UK) | Emissions | Vehicle | Combined | Establishment | Y | N |
| Anand et al. (2014) | Rotterdam (NL) | Policy | Delivery | Combined | Establishment | Y | N |
| De Bok and Tavasszy (2018) | Rotterdam (NL) | Policy | Vehicle | Combined | Establishment | Y | N |

## 2.5. Mitigation measures in existing models

This section discusses the implementation and assessment of the identified mitigation measures from section 2.1.1 in the existing models as discussed in section 2.4. Other applications of these measures in more operations-focused literature have been found as well, but these have not been included because they are not in the scope of the literature review in section 2.4.

**Zero/low-emissions vehicles**

Aditjandra et al. (2016) mention that one of the scenarios that they explore could resemble the introduction of electric vehicles. The scenario does not take into account any freight traffic in the study area, and shows a significant decrease in emissions. This does remain a very simplified solution and only shows how emissions would reduce if commercial trips were banned altogether. It does not consider changing interactions with other vehicles.

**Restricted access to zones**

Two models are used to assess the effects of restricted access to zones, both related to area restrictions during peak hours. Yannis et al. (2006) explore two scenarios in which deliveries are restricted during peak hours, either for all commercial establishments or only for supermarkets and department stores. The scenarios show an increase of the average traffic speed during peak hours, but a decrease in average speed during non-peak hours. The authors also observe the effects of these measures on the emissions of CO and $SO_2$, and show that the reduction in the emissions of the pollutants during peak hours outweighs the increase of emissions during non-peak hours.

Another implementation of restricted access to zones can be found in Hosoya et al. (2003), who investigate the effects of large-size truck bans during morning peak-hours for an inner-city zone. They observe that the distance driven by small trucks almost triples, while the distance driven by large trucks decreases by 60 percent. This leads to a reduction of $NO_x$ emissions of almost 20 percent.

**Pricing measures**

Three articles mention the implementation of pricing measures. Road pricing has been assessed by Hosoya et al. (2003), who, similar to their implementation of zone restrictions, investigate the effects of road pricing inside a certain zone during daytime for the city of Tokyo. Several tariffs that differ per vehicle type have been tested. Effects that are similar to restricted access can be observed: an increase in distance travelled for small trucks and a decrease for large trucks, which leads to an overall reduction of sixteen percent in $NO_x$ emissions.

Hunt and Stefan (2007) assess two different pricing measures in their model of Calgary: a 25 percent increase in the cost per unit distance, and a stop charge for vehicles making stops in the central business district (CBD), which increases with the heaviness of the truck. Both measures show an increase in the number of trips and the number of tours relative to the base case. With regards to vehicle kilometres travelled, the increased cost scenario shows a decrease, while the CBD charge shows a very small increase in vehicle kilometres.

The most recent implementation of pricing measures has been done in MASS-GT (De Bok et al., 2019). The authors explain the implementation of an emission-based truck charge, in which a certain cost per kilometre is added. They observe a small shift from high to low emission vehicles: five percent of trips for a non-bulk commodity and sixteen percent of trips for a bulk commodity.

**Urban consolidation centres**

Three of the models that have been reviewed were used to assess the effects of UCCs. Boerkamps and Van Binsbergen (1999) examine the change in distribution patterns when a UCC would be implemented. They conclude that the implementation of a UCC would significantly reduce the distance that is travelled by trucks, but that it would significantly increase the total mileage of vans. There is an increase in $CO_2$ emissions of more than 20 percent. The emissions inside the city centre decrease, but the emissions outside the city centre increase. Naturally, this would change if instead of conventional vans, electric vans would be used.

Hosoya et al. (2003) evaluate the use of logistics centres based on the percentage of construction and maintenance costs that a firm would have to pay. They show that even if this percentage would only be 25 percent, only 4.5 percent of the firms would use the logistics centre. Thus, the changes in the use of small and large trucks and $NO_x$ emissions are zero. They also perform a cost study, and conclude that the implementation of a UCC would be infeasible.

De Bok et al. (2020) describe the implementation of a zero-emission zone in combination with UCCs: four UCCs are placed at the border of the zero-emission zone, in which shipments are consolidated to be distributed inside the zero-emission zone. They observe an increase in vehicle-kilometres, but this increase is partly absorbed by a higher consolidation of shipments into the same tour. Within the zero-emission zone, emissions are reduced.

**Intelligent Transport Systems**
None of the models in section 2.4 mention the implementation of this innovation.

## 2.6. The scientific gap

In the review of models in section 2.4 and the summary in table 2.2, a lack of models that are both suitable for policy testing and can be transferred to other areas can be observed. There are only two models that accomplished this: Freturb by Routhier and Toilier (2007), and Hunt and Stefan (2007)'s model for Calgary, which was transferred to Toronto by Ferguson et al. (2012). However, in the latter case, Ferguson et al. (2012) state that the adaptation was not simple. The model had to be re-estimated, and the authors had some challenges with the re-estimation of location-specific model parameters. Moreover, the tour generation approach was fundamentally different from the approach of Hunt and Stefan (2007). In terms of transferability, the Freturb model is the most appropriate example that has been found, since it has already proven its worth in a large number of cities. However, since the models need a detailed database of the establishments in the city, the question remains if this model could be applied to all countries in Europe, since it is not clear if these countries all have easily accessible databases of their firms.

Concluding: no models have been found that are easily transferable, appropriate to assess policy measures, and that are based on easily accessible data. Moreover, policy assessment seems to be nearly nonexistent in more recent models, with only three of the fifteen reviewed articles from the past ten years describing the assessed effects of policy measures. The other articles all seem to focus on modelling efforts rather than the societal impact of these models. One can see that there is a clear need for a generalised, aggregate model for urban logistics, which is based on publicly available data. These data include data on land use, grid-based counts of urban establishments in certain sectors, and general freight transport characteristics on the NUTS3 level that can be provided by Eurostat.

# 3 Methodology

This chapter elaborates on the methodology that has been established to create a model for freight transport in the Groot-Rijnmond region. First, the boundaries for the study are set by establishing transferability requirements in section 3.1. Then, the modelling structure and methodology are clarified in section 3.2. Finally, in section 3.3 it is explained how the selected mitigation measures can be implemented in the model.

## 3.1. Transferability requirements

In terms of transferability requirements, data availability is essential. Transferability is enhanced by the use of data sources that are widely available (Giuliano et al., 2010). Thus, to be able to transfer the model to other urban areas in Europe, the underlying data of the demand model should come from datasets that are available for the entire European Union, and that are accessible by the ITF/OECD. Considering the data sources that have been used in this study as elaborated in chapter 4, it should be noted that the socio-economic dataset that is provided by the CBS is not available for countries other than the Netherlands. Comparable datasets could be available, but it would be very time-intensive to find these for all countries in the EU. Furthermore, it could be even more time-intensive to convert them to the same structure for all countries. Therefore, it is interesting to analyse the difference in results between models that make use of CBS spatial data, and models that are solely based on European data by the ITF/OECD and the EU (see section 4.1 for a description of the datasets). This is briefly described in section 5.1.1. Since truck trip generation is usually not spatially transferable, the modelling structure is commodity-based because of its underlying indicators for freight demand (Giuliano et al., 2010).

To deal with the limited data availability, some assumptions were made for the different modelling steps. The main transferability issue is freight demand, since this is highly location-specific. Whereas Holguín-Veras et al. (2013) show that freight generation models can in some cases be transferred between areas, it could still be wise to validate the transferability of the parameters of the generation model for other cities using freight surveys. However, this was outside of the scope of this thesis. With regards to creating OD flows for freight in the distribution step, the importance of uniformly sized zones have to be taken into account, as the parameters of a gravity model are not transferable in the case of differently sized zones (Moeckel and Donnelly, 2016).

The steps that lead from OD flows to vehicle trips can be based on Eurostat European Road Freight Transport (ERFT) survey data on the NUTS3 level. Starting with the creation of shipments, Koning et al. (2018) show that shipment size choice can be transferred between France and Germany. Based on this outcome, the assumption was made that shipment size choice is at least the same within one country. Additionally, the assumption was made that the ERFT data on the NUTS2 or NUTS3 level are accurate enough to predict vehicle choice.

## 3.2. Structure of the model

The structure of the modelling methodology has been created with the idea that it should be possible to use the methodology in all European urban areas. In this, it differs significantly from all urban logistics modelling literature as discussed in section 2.4. The model that has been created is a commodity-based model based on socio-economic spatial data. The model is commodity-based because this enables the estimated demand-model to be calibrated on the ITF regional freight model or on Eurostat freight statistics on the NUTS3-level. It is an adjusted four-step model, without assignment to the road network but with an additional emissions model. In figure 3.1, a visualisation of the conceptual model can be seen that shows the highest level of hierarchy of the model.

Figure 3.1 gives a technical visualisation of the model as a flowchart. The figure shows the different modelling steps indicated by dashed rectangles. The technical model shows the modelling structure as an adapted four-step model, with the first two steps leading to commodity flow OD matrices. An emissions model can be applied after the creation of trips performed by a certain vehicle, and gives the final output of the model: the total emissions for the region. The transferability framework is indicated by a red line, which shows that all the data sources that are located within the line are available for all of Europe. In the next sections, more detailed descriptions of the separate modelling steps are given along with visualisations of the decision structure.

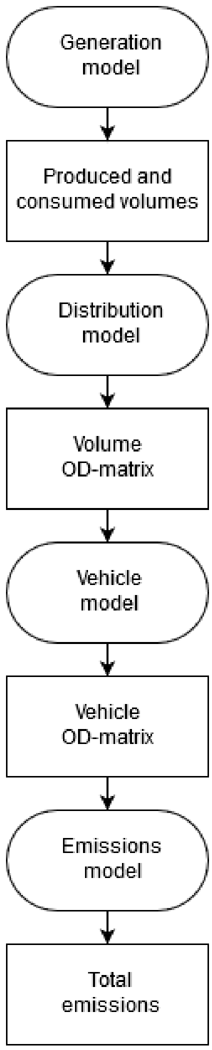



Figure 3.1: Conceptual model (adapted from Comi et al. (2012))

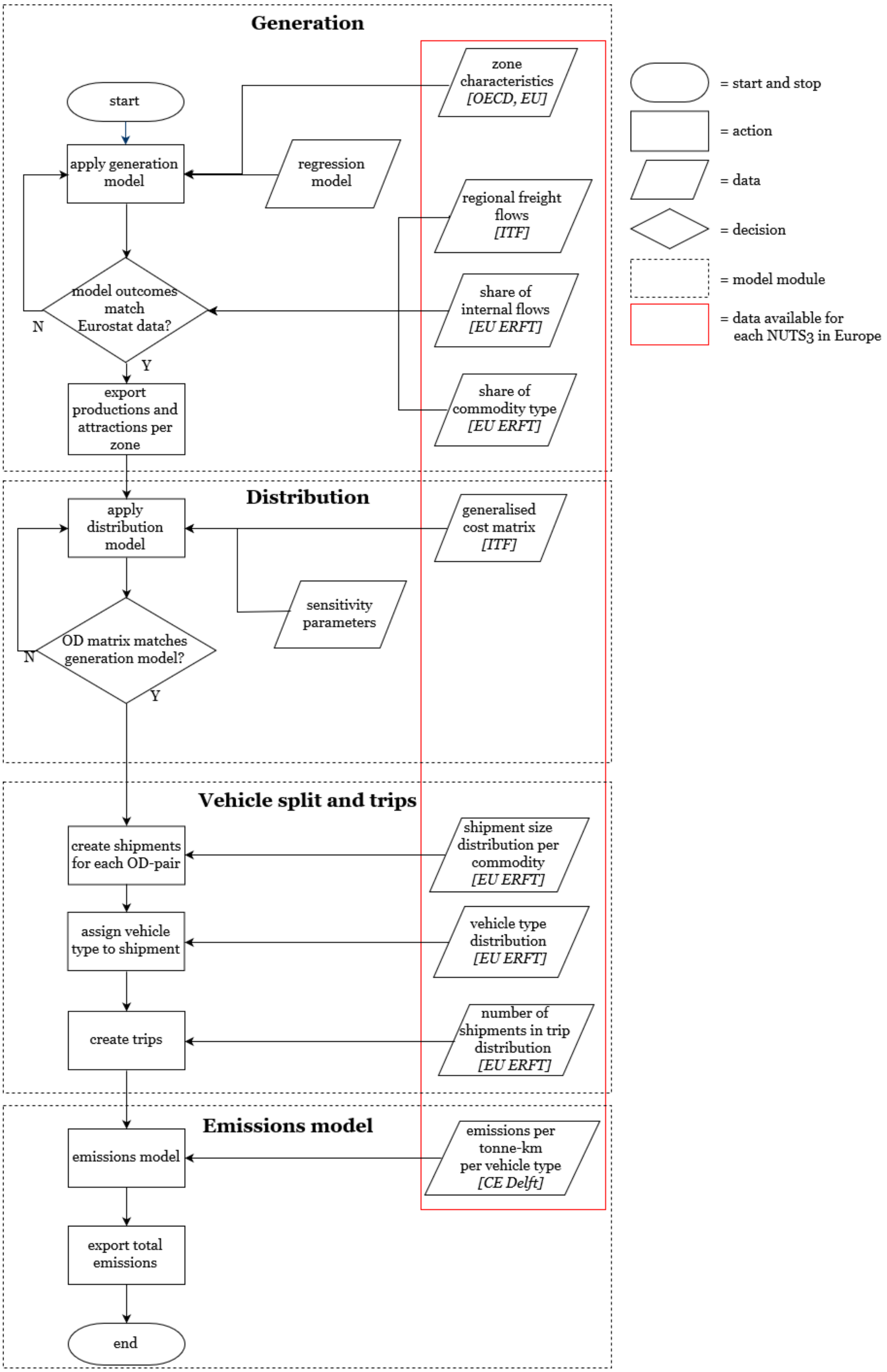



Figure 3.2: Flowchart of the modelling steps

### 3.2.1. Generation of freight volumes

Figure 3.3 shows the detailed modelling structure of the generation step. The estimation of the generation model is based on commodity volumes that are produced and consumed in 1x1km zones. More information about these zones is given in section 4.2.1. The variable ”in_model” defines if a certain zone should be used for demand generation. For example, zones that consist of water for the largest part, have been given a value of zero, meaning that they are not included in demand estimation. A generalised linear model (GLM) has been estimated to predict freight production and consumption in each included zone per commodity type. The model uses observed freight volumes as the dependent variable and a set of zonal characteristics as independent variables. Three different types of GLMs have been assessed on their fit to the data and the accuracy of their predictions: a zero-truncated ordinary least squares (OLS) regression model, a Tobit model, and a zero-inflated negative binomial (ZINB) model.

An OLS model has the following structure:

$$y_i = \beta_0 + \beta_1 x_{i1} + ... + \beta_n x_{in} + \epsilon_i$$

In this structure, $y_i$ is the estimated freight production or consumption in zone $i$, $\beta_0$ is a constant in the equation, and $\beta_n$ is the coefficient for variable $n$ that should be multiplied by the value $x_i n$ of variable $n$ in zone $i$. $\epsilon_i$ is the error term of the model, which is normally distributed. Negative estimations of the model are adjusted to zero, since negative freight production or consumption is not possible.

A Tobit model can be defined as follows:

$$y_i^* = \beta_0 + \beta_1 x_{i1} + ... + \beta_n x_{in} + \epsilon_i$$

where

$$y_i = \begin{cases} 0 & \text{if } y_i^* \leq 0 \\ y_i^* & \text{if } y_i^* > 0 \end{cases}$$

This model is naturally able to deal with zero-inflated data, which can be the case in terms of freight production and consumption in the different zones. Not all zones produce or consume freight, so the predicted value should be zero. The error term of the Tobit model is normally distributed as well.

The difference between the OLS and Tobit models and ZINB models is the probability distribution of the error term: while following a normal distribution in the case of OLS and Tobit GLMs, the error term follows a negative binomial distribution in the case of a ZINB GLM. The ZINB model consists of two parts: a negative binomial logistic part and a binomial logit part. The first part defines the estimation of the produced and consumed freight volumes, while the second part estimates the probability that the volume is zero. Although this model is particularly used for count data, it is still interesting to analyse its performance since a certain tonnage could be seen as a count as well. The results of the estimation of the different methods can be found in section 5.1.

For commodity flows coming into and going out of the region, one external zone is defined. The flows coming out of and going into this zone can be calibrated based on the ITF regional freight model, that includes all urban NUTS3 regions in Europe as separate zones. A general multiplication factor can then be applied to all generations to match the volume defined by the ITF model. It is assumed that the generation of the internal zones changes proportionally to the change that is needed to match the incoming and outgoing flows.

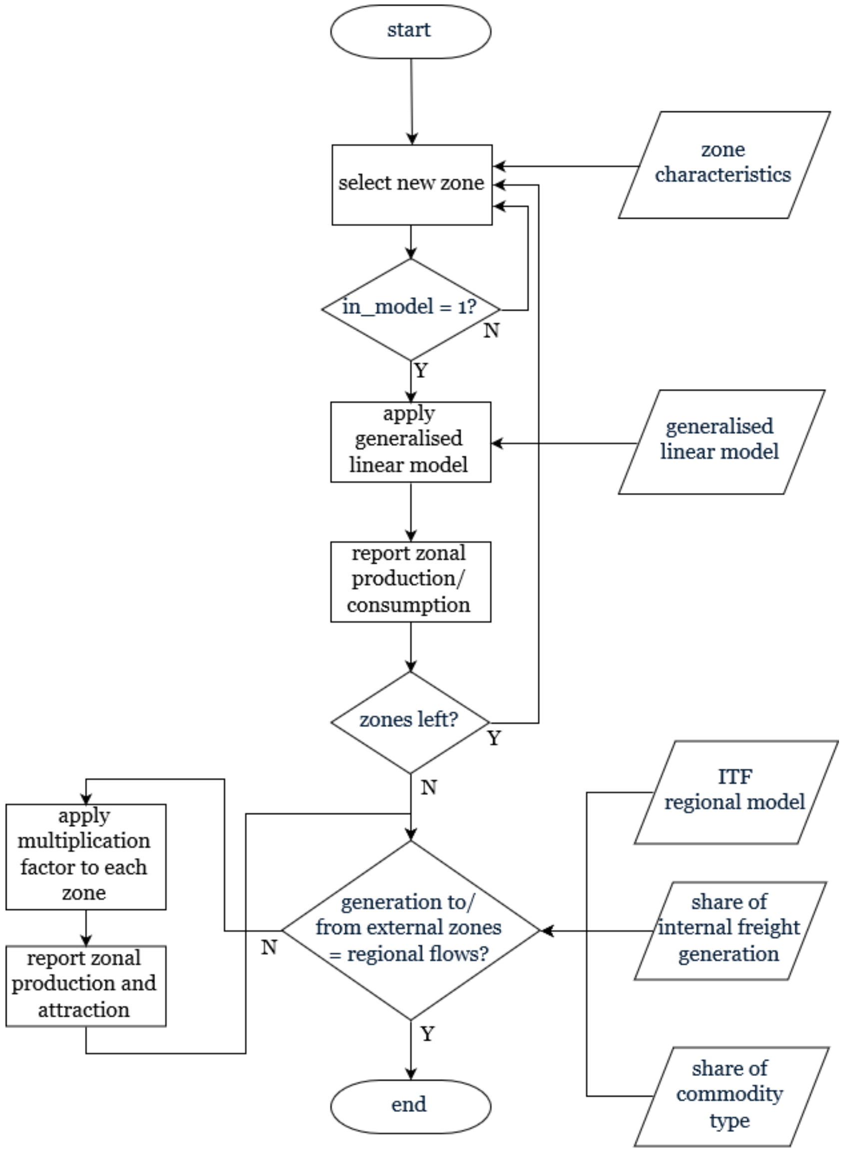



Figure 3.3: Technical model for freight generation

### 3.2.2. Distribution of freight flows

The distribution step is based on a doubly constrained gravity model. Its structure is shown in figure 3.4. The mathematical formulation of the model is as follows:

$$V_{ij} = p_i * P_i * q_j * C_j * f(c_{ij})$$

In this equation, $V_{ij}$ denotes the transported freight from zone $i$ to zone $j$, while $P_i$ and $C_j$ are the reported production and consumption of freight in the corresponding zones, multiplied by zone-specific multiplication factors $p_i$ and $q_i$. These are multiplied by function $f$ that determines the accessibility of the destination zone based on the travel cost between zones $c_{ij}$:

$$f(c_{ij}) = e^{-\beta c_{ij}}$$

In this function, $\beta$ is a sensitivity parameter, while $cij$ is based on impedances between zones that are given by a skim matrix, that take into account uncongested travel times and travel distances (at 80 percent of the maximum speed), because most shipments are transported during non-peak hours (see section 4.3.2, figure 4.7). This skim matrix is based on the existing network definition that is used by the ITF, and a generalised cost function by Rijkswaterstaat (2016). The idea to use a generalised transport cost function as the main input for the distribution model was taken from Davydenko and Tavasszy (2013). However, a large difference is that the possibility to form detours via warehouses was omitted. This choice was made because considering the fact that the study region has 1892 zones, this would add a significant amount of computation time.

An iterative method is used to estimate the sensitivity parameters and thus to calibrate the accessibility functions, based on average kilometres driven per tonne for each commodity. The difference between the empirical tonne-kilometres and the estimated tonne-kilometres is minimised:

$$minimise|\sum_{i=1}^{N-1}\sum_{j=1}^{N-1}V_{ij}d_{ij} - |\sum_{i=1}^{N-1}\sum_{j=1}^{N-1}V_{ij}D|$$

In this formula, $V_{ij}$ is the transported flow between zones, $d_{ij}$ is the distance between zones according to the skim matrix, and $D$ is the average distance that is driven per tonne for a given commodity. The calibration of the final freight flows is done in 20 iterations, as this proved to be a number at which the multiplication factors for most commodities approach one.

### 3.2.3. From freight flows to trips

To calculate emissions, the estimated freight flows as described in section 3.2.2 have to be converted into trips. This is done in two steps: first, OD volumes are converted into shipments, after which these shipments are combined into trips. Tours (round trips) are not included in the model, since this would add complexity, and since tours only account for a small percentage of all the transported goods (see section 4.3.2).

Figure 3.5 shows the first step of this model module: the creation of shipments. This modelling step is based on the shipment synthesizer procedure as described by De Bok and Tavasszy (2018), with the exception that no production and consumption firm are selected. The shipment creation procedure entails an iterative procedure for each OD flow, that is split into shipments based on an empirical shipment size distribution. Using shipment size clusters, vehicles are allocated to the shipments (see appendix F for the distributions). Additionally, the distance travelled is added, based on the congestion in the network at the allocated hour of departure. Relevant peak hours are taken from TomTom traffic reports (TomTom, 2019), which show that peak hours in Rotterdam take place during 7-8am and 4-5pm. When there is no freight volume left between the selected OD pair, the procedure stops.

After the creation of shipments, trips are created to be able to estimate emissions. The flowchart for the creation of trips is shown in figure 3.6. This procedure is performed for each OD pair. Within the list of shipments for that OD pair, a shipment is selected that is not part of a trip yet, for which a number is drawn from an empirical (commodity-specific) distribution that gives the probability of the number of shipments within the trip. If this number is larger than one, an iterative procedure starts that adds shipments to the trip, until the maximum permissible weight (according to numbers by International Transport Forum (2015)) or the maximum number of shipments is reached. A requirement to cluster shipments into one trip is that they were assigned the same vehicle type during the creation of shipments.

### 3.2.4. Emissions model

A simplified emissions model has been applied, based on the driven distances per vehicle type and the load of the vehicle. This is based on research by Otten et al. (2017). It should be noted that this is not the most accurate solution since it does not take into account the speed and acceleration of the vehicle. However, for an aggregate model, this solution is sufficient

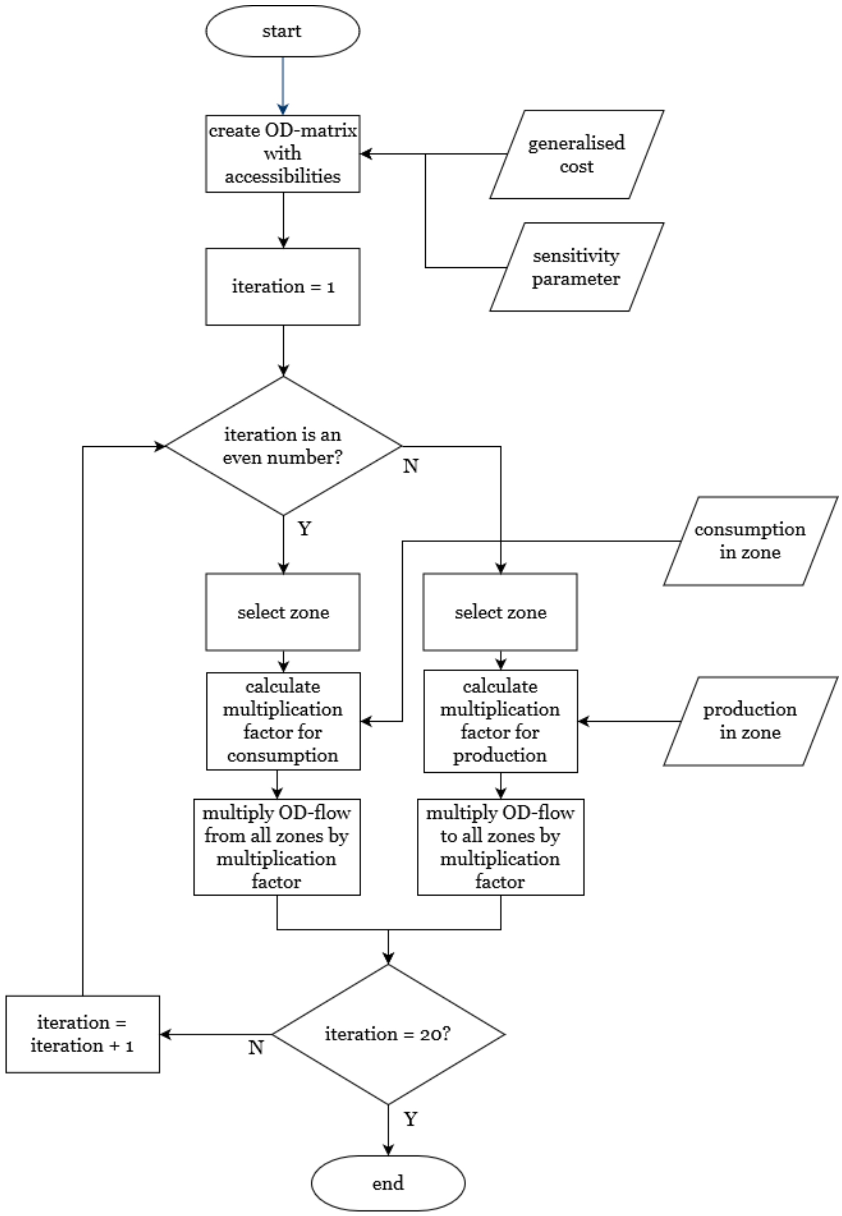



Figure 3.4: Technical model for freight distribution

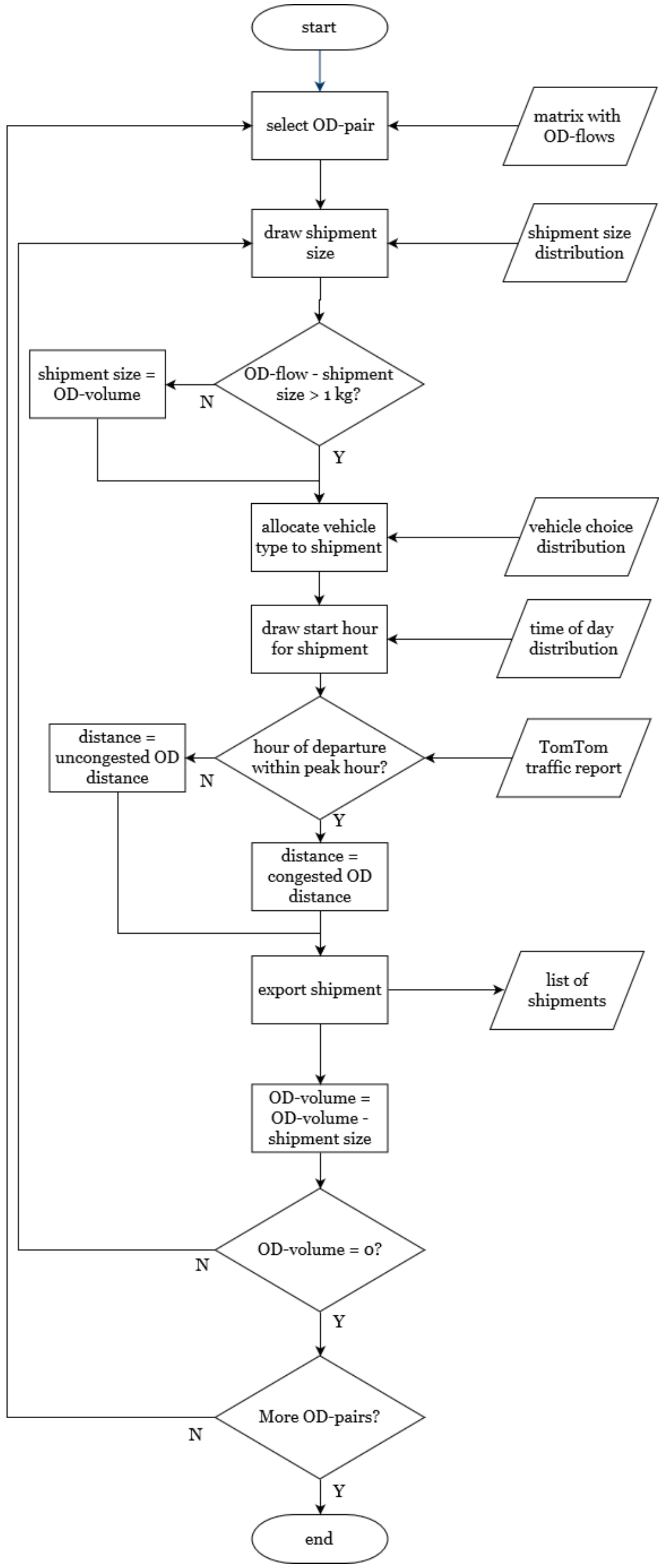



Figure 3.5: Technical model for creation of shipments

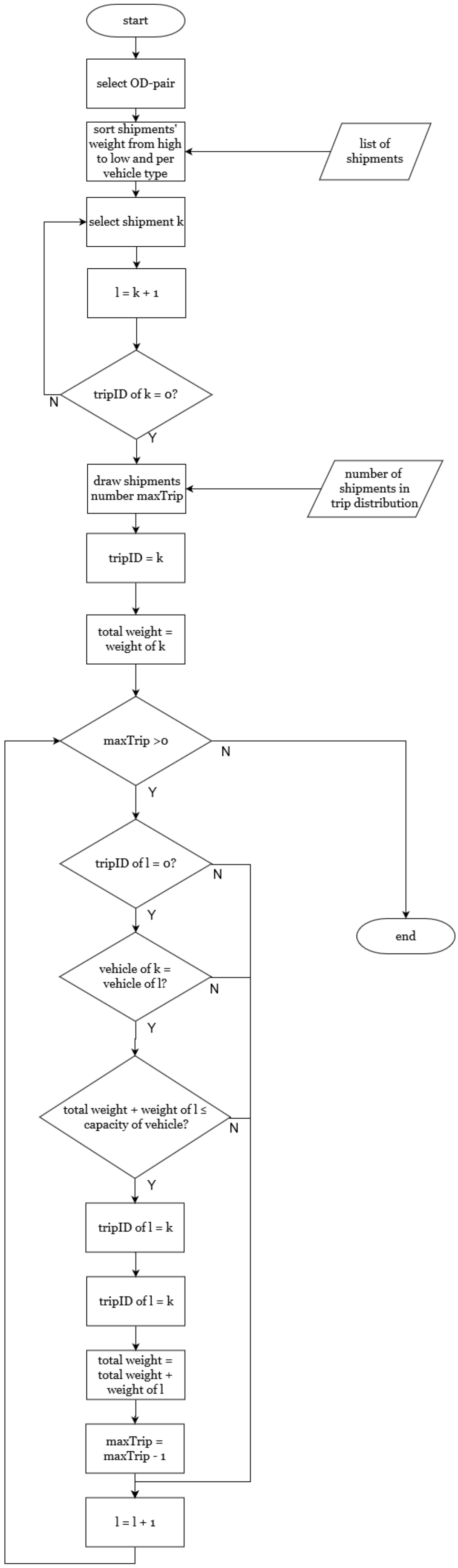



Figure 3.6: Technical model for creation of trips

as it gives a good approximation of the emissions, and can still be used to assess the effects of mitigation measures. Additionally, it should be noted that only tank-to-wheel emissions are considered.

The emissions are different for each of the six vehicle-types in the data, as is described in section 4.3.2. There is a differentiation between cargo types: there is one emissions model for commodity types that mainly consist of bulk and general cargo, and another emissions model for commodities that are mainly transported in containers. Exact values of the emitted $CO_2$ per km and tonne can be found in appendix G.

## 3.3. Modelling mitigation measures

This section discusses how the various policy measures for mitigation of $CO_2$ emissions can be implemented in the model. The first subsection broadly explains possible model implementations for all the measures as defined in the literature review in section 2.1.1. The second subsection discusses the chosen methodology for the inclusion of the implemented measures (zero-emissions vehicles and pricing) in more detail.

### 3.3.1. Possibilities for modelling mitigation measures

This subsection explains the possibilities for implementing $CO_2$ mitigation measures for each of the measures as defined in section 2.1.

**Zero/low emissions vehicles**

There are two possibilities to model zero/low emissions vehicles. The first and most simple one is to only include them in the emissions model. The emissions per alternative fuel type have to be estimated, and can be multiplied by a share of alternative fuel vehicles within a vehicle type. The second possibility is to include alternative fuel vehicles as a separate vehicle type. They could take the characteristics of an existing vehicle type in terms of their probability to be used for the different commodity types, but have a different tonne-km to emissions conversion in the emissions model.

For the probability density function for the choice of a certain vehicle type, a new estimation would have to be made based on literature, expert judgement or known observed data. Ideally, this would imply the creation of a new deterrence function, but in the proposed methodology this is not possible because the allocation of vehicles is based on empirical distributions. This implementation also has implications for the creation of shipments, since certain goods would not be as suitable to be transported by electric vehicles (e.g. cooled goods and very large goods would cause difficulties).

**Restricted access to zones**

These restrictions can be implemented by significantly increasing the cost of a certain link in the network, based on the cost of a fine for entering a zone. This does, however, need specifications for vehicle type and time of day. Therefore, an integrated modelling approach, e.g. simultaneous distribution and vehicle split based on a deterrence function, becomes important when implementing this type of measure. When using vehicle distribution as is proposed in this project, restricted access to zones is expected to lead to an increase in vehicle kilometres.

**Pricing measures**

These restrictions can be implemented by increasing the cost of a certain link in the network, based on toll cost for entering a zone. This changes the travel impedance between certain zones, but can also affect assignment to the network. This can be done based on time of day and type of vehicle and implies the need for an integrated modelling approach (just as for the implementation of restricted access to zones).

**Urban consolidation centres**
The implementation of this measure is quite elaborate, considering the change in distribution structures that this measure causes. First of all, zones with UCCs would have larger freight production and consumption: their share in freight generation increases while the total freight generation of the region stays the same. Second, these zones should have specific vehicle split functions, and drastically change how shipments are grouped in a tour. Moreover, tour formation has to be included to account for the fact that tours would start or end more often in zones with a UCC.

As for the sub-measures as mentioned in section 2.1, the use of "human" modes would imply the use of new, entirely different modes, that can be used only for very short distances (e.g. only intra-zonal trips) and for very small shipment sizes (e.g. up to 30kg). The implementation of pick-up consolidation would be similar to the general implementation of UCCs. An addition that is specific for this measure would be that there is a reduction in consumption for congested zones nearby, since the consumption of these zones is included in the consumption of the zone with the UCC.

**Intelligent Transport Systems**
As for the two sub-measures that fall under ITS, for more efficient routing, instead of using an all-or-nothing assignment with capacity restraints (Van Binsbergen, 2018; Ortuzar and Willumsen, 2011), which is generally sufficient for modelling urban freight transport, it could be chosen to use system optimum assignment. The implementation of eco-driving is fairly straightforward. It can be done by adjusting the emissions model with a lower factor for $CO_2$ emissions, based on values found in literature or empirical examples.

### 3.3.2. Chosen methodology for the inclusion of mitigation measures

Not all measures that were mentioned in section 3.3.1 have been assessed during this project. The choice of measures was based on what has previously been done in other studies about urban logistics (as was discussed in section 2.5). Earlier assessed measures include zero/low emissions vehicles, restricted access to zones, pricing measures and UCCs. Since the modelling of UCCs adds significant complexity to the creation of the model, this measure was excluded. Furthermore, since pricing and restricted access to zones have similar implementations and effects, the choice was made to only assess a low emission zone based on pricing. An experimental plan to assess the effects of the measures is elaborated on in chapter 6, along with the results of the assessment.

Figure 3.7 shows the updated technical model including the implementation of the mitigation measures. The bright yellow data parallelograms indicate where differences were needed. Looking at the figure, it is clear that the implementation of the chosen measures is relatively straightforward. For pricing measures, a new generalised cost matrix has been estimated based on road tolls to specified zones. In some cases, the shortest path that was found to a destination in the creation of the skim matrix changed because of the added cost to certain links in the network. Additionally, to be able to assess the effects of certain shares of zero-emissions vehicles, the only aspect that had to be changed was the input of the vehicle distribution functions.

It should be noted that the chosen implementation is not ideal, as it only takes into account exogenous changes in vehicle types as a result of the vehicle choice being based on an empirical distribution. In future updates of the model, this should be one of the first aspects that is taken care of. Thus: the vehicle choice model should be endogenous and should perform based on deterrence functions between zones. The vehicle model should also be dependent on shipment size and cargo type. This way, measures such as low emission zone or restricted access to zones will directly impact vehicle choice. The expectation for the measures as they have been implemented in this model, is that an increased share of electric vehicles will lead to a reduction in emissions, but that zone pricing will lead to more kilometres driven and thus more emissions.

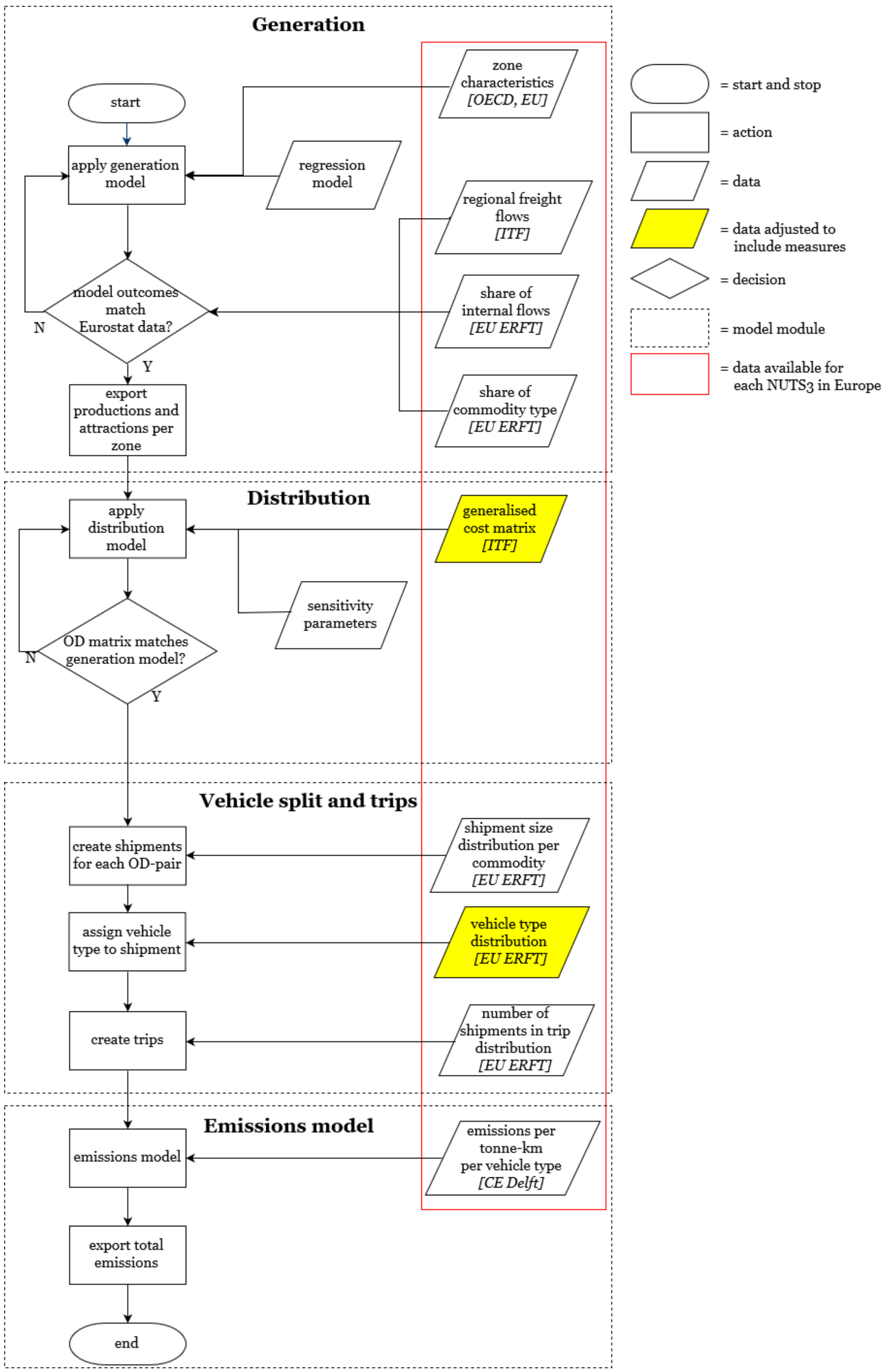



Figure 3.7: Technical model including implementation of $CO_2$ mitigation measures

# 4 Data

This chapter gives an overview of the data that were used to estimate the model. First, the source data are introduced in section 4.1, after which an explanation of the data manipulation needed to make model estimations is given in section 4.2. Finally, the structured data are discussed in section 4.3.

## 4.1. Description of available data

An overview of the data sources that were used to estimate the model is given in table 4.1. They are sorted by the organisation that is the source of the data.

Table 4.1: Overview of data sources

| Organisation | Data source name | Data |
|---|---|---|
| CBS | Wijk- en buurtkaart 2017 | Socio-economic data |
| CBS | XML-data freight transport survey | Detailed freight patterns |
| ITF/OECD | Services in urban areas | Grid of 1 x 1km with the number of commercial services |
| ITF/OECD | ITF regional freight model | Freight volumes entering and exiting the urban region |
| ITF/OECD | OECD population and GDP | Data on population and GDP |
| EU | CORINE Land Cover (CLC) | Spatial land use characteristics |
| EU | European Road Freight Transport survey | Regional freight statistics |

Two data sources from the CBS were used, one of which is publicly available, and one of which is a protected data source. The public data that were used contain socio-economic statistics on the level of neighbourhoods, and date from 2017 (CBS, nd). The variables that are included in this dataset can be used as independent variables to estimate freight demand. The data that are available on the neighbourhood level include e.g. data on population, composition of the population, the number of establishments and residences. The size of a neighbourhood (in terms of land surface) is very variable, and thus still needed to be converted to a uniform scale. The second data source by the CBS contains XML microdata from a road transport survey that is conducted in the Netherlands. The entire dataset contains over 2.5 million shipments, with information about the vehicle type in which the shipment is transported, the weight of the shipment, the commodity type, the location of origin and destination, the trip characteristics, etc.

From the ITF/OECD, three data sources were used. First of all, the ITF established a 1x1km grid for all urban areas in Europe, that contains data on the number and type of commercial services per zone. The data are based on area data by TomTom, and contain for example the number of supermarkets, the number of healthcare services, the number of shops etc. An important remark to make is that these numbers are based on reports of users, and could, therefore, contain inaccuracies. Because of the uniform nature of the grid, it could be used as zoning system for the model. The second data source that was used, is output from the regional freight model of the ITF, which could be used to calibrate the freight flows that have been estimated with the urban model. The last data source is a map (shapefile) with population and GDP by the OECD, that has a larger scale than the neighbourhoods data from the CBS. So conversion to the 1x1km grid was needed for these data.

Two publicly available EU data sources were used. The first is another spatial data source: the Corine Land Cover (CLC) by Copernicus (Copernicus, 2018). Copernicus is an initiative from the EU that uses satellite data to analyse spatial patterns, with the ultimate goal of improving the quality of life for the citizens of Europe (Copernicus, nd). The CLC provides small-scale data on the land use of specific areas, which are publicly available as shapefiles on the website of Copernicus. The second European data source that was used, is the European Road Freight Transport (ERFT) survey by Eurostat (Eurostat, nd). The survey offers general, anonymised freight transport statistics on the NUTS3 level, differentiated per commodity. This includes statistics on average shipment size, type of vehicle used and the load factor, and could be useful as a replacement for the statistics from the CBS microdata for the Netherlands.

## 4.2. Structuring the data

Since various data sources were used, they could not be used immediately, but data structuring was needed to be able to use them for model estimation. Moreover, only useful data was to be used and converted to a meaningful structure.

### 4.2.1. Spatial structuring

Spatial structuring was used to ensure that all data sources comprised the same region and used the same zoning system. Therefore the following data structuring was done:

- CBS XML-data freight transport survey: first of all, only shipments with an origin and/or destination within the Groot-Rijnmond region were selected, based on their four-digit postal code (PC4-code). Shipments with a transported weight of zero were removed, thus leaving out empty trips. Based on the reported commodity volumes, the total production and consumption of all commodity types were reported per PC4-code. Then, using overlapping surface, the production and consumption were assigned to the 1x1km grid that was used for this model. Freight production and consumption were the dependent variables in the estimation of the generation model (see section 3.2.1).
- CBS Wijk- en buurtkaart 2017: these data were converted to fit the 1x1km grid based on overlap in surface as well. Absolute numbers were divided by the surface overlap, while relative numbers were based on averages and were fit to sum to 100 percent for each zone. The level of urbanity, which is given on a scale, was recoded into dummy variables.
- ITF/OECD Services in urban areas: these data were converted to fit the 1x1km grid based on overlap in surface as well. A principal component analysis (PCA) was conducted to investigate whether some of these services could be grouped, to avoid unwanted correlations while estimating the generation model (see appendix C for details). However, differences between sample sets of different urban areas in Europe were too large to be able to do this. Grouping the different services together would not allow a generation model for one region to be transferred to another region.
- ITF/OECD Population and GDP: these data were converted to fit the 1x1km grid based on overlap in surface as well.
- EU CLC: these data were converted to fit the 1x1km grid based on overlap in surface as well - the type of land use that had the largest surface within a zone became the

dominant type within that zone. This was recoded into dummy (binary) variables for each land-use type. The land use of Maasvlakte 2 was changed from "construction area" to "port area".

- An additional binary variable that was added, is a dummy variable to indicate if a zone is a logistic hub. This variable was set from to one instead of zero for zones that belong to the ten percent largest producers as well as the ten percent largest consumers of freight. The fact that this variable was derived from data specifically for Groot-Rijnmond implies that a separate model had to be estimated to determine the fact if a zone is a logistics hub. This model is explained in section 5.1.2.

### 4.2.2. Creation of new commodity types

Within freight modelling, it is important to differentiate between commodity types and their supply chains, as they all have different characteristics that define the typical way of transporting them (Alho and De Abreu e Silva, 2014; Boerkamps and Van Binsbergen, 1999; Gentile and Vigo, 2013; Lawson et al., 2012). The data in the CBS freight survey differentiate commodity types based on NST/R classification and subclassifications. However, this classification is very industrially oriented, while it would improve the performance of the model to group commodities together based on their transportation requirements.

For a first impression of typical goods in urban logistics, a study was conducted of mentions of commodity types in literature about existing urban freight models and general urban freight literature (see appendix B). In those sources that do give an explicit explanation of the different commodity types (which is a limited number), there are a few that are mentioned very often: fresh food, non-fresh food, services, construction and building materials, and manufactured products. In the main NST/R classes, most of these commodities are not explicitly mentioned. Therefore, a new classification of goods was established, aimed at better catching the typicalities of urban logistics. Services are not included in this classification, since in the ITF regional model these are not included as well (see appendix B for a list of the ITF regional commodity types).

First, a cluster analysis was done on the shipments in the microdata, to group shipments with similar shipment sizes and vehicles types. However, this cluster analysis did not provide satisfactory results. In fact, many shipments of the same commodities were allocated to very different clusters, which illustrates the fact that there is a large variance within the commodity types. In a second attempt, a manual division was made. Ten typical goods categories were defined, and the different NST/R subclasses were allocated to these categories. This categorisation can be found in table 4.2. The categorisation was only done for the NST/R subclasses that are included in the survey data for Groot-Rijnmond.

This new categorisation offers commodity classes that are specifically oriented towards urban freight transport, and that are important to consider when implementing policy measures. For example, type 1 contains fresh foods, flowers and plants, and in terms of electrification of goods vehicles, it could become an issue to ensure the climate control in the goods vehicle because of their higher energy consumption. Another important separate category is that of transportation equipment, such as empty containers, since in cities with large ports they form a significant portion of the total goods transport. In terms of future trends, type 10 (parcels) is relevant, because it allows to account for growth in e-commerce. The new commodity groups are convertible to the goods categories that the ITF already uses for their regional models (see appendix B for the full list), but conversion factors are still needed.

Table 4.2: New goods classification

| Number | Commodity | NST/R references |
|---|---|---|
| 1 | Climate-controlled goods | 02**, 03**, 06**, 1390, 14** |
| 2 | Non-fresh food | 01**, 11**, 12**, 132*, 133*, 136*, 16**, 17**, 18** |
| 3 | Manufactured goods | 91**, 92**, 03**, 94**, 96**, 97** |
| 4 | Construction | 55**, 56**, 61**, 62**, 63**, 64**, 65**, 69**, 891*, 892*, 951*, 992*, 993* |
| 5 | Raw materials | 2***, 31**, 32**, 33**, 515*, 542* |
| 6 | Paper and wood | 05**, 972*, 973*, 974* |
| 7 | Chemicals | 092*, 34**, 719*, 81**, 893* |
| 8 | Waste | 049*, 462*, 842*, 896* |
| 9 | Transportation equipment | 9761, 9910 |
| 10 | Parcels | 9790 |

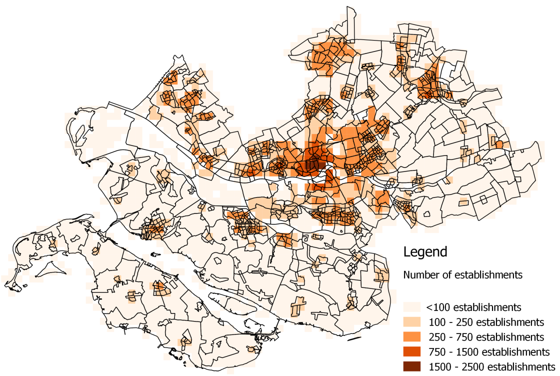
## 4.3. Characteristics of the structured data

This section discusses some of the main characteristics of the spatial data of the ITF/OECD and the shipments data of the CBS. The spatial data in section 4.3.1 give more general information about the study region, while the shipments data in section 4.3.2 give statistics that were used in building the model.

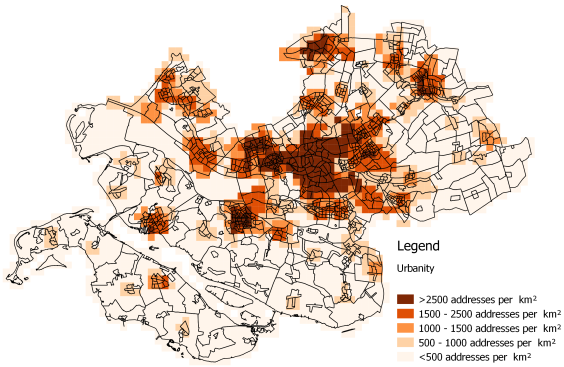
### 4.3.1. Spatial data

A visual impression of the zonal structure of the socio-economic data and the characteristics of the zones can be found in figures 4.1 and 4.2. Figures 4.1c and 4.1d show the difference in detail between the population data from the CBS and the OECD: it is clear to see that the OECD source data have a much larger scale. However, the total population for the whole region is approximately the same for both datasets. Furthermore, it is clear to see that most activity in the region is concentrated around the city of Rotterdam.

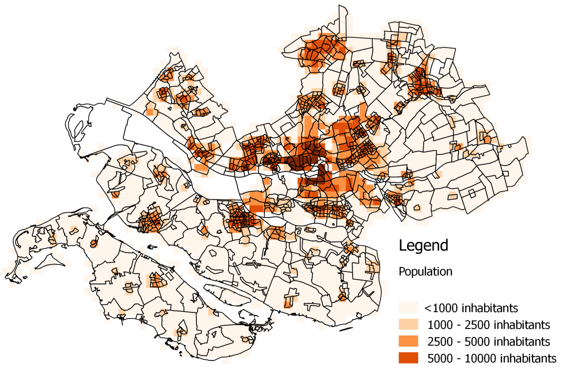
Figures 4.2 and 4.3 give more detail about the land use types in the zones. The choice was made to base the model on the dominant land use type in a zone, so not on the share of different land uses in a zone. Figure 4.3 especially shows that there are three main dominant land-use types: pastures, non-irrigated arable land and discontinuous urban fabric. The latter is concentrated around the city of Rotterdam, while pastures and non-irrigated arable land show higher occurrence in regions with a lot of agriculture.



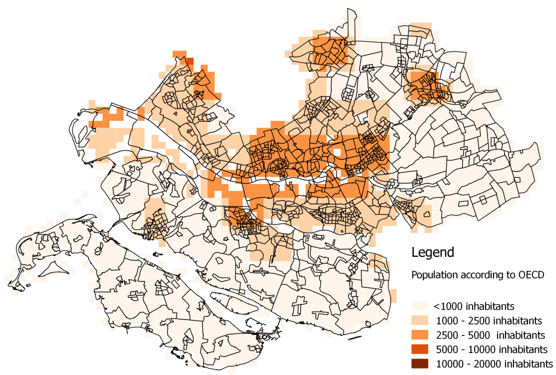

(a) Number of establishments in the modelling grid



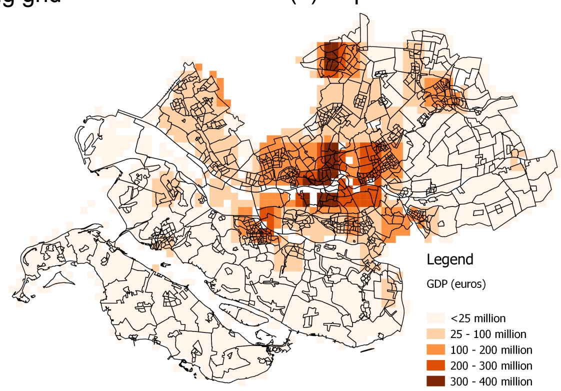

(b) Urbanity in the modelling grid




(c) Population in the modelling grid




(d) Population in the modelling grid (ITF/OECD data)




(e) GDP in the modelling grid (ITF/OECD data)

Figure 4.1: Socio-economic data of the modelling grid

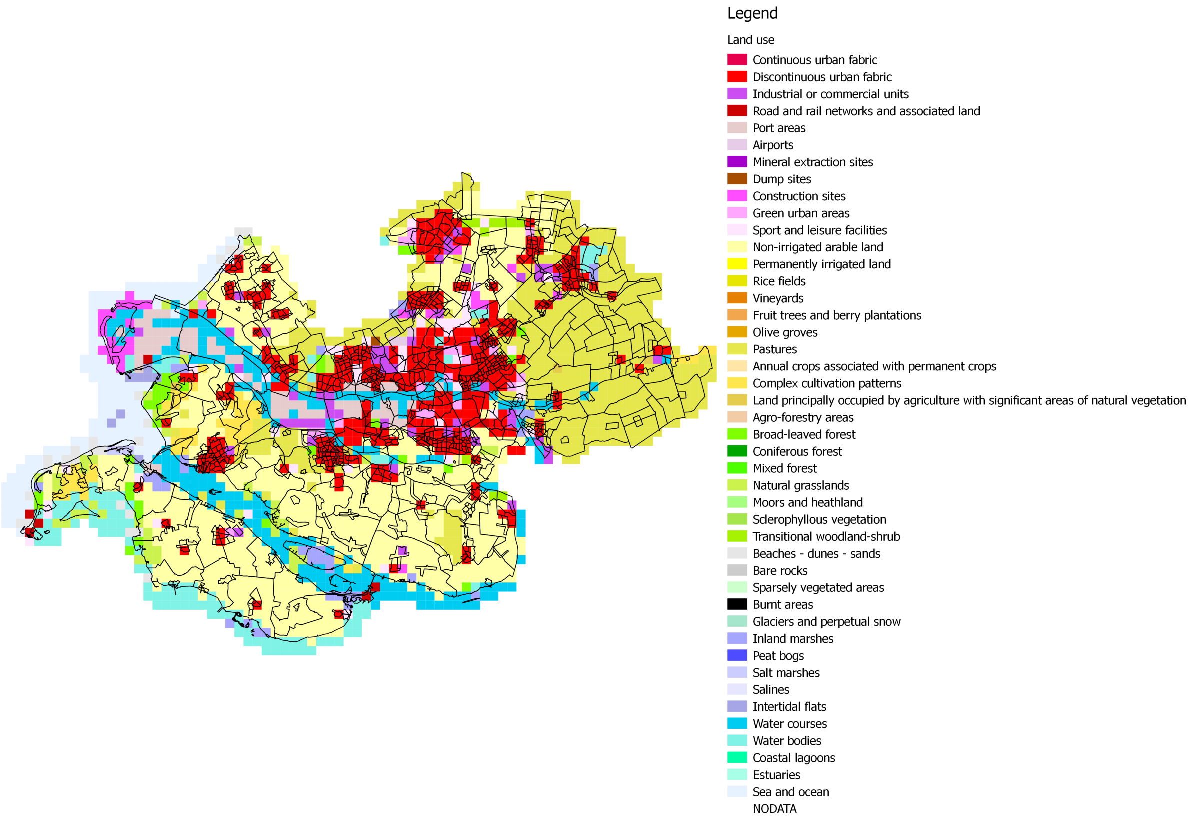



Figure 4.2: Land use in the modelling grid

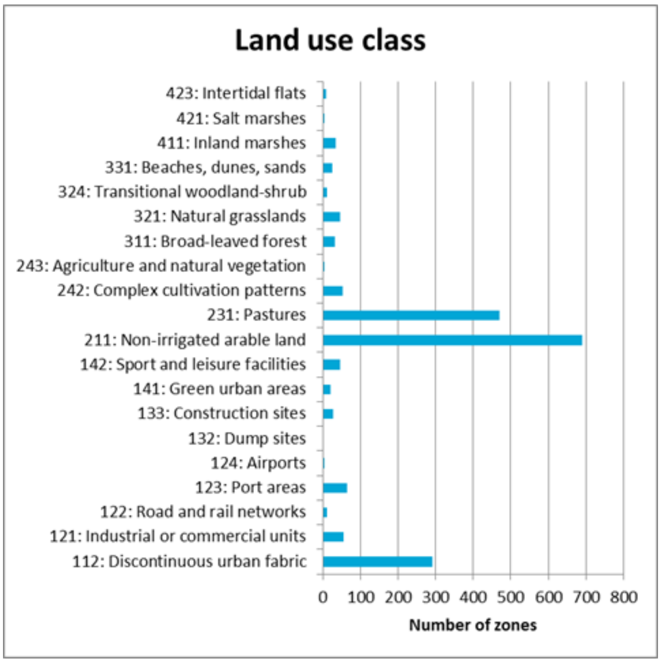
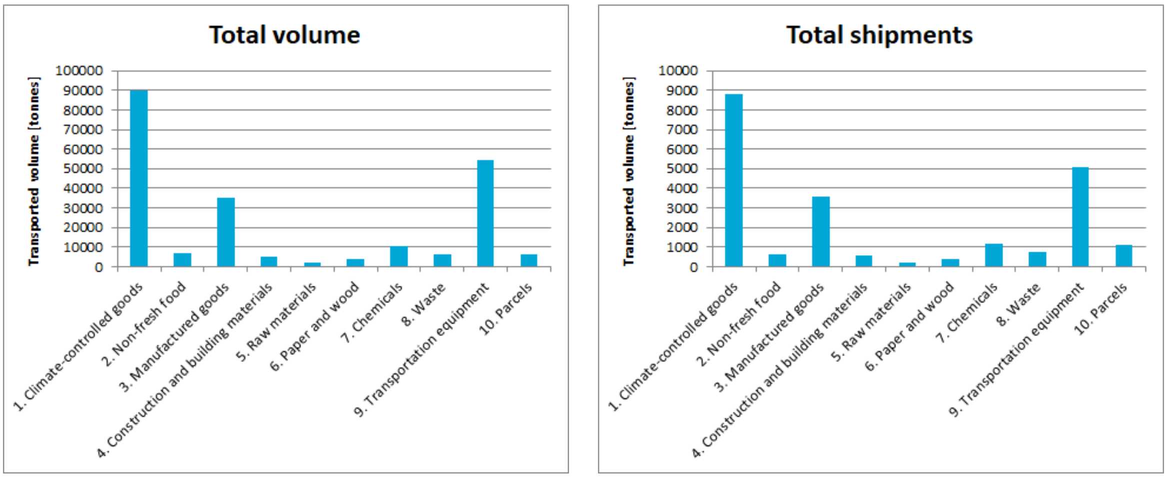



Figure 4.3: Dominant land use in zones

### 4.3.2. Shipments data

This section discusses the data on individual shipments that are described in the CBS microdata. If not mentioned otherwise, this concerns a selection of shipments that are transported to, from, or within the Groot-Rijnmond region according to the selection procedure as described in section 4.2.1. For some of the statistics that describe the microdata, comparable statistics can be found in Eurostat or ITF data. This is important because it enhances transferability. For all the statistics that are shown in this section, an indication is given about the possibilities to find comparable data for other European urban areas.

Figure 4.4 shows the occurrence of the ten commodity types in the microdata, in terms of individual shipments and total volume. The proportion of all commodities looks similar in the two graphs, since most commodity types have similar average shipment sizes (see table 4.3). This is only different in the case of parcels, because they have a much smaller average shipment size. In these graphs, it can be observed that climate-controlled goods, manufactured goods and transportation equipment are the most occurring commodity types in the microdata. This corresponds with the fact that the Port of Rotterdam is a very large port, which creates the need for a large number of containers (transportation equipment) to be transported, and a lot of transport of manufactured goods as well. Since the region around Rotterdam has a lot of agriculture (as discussed in section 4.3.1), it also comes as no surprise that there is a large volume of transported climate-controlled goods (e.g. fresh food, plants and flowers). Regarding the applicability of these statistics to other urban areas, Eurostat as well as the ITF have data on the share of each goods type that is transported to and from the region. One thing that is still needed to apply these statistics to the model, is to create a conversion factor that describes how to convert ITF commodity types or NST2007 commodity types (used by Eurostat) to the newly defined urban commodity types.




(a) Total volume per commodity (b) Total number of shipments per commodity

Figure 4.4: Volume and shipments share per commodity in the microdata for Groot-Rijnmond

Table 4.3 shows the shipment size mean and standard deviation for each commodity. It is immediately notable that the standard deviations are very large, in the case of parcels even larger than the average shipment size. This could be due to the fact that in the microdata, many shipments with a weight of 1 kg are recorded. Although in the analysis all records with a weight of 0 kg (empty trips) were removed, the shipments with a weight of 1 kg still cause a large variation in the data. This implies that when using these statistics for predicting shipments, the predictions will be inaccurate. In the ERFT survey by Eurostat, the weight of shipments is reported as well in multitudes of 100 kg and can be differentiated per NUTS3 region, which can be used when spatially transferring the model.

Table 4.3: Shipment size statistics of the different commodities

| **Commodity type** | **Mean weight [tonne]** | **Standard deviation** |
|---|---|---|
| 1. Climate-controlled goods | 10.188 | 6.196 |
| 2. Non-fresh food | 10.677 | 4.874 |
| 3. Manufactured goods | 9.779 | 5.741 |
| 4. Construction and building materials | 8.687 | 4.858 |
| 5. Raw materials | 9.616 | 4.590 |
| 6. Paper and wood | 10.433 | 4.924 |
| 7. Chemicals | 9.190 | 4.083 |
| 8. Waste | 8.074 | 4.658 |
| 9. Transportation equipment | 10.645 | 4.264 |
| 10. Parcels | 5.864 | 6.926 |

Table 4.4 shows the distribution of vehicle types for each commodity. Three main vehicle categories can be observed, that can be split into six vehicle types based on whether they have a trailer or not. Shipments that are transported by a tractor without trailer or by ”other” vehicle types are very rare. Furthermore, the table shows the predominant cargo type as which the commodities are transported, which becomes relevant when calculating emissions.

Table 4.4: Vehicle split and cargo type per commodity

| Commodity type | Truck | | Tractor | | Other | | Dominant cargo type |
|---|---|---|---|---|---|---|---|
| | without trailer | with trailer | without trailer | with trailer | without trailer | with trailer | |
| 1. Climate-controlled goods | 2.85% | 29.32% | 0.00% | 67.83% | 0.00% | 0.00% | Bulk/piece |
| 2. Non-fresh food | 5.02% | 24.92% | 0.00% | 70.06% | 0.00% | 0.00% | Bulk/piece |
| 3. Manufactured goods | 11.58% | 8.66% | 1.03% | 75.92% | 1.06% | 1.75% | Bulk/piece |
| 4. Construction and building materials | 20.11% | 42.03% | 0.00% | 37.86% | 0.00% | 0.00% | Bulk/piece |
| 5. Raw materials | 13.37% | 11.76% | 0.00% | 74.87% | 0.00% | 0.00% | Bulk/piece |
| 6. Paper and wood | 11.23% | 30.75% | 0.00% | 58.02% | 0.00% | 0.00% | Container |
| 7. Chemicals | 7.96% | 1.95% | 0.00% | 90.10% | 0.00% | 0.00% | Bulk/piece |
| 8. Waste | 52.97% | 37.38% | 0.00% | 9.64% | 0.00% | 0.00% | Bulk/piece |
| 9. Transportation equipment | 7.23% | 7.63% | 1.17% | 83.94% | 0.02% | 0.00% | Container |
| 10. Parcels | 4.15% | 14.24% | 0.00% | 81.60% | 0.00% | 0.00% | Bulk/piece |

With regards to transferability of the vehicle model to the rest of Europe, a positive remark is that the vehicle types that are defined in the CBS microdata and the vehicle types that are defined in the Eurostat ERFT data are comparable, as can be seen in table 4.5. The ERFT survey even defines more detailed vehicle types. The only category that is not considered in the ERFT survey, is the category ”other”. However, the occurrence of this category is so rare that neglecting it in models for other urban areas would be justifiable. Using the comparable vehicle types in the Eurostat data, accurate vehicle shares for every urban area can be used.

Table 4.5: Comparison of vehicle types in different data sources

| CBS vehicle type | Eurostat vehicle type |
|---|---|
| Truck without trailer | Lorry - 2 axles<br>Lorry - 3 axles<br>Lorry - 4 axles<br>Lorry - other |
| Truck with trailer | Lorry and trailer 2+1axles<br>Lorry and trailer 2+2<br>Lorry and trailer 2+3<br>Lorry and trailer 3+2<br>Lorry and trailer 3+3<br>Lorry and trailer other |
| Tractor with trailer | Tractor/semi-trailer 2+1<br>Tractor/semi-trailer 2+2<br>Tractor/semi-trailer 2+3<br>Tractor/semi-trailer 3+2<br>Tractor/semi-trailer 3+3<br>Tractor/semi-trailer other |
| Tractor without trailer | Road tractor alone |
| “Other” with trailer<br>“Other” without trailer<br>Van | Undefined in data |

Figures 4.5 and 4.6 show the distribution of the number of shipments in trips and tours. Trips can be considered as a collection of shipments that have the same origin and destination, while tours combine shipments that go to different destinations. It is clear from figure 4.5 that the share of tours is very small (except for the case of commodity 6), which justifies the fact that no tour formation procedure has been included in this model.

Additionally, the graphs in figure 4.6 show that for all commodities, the most occurring type of trip is one in which only one shipment is transported. This is especially strong in the case of paper and wood, wood and transportation equipment, where more than 95 percent of the trips only consists of one shipment. The distributions were used in the trips creation procedure, as explained in section 3.2.3.


Figure 4.5: Number of shipments in trip and tours for all commodities

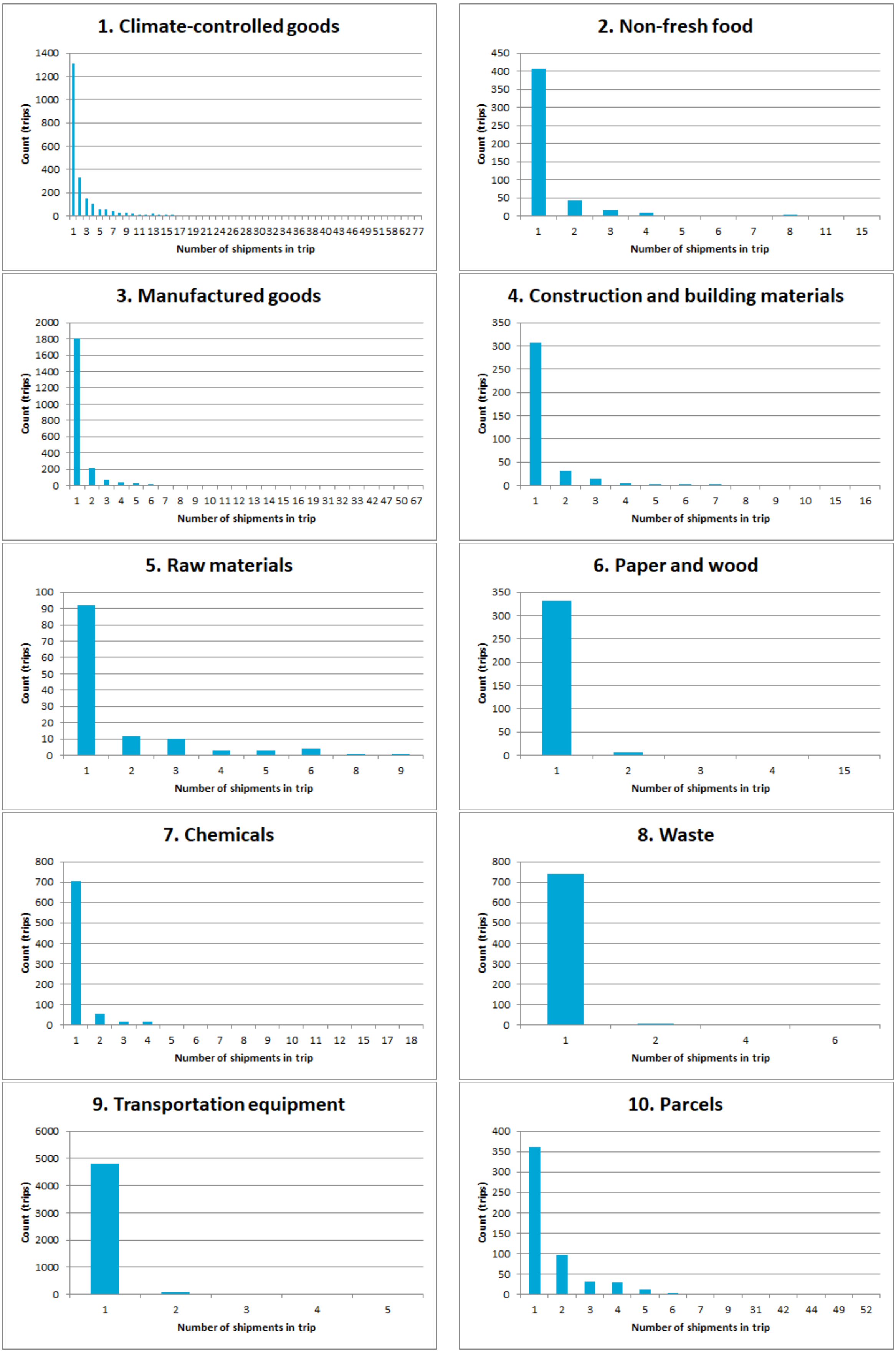



Figure 4.6: Number of shipments in trip for all commodities

The time of day statistics in figure 4.7 were taken from the complete CBS dataset for the Netherlands, as opposed to all the other shipments data that are discussed in this section. The reason that national, non-commodity specific statistics were used in this case, is because the time of day data proved to be very unreliable. In most cases, the data were missing, and there was an extremely large number of shipments that had ”00.00.00” (12.00 am) or ”00.00.01” (12.01 am) as their start time. The time of day is used to determine which skim matrix to use when determining the distance travelled for a trip. When assigned to hour 7, 8, 16 or 17, the distance is taken from the congested skim matrix. Furthermore, these statistics justify why, for the calibration of OD flows, the uncongested skim matrix was used: most trips start outside peak hours.

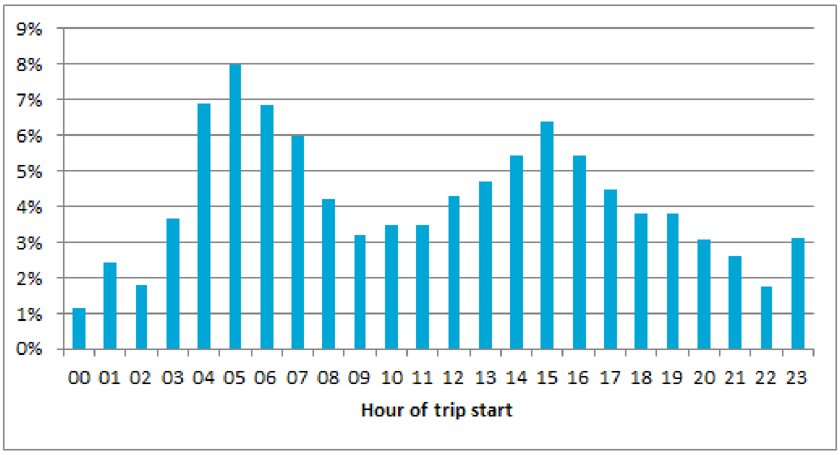



Figure 4.7: Distribution time of day of the start of the trip

The monthly statistics in figure 4.8 can, later on, be used for an assignment step, but it should be questioned if this step is needed for a model that has the purpose of aggregately estimating $CO_2$ emissions, and not to estimate traffic conditions. Still, these graphs are interesting to show because they also show some validation for some commodity types. Interesting results can mainly be seen for commodities 4 and 10. Commodity 4 shows a large decrease in shipments in holiday periods, especially around the ”bouwvak”, and shows an increase in the transport of construction materials after these holidays. In the case of parcels, a large peak can be seen in November, just before Sinterklaas and Christmas. The reason that this peak is not observed in December, is that the microdata track larger freight vehicles and not consumer traffic, so the larger shipments of parcels to distribution centres are shown but not the shipments to the homes of the end-consumers and smaller stores. This is the flaw of using a survey that does not include vans, and to be able to predict transport patterns of vans more accurately, it would be needed to estimate a separate model.


Figure 4.8: Percentage of shipments per month for all commodities

# 5

# An empirical model for urban freight transport

Combining the methodology in chapter 3 and the data as described in chapter 4, an empirical model for urban logistics has been created. In this chapter, the details of the various modelling steps are explained. In sections 5.1 and 5.2, the estimation of the generation and distribution model are explained. Subsequently, in section 5.3 a description of the procedure to create vehicle trips from OD flows is given. The chapter ends with an elaboration on the results of the model in section 5.4.

## 5.1. Generation model

The following subsections explain the establishment of a freight generation model for the Groot-Rijnmond region.

### 5.1.1. Modelling urban freight production and consumption

This section elaborates on the creation of the generation model, and the GLMs that can be used to forecast freight demand. Table 5.1 shows a comparison of the results of the three GLMs as defined in section 3.2.1. The three models were tested on a consumption and a production model for two different commodities: the consumption of climate-controlled goods and the production of manufactured goods. The $R^2$ gives the proportion of variance of the dependent variable (the production or consumption of goods) that is explained by the independent variables, while $\rho^2$ gives the relative improvement of the estimated model compared to an intercept-only model. The RMSE (in tonnes) is a measure for the quality of the predictions by the model. In case of the ZINB model, these values are based on the average of a simulation of 10,000 runs, as this model includes a logit model that gives different results based on the chosen seed.

As suggested in section 3.1, models with and without the inclusion of CBS spatial data for the Netherlands were compared. Since the performance was not much better when CBS Wijk-en Buurt data were included, it was decided to drop these data. This has a positive impact on the transferability of the model, since the generation model currently only uses data that are available for all urban areas in Europe.

From these results, it can very clearly be seen that regarding $R^2$ and RMSE, the ZINB model performs much worse than the zero-truncated OLS and Tobit models. The model does perform better in terms of $\rho^2$, but this is only compared to a negative binomial intercept-only model, and therefore does not give a good indication for the predictive quality of the model. Therefore, it was decided to drop the ZINB model as a possible method for estimating freight generation and to continue with a more elaborate comparison of OLS and Tobit models.

Table 5.1: Comparison of different methods for two generation models

| | **Consumption commodity 1** | | | **Production commodity 3** | | |
|---|---|---|---|---|---|---|
| | OLS | Tobit | ZINB | OLS | Tobit | ZINB |
| $R^2$ | 0.227 | 0.213 | 0.018 | 0.471 | 0.472 | 0.287 |
| $\rho^2$ | 0.009 | 0.010 | 0.039 | 0.027 | 0.031 | 0.037 |
| RMSE | 86.4 | 87.1 | 179.1 | 20.1 | 20.2 | 27.2 |

The results of the OLS and Tobit models for all consumption and production models of the ten commodities can be found in tables 5.2 and 5.3. $R^2$s of the zero-truncated OLS models were adjusted after changing the negative predictions to zero. It can quite clearly be seen that the results of the two methods show no obvious difference in performance. The $R^2$s of the Tobit models are slightly higher, while the RMSEs of the OLS models are slightly lower. Since there is no definitive conclusion to be drawn from this information, the choice was made to further continue with the OLS models, since these are easiest to interpret.

Table 5.2: Performance results of OLS and tobit GLMs for freight production

| Commodity | **OLS** | | **Tobit** | |
|---|---|---|---|---|
| | $R^2$ | RMSE | $R^2$ | RMSE |
| 1 | 0.25 | 152.2 | 0.23 | 153.9 |
| 2 | 0.21 | 7.5 | 0.23 | 7.5 |
| 3 | 0.47 | 20.1 | 0.47 | 20.2 |
| 4 | 0.26 | 3.7 | 0.24 | 3.7 |
| 5 | 0.12 | 3.5 | 0.08 | 3.6 |
| 6 | 0.20 | 10.7 | 0.21 | 10.6 |
| 7 | 0.26 | 15.3 | 0.30 | 15.0 |
| 8 | 0.08 | 30.6 | 0.11 | 30.2 |
| 9 | 0.47 | 42.9 | 0.47 | 42.9 |
| 10 | 0.14 | 10.5 | 0.19 | 10.3 |

Table 5.3: Performance results of OLS and tobit GLMs for freight consumption

| Commodity | **OLS** | | **Tobit** | |
|---|---|---|---|---|
| | $R^2$ | RMSE | $R^2$ | RMSE |
| 1 | 0.23 | 86.4 | 0.21 | 87.1 |
| 2 | 0.19 | 5.4 | 0.20 | 5.4 |
| 3 | 0.47 | 21.3 | 0.48 | 21.3 |
| 4 | 0.33 | 3.9 | 0.33 | 4.0 |
| 5 | 0.25 | 2.0 | 0.23 | 2.1 |
| 6 | 0.19 | 8.8 | 0.20 | 8.8 |
| 7 | 0.23 | 11.3 | 0.25 | 11.3 |
| 8 | 0.26 | 4.9 | 0.32 | 4.8 |
| 9 | 0.57 | 33.4 | 0.57 | 33.6 |
| 10 | 0.15 | 16.4 | 0.17 | 16.3 |

The $R^2$s of the generation models seem low at first sight, but it is important to view them in context of other freight models. Several examples were examined to compare the results of the generation model. Ducret and Gonzalez-Feliu (2015) report $R^2$s for deliveries to establishments from as low as 0.0000187 to craftsmen, to 0.81 for deliveries to stores, based on the number of employees. The average $R^2$ of eight establishment types equals 0.186. González-Feliu et al. (2014) also report varying values for an establishment freight production model, based on the number of employees and a class variable. Their adjusted $R^2$s take values from 0.009 to 0.81, averaging 0.254 over eleven establishment types. Hunt and Stefan (2007) estimate tour generation for five types of establishments, with a minimum and maximum $R^2$ of 0.087 and 0.590 respectively, the average being 0.263. Gonzalez-Feliu and

Peris-Pla (2017) also estimate freight attraction based on the number of employees, and report the most constantly well-performing $R^2$s of the literature that was found regarding the topic: between 0.35 and 0.78 with an average of 0.539 for 15 establishment types. The final article that was found, by Sánchez-Díaz et al. (2016), reports adjusted $R^2$s for weekly deliveries at establishments between 0.20 and 0.94, averaging 0.72. Unfortunately, no comparable results were found for models that use spatial data as freight predictors. However, as the model in this study shows comparable results to those in related studies, and considering the fact that this model uses limited data, it can be concluded that the results are promising.

The standardised values of the significant parameters of the production and consumption models are summarised in tables 5.4 and 5.5. These values give an indication of their relative importance for predicting freight generation of a certain commodity. The models with the absolute values can be found in appendix D. Important to note is that these values do not give the exact freight generation in a zone, but the freight generation relative to other zones. A multiplication factor still has to be applied to match the total generation of freight in the region. In future updates of the model, output from the ITF regional freight model should be used as matching values. Currently, as temporary solution, regional statistics from Eurostat (2019a) and Eurostat (2019b) have been used as total production and consumption to match for the whole NUTS 3 region.

An overview of the characteristics of the variables is given in section 4.2.1. The variable ”logistics hub” is included in all but one model (the production model for raw materials). Since this variable is derived empirically from the freight data for Groot-Rijnmond, a separate model is needed to determine where logistics hubs are located. This model is further explained in section 5.1.2.

Table 5.4: Betas of the freight production model, *** = 0 significance level, ** = 0.001 significance level, * = 0.01 significance level, . = 0.05 significance level

| Variable | *1. Climate-controlled goods* | *2. Non-fresh food* | *3. Manufactured goods* | *4. Construction and building materials* | *5. Raw materials* | *6. Paper and wood* | *7. Chemicals* | *8. Waste* | *9. Transportation equipment* | *10. Parcels* |
|---|---|---|---|---|---|---|---|---|---|---|
| Logistics hub | 0.595*** | 0.462*** | 0.382*** | 0.343*** | | 0.119*** | 0.309*** | 0.092** | 0.606*** | 0.314*** |
| Population | -0.080*** | 0.109** | | 0.287*** | 0.262*** | 0.153*** | 0.262*** | -0.144*** | -0.105*** | |
| GDP | | -0.193*** | 0.125*** | -0.141*** | -0.129*** | -0.171*** | -0.234*** | 0.285*** | 0.174*** | 0.149*** |
| LU: Discontinuous urban fabric | | | | | | | | -0.062. | 0.076*** | |
| LU: Industrial or commercial units | -0.049. | | 0.100*** | 0.061* | 0.078*** | | 0.128*** | 0.062* | | |
| LU: Port areas | -0.295*** | -0.074* | 0.345*** | | 0.226*** | 0.314*** | 0.108*** | 0.118*** | 0.097*** | -0.139*** |
| LU: Dump sites | | | 0.036. | | | | | | | |
| LU: Construction sites | | | | | | | | | 0.048* | |
| LU: Green urban areas | | | | | | | | | | 0.135*** |
| LU: Non-irrigated arable land | 0.071** | 0.061* | | | | | | | | |
| LU: Complex cultivation patterns | 0.046. | | | | | | | | | |
| LU: Land principally occupied by agriculture | | | | | | | | | | |
| Market | 0.043. | | | | | | | | | |
| School | | | | | | 0.053* | | | | |
| Shop food | | 0.082** | | | | | | | | |
| Shop other | | | | 0.098*** | | | | | | |

Table 5.5: Betas of the freight consumption model, *** = 0 significance level, ** = 0.001 significance level, * = 0.01 significance level, . = 0.05 significance level

| Variable | *1. Climate-controlled goods* | *2. Non-fresh food* | *3. Manufactured goods* | *4. Construction and building materials* | *5. Raw materials* | *6. Paper and wood* | *7. Chemicals* | *8. Waste* | *9. Transportation equipment* | *10. Parcels* |
|---|---|---|---|---|---|---|---|---|---|---|
| Logistics hub | 0.565*** | 0.488*** | 0.445*** | 0.228*** | 0.203*** | 0.123*** | 0.242*** | 0.407*** | 0.698*** | 0.379*** |
| Population | -0.092*** | | | 0.230*** | 0.222*** | 0.166*** | 0.169*** | 0.205*** | 0.148*** | |
| GDP | | -0.072** | 0.180*** | | -0.146*** | -0.18*** | -0.12*** | -0.126*** | 0.26*** | |
| LU: Discontinuous urban fabric | | | | | | | | 0.056. | | |
| LU: Industrial or commercial units | | | 0.153*** | 0.220*** | 0.137*** | 0.043. | 0.085*** | 0.102*** | | -0.045. |
| LU: Road and rail networks | | | | | | | | | 0.045* | |
| LU: Port areas | -0.256*** | -0.110*** | 0.223*** | 0.122*** | 0.244*** | 0.294*** | 0.23*** | -0.067* | 0.061** | -0.176*** |
| LU: Dump sites | | | | | | | | 0.055* | | |
| LU: Green urban areas | | | | | | | | | | 0.163*** |
| LU: Complex cultivation patterns | 0.042. | | | | | | | | | |
| LU: Land principally occupied by agriculture | | | | | | | | 0.084*** | | |
| Market | 0.059* | 0.048. | | | | | | | | |
| School | | | | | | 0.051. | | | | |
| Shop other | | | | 0.128*** | | | | | | 0.066* |

### 5.1.2. Prediction of logistics hubs

A separate GLM was estimated to predict logistics hubs, which are zones that produce and consume very large volumes of freight. This model was needed because logistics hubs are the most important predictors in the freight generation models, but were derived empirically for the Groot-Rijnmond model. A different type of GLM was used in this case, since the dependent variable is binary: a binary logistic model, that estimates probability with the following function:

$$p(X) = \frac{e^{\beta_0+\beta_1 X+...+\beta_n X}}{1+e^{\beta_0+\beta_1 X+...+\beta_n X}}$$

Zones with a p(X) closer to one will have a higher probability to be a logistics hub than zones with lower values. The estimation of the model is shown in table 5.6. A positive remark can be made regarding the fit of the model, since the $\rho^2$ is quite high (0.368) - much higher than the $\rho^2$ of the generation models in section 5.1.1. The main predictor is the dummy land-use variable for ports. This is not surprising, since ports are places where a lot of freight movement is concentrated.

Table 5.6: Parameters of the logistics hubs prediction model (binary logistic GLM)

| Parameter | B |
|---|---|
| Intercept | -13.508*** |
| GDP (in bn. euros) | 5.567** |
| Population | -0.001*** |
| LU: Discontinuous urban fabric | 1.452*** |
| LU: Commercial and industrial units | 2.768*** |
| LU: Road and rail networks | 2.738*** |
| LU: Port areas | 6.202*** |
| LU: Construction sites | 2.035. |
| LU:: Green urban areas | 1.731* |
| LU: Non-irrigated arable land | 1.134*** |

## 5.2. Distribution model

The first step of the distribution stage is the creation of an OD matrix with distances and travel times between all zones in the model. The OD matrices that have been created, are based on a shortest path algorithm that calculates travel times based on an average speed of 80 percent of the maximum speed. The calibration of the distribution model is based on an uncongested network, since most freight is transported during off-peak hours (see section 4.3.2). Distances to external zones were set to 200 kilometres as this provided the most accurate calibration results in terms of shares of intraregional versus interregional transport.

With these OD matrices, the sensitivity parameters of the cost function (as explained in section 3.2.2) could be calibrated. Unfortunately, it was not possible to use the exact OD flows as input for the estimation of the model. This was caused by the fact that the spatial scale that is used to describe shipments in the CBS microdata is very different from the scale of this model. To overcome this, an aggregate approach was used based on total tonne-kilometres. This was done as follows: the location variables in the CBS microdata were linked to a skim matrix with distances between all postal codes in the Netherlands. Afterwards, an estimation of the distance for each shipment within the Groot-Rijnmond region could be made. Combined with the tonnage of each shipment, an average distance per transported tonne could be estimated. The average distances for each commodity can be seen in table 5.7. Using these values, total tonne-kilometres could be calculated for freight transport within the Groot-Rijnmond region. Based on an iterative calibration that minimises the difference between the estimated tonne-kilometres and the empirical tonne-kilometres, as explained in section 3.2.2, the sensitivity parameters as shown in table 5.7 have been derived.

As can be seen in table 5.7, most commodities have comparable sensitivity parameters that fluctuate -0.55 and -0.65. Two clear outliers can be observed: commodity 1 and commodity 6. Commodity 1 is not as sensitive to higher transportation cost as the other commodities, which intuitively seems right as the goods are climate-controlled and can, therefore, be kept fresh for a longer time. As for commodity 6, paper and wood, it is not as clear why these goods are so sensitive to transportation cost, but it can be observed that the average distance per tonne is also very low. There is a third commodity that does not fall within the -0.55 to -0.65 range, although not as far as the other two: transportation equipment. There is no clear explanation as to why this commodity is less sensitive to transportation cost.

Table 5.7: Sensitivity parameters of the distribution model

| Commodity | Av. distance per tonne | β |
|---|---|---|
| 1. Climate-controlled goods | 2.37 | -0.41 |
| 2. Non-fresh food | 1.30 | -0.64 |
| 3. Manufactured goods | 1.51 | -0.60 |
| 4. Construction and building materials | 1.50 | -0.64 |
| 5. Raw materials | 1.47 | -0.60 |
| 6. Paper and wood | 0.60 | -0.79 |
| 7. Chemicals | 1.30 | -0.62 |
| 8. Waste | 2.59 | -0.61 |
| 9. Transportation equipment | 2.00 | -0.49 |
| 10. Parcels | 1.56 | -0.57 |

## 5.3. Vehicle trips model

Using the decision structure in figure 3.5 and the statistics in tables 4.3 and 4.4, a separate shipment dataset can be generated for each commodity, containing shipments for a full year. This is done with parallel processing using 30 cores, in which shipments from each origin zone are computed in a different process. This significantly decreases computation time.

The first step of the shipments procedure is the creation of a set of shipments with certain sizes based on the statistics as shown in table 4.3. Subsequently, vehicles are assigned to the shipments based on the weight of the shipment and the commodity type, according to the statistics in appendix F.

One manual adjustment was made in the allocation of vehicles, because the CBS microdata that are used for this project do not include vans transport. Although there is a separate microdataset for vans, this dataset is not connected to the truck microdata and therefore does not indicate the share of vans compared to other vehicle types. Thus, the decision was made to manually include vans in the vehicle model. According to CBS (2015), vans are mainly used for transporting goods in construction and the catering industry, in which they account for 60 percent of the kilometres driven for goods transportation. The recent growth of e-commerce also shows a large number of parcels being delivered with vans. Since the catering industry is not explicitly considered in the ten commodity types, vans were added manually to commodity types 4 and 10. According to De Groot et al. (2017), vans can transport a maximum load of 3.5 tonnes, so it was assumed that all shipments under 3.5 tonnes are allocated to a van. However, even using this distribution, the share of kilometres driven by vans for construction is lower than the previously mentioned 60 percent (see section 5.4). Another drawback of this approach is that the transportation patterns that are observed, do not match van patterns, since they are based on a dataset that observes trucks, not vans.

With regards to the reported driven distance, as described in chapter 3, for shipments during peak hour a congested skim matrix is used, and for shipments outside of peak hour, an uncongested skim matrix is used. The uncongested skim matrix uses speeds based on 80 percent of the maximum speed on the reported roads, and the congested matrix uses a congestion level of 42 percent (the average of the congestion levels of the morning and the evening peak according to TomTom (2019)) to calculate the shortest path. Table 5.8 shows an example of the first five rows of output of the shipments procedure for commodity 5.

Table 5.8: Example of a shipments output table for commodity 5

| shipment_nr | origin | destination | weight | vehicle | month | day | hour | minute | distance |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 1 | 1 | 4.88 | 5 | 5 | 5 | 19 | 34 | 0 |
| 2 | 1 | 2 | 0.42 | 5 | 1 | 11 | 5 | 13 | 1.413196 |
| 3 | 1 | 3 | 0.371 | 5 | 1 | 17 | 7 | 14 | 1.000518 |
| 4 | 1 | 4 | 0.137 | 5 | 2 | 22 | 17 | 18 | 1.413113 |
| 5 | 1 | 5 | 0.112 | 5 | 3 | 21 | 6 | 33 | 2.826392 |

Once the shipments are created, they can be combined into trips as described in figure 3.6 and using the statistics in figure 4.6. For this procedure, again parallel processing is used for each separate OD pair. In this step, the vehicle type and total weight of the shipment are also used to calculate emissions of $CO_2$, $SO_2$, $PM_{10}$ and $NO_2$, using reported statistics from Otten et al. (2017). More information about the values used for calculation can be found in appendix G. An example of the outcomes of the trips procedure is shown in table 5.9.

Table 5.9: Example of a trips output table for commodity 1

| origin | destination | vehicle | capacity | tripID | month | day | hour | minute | distance | co2 | so2 | pm10 | nox | trip_weight | sh_in_trip |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1 | 3 | 28 | 1 | 5 | 9 | 13 | 47 | 0 | 0 | 0 | 0 | 0 | 21.786 | 2 |
| 1 | 2 | 3 | 28 | 3 | 8 | 9 | 14 | 28 | 1.413196 | 649.3546 | 0.003805 | 0.118583 | 5.00967 | 2.692346 | 1 |
| 1 | 2 | 5 | 29.2 | 4 | 6 | 9 | 4 | 45 | 1.413196 | 19.42367 | 0.000148 | 0.002514 | 0.103527 | 0.104654 | 1 |
| 1 | 1893 | 2 | 13 | 285 | 3 | 12 | 21 | 25 | 100 | 382778.8 | 2.343988 | 104.2802 | 3903.013 | 9.812045 | 1 |
| 1 | 1893 | 5 | 29.2 | 352 | 12 | 14 | 15 | 58 | 100 | 59778.42 | 0.455166 | 7.737816 | 318.616 | 17.42856 | 6 |

## 5.4. Model outcomes and validation

Table 5.10 shows the final results of the model in terms of the main variables. Internal statistics refer to trips with their origin and destination inside the Groot-Rijnmond region, while external statistics refer to trips that have their origin OR their destination in the Groot-Rijnmond region, but not both. A positive remark is that the outcomes of the model are quite stable, even though some probabilistic functions were used to draw numbers from empirical distributions. Over five model runs, the standard deviation of the main model outcomes is less than one percent of the mean for all main variables.

No regional statistics have been found to compare these values with. Therefore, the outcomes (total values, so internal as well as external trips) have been compared to total Dutch transport statistics. Statistics for total transported weight, tonne-kilometres, vehicle-kilometres and trips have been taken from CBS (2019b), statistics on $NO_x$, $PM_{10}$ and $SO_2$ have been taken from CBS (2019a), and $CO_2$ statistics have been taken from a report by Otten et al. (2016). All emissions are tank-to-wheel emissions. The last column of table 5.10 shows the percentage to which the Groot-Rijnmond region contributes to the total numbers of the Netherlands.

Although Groot-Rijnmond is only one of forty NUTS3 regions in the Netherlands, it is plausible that this region contributes to a relatively sizeable share of emissions. Around 20 percent of the volume of goods that are transported in the Netherlands has Groot-Rijnmond as origin or destination, which makes sense because this is where the Port of Rotterdam is located. However, the percentages related to distances and emissions that are shown in table 5.10 seem very large. This is due to the fact that the trip length of trips to external zones is set to 200 kilometres in the distribution step. Naturally, this causes an over-exaggeration of external statistics.

Table 5.10: Summary of results (5 runs)

| | Mean | Standard deviation | Total in NL | Percentage of GR |
|---|---|---|---|---|
| Weight [Mtonne] | 110.11 | 0.00 | 535.52 | 20.6% |
| Trips [x mln] | 7.21 | 0.00 | 39.26 | 23.9% |
| Tonne-km internal [x mln] | 38.42 | 0.00 | 59,226 | 32.0% |
| Tonne-km external [x mln] | 18,939.15 | 0.00 | | |
| Vehicle-km internal [x mln] | 28.65 | 0.01 | 4,415 | 21.0% |
| Vehicle-km external [x mln] | 897.18 | 1.37 | | |
| $CO_2$ internal [ktonne] | 4.45 | 0.03 | 8,728 | 21.9% |
| $CO_2$ external [ktonne] | 1,905.97 | 8.54 | | |
| $NO_x$ internal [ktonne] | 0.03 | 0.00 | 42.82 | 32.1% |
| $NO_x$ external [ktonne] | 13.72 | 0.10 | | |
| $PM_{10}$ internal [tonne] | 0.82 | 0.01 | 930 | 39.2% |
| $PM_{10}$ external [tonne] | 365.09 | 2.59 | | |
| $SO_2$ internal [tonne] | 0.03 | 0.00 | 60 | 21.5% |
| $SO_2$ external [tonne] | 12.92 | 0.05 | | |

To correct for the over-exaggeration of the values of the external variables, a corrective action was applied to the model outcomes. For the external trips, the driven distance was manually changed to half the maximum distance between zones within the region. This means that the distance for external trips was set to 54 kilometres instead of 200 kilometres. This way, an estimation could be made of the part of these trips that is conducted within the region. The results of the model after this correction are shown in table 5.11. They give a good approximation of total emissions by freight transport in the region.

As shown in table 5.11, the total transported weight and the number of trips to and from the Groot-Rijnmond region still account for more than twenty percent of goods transport in the Netherlands. The values of the variables that are related to distance and emissions, however, seem more plausible now. It makes sense that these account for approximately five to ten percent of the total numbers for the Netherlands. This is still more than 1/40, but that can be explained by the fact that there is so much freight activity in the Groot-Rijnmond region.

Table 5.11: Summary of results after correction for distance

| | Model outcome | Total in NL | Percentage of GR |
|---|---|---|---|
| Weight [Mtonne] | 110.11 | 535.52 | 20.6% |
| Trips [x mln] | 7.21 | 39.26 | 23.9% |
| Tonne-km internal [x mln] | 38.42 | 59,226 | 8.6% |
| Tonne-km external [x mln] | 5,080.72 | | |
| Vehicle-km internal [x mln] | 28.65 | 4,415 | 6.1% |
| Vehicle-km external [x mln] | 240.68 | | |
| $CO_2$ internal [ktonne] | 4.45 | 8,728 | 5.9% |
| $CO_2$ external [ktonne] | 511.30 | | |
| $NO_x$ internal [ktonne] | 0.03 | 42.82 | 8.7% |
| $NO_x$ external [ktonne] | 3.68 | | |
| $PM_{10}$ internal [tonne] | 0.82 | 930 | 10.6% |
| $PM_{10}$ external [tonne] | 97.94 | | |
| $SO_2$ internal [tonne] | 0.03 | 60 | 5.8% |
| $SO_2$ external [tonne] | 3.47 | | |

After analysing the general outcomes of the model, some detailed model characteristics can be analysed as well. A few comparisons with the empirical data have been performed, related to vehicle types, shipment size and composition of trips.

A comparison of vehicle type distribution is shown in figure 5.1. Commodities 1, 3 and 9 do not show large differences in vehicle split between the data and the model. Commodities 4 and 10 do show differences that are mainly caused by the addition of vans in the model. Fifteen percent of kilometres driven by vans transporting goods of commodity type 4 are transported by vans. This is less than the 60 percent mentioned by CBS (2015), which is caused by a lack of van-specific data. All modelled trips of commodity 4 with a weight under 3.5 tonnes are allocated to vans, but the empirical shipment size distribution has a greater share of large shipments because the CBS microdata only includes larger freight vehicles.

Other commodities that show differences with the empirical data are commodities 2, 5, 6, 7 and 8. Commodity 2 has a smaller share of tractors with trailers, while for commodity 5 the opposite can be observed. For commodities 6, 7 and 8 an increase in trucks without trailers can be observed. In the case of commodities 6 and 7, this eats away from the share of tractors with trailers, but in the case of commodity 8 this causes a reduction in the shares of both trucks and tractors with trailers.

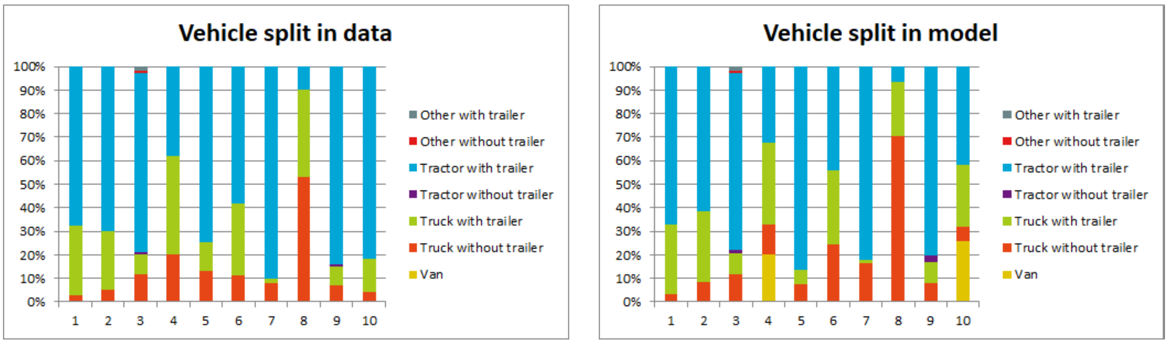



Figure 5.1: Comparison vehicle split data and model

Another variable to observe in more detail is the shipment size. Figure 5.2 shows a comparison between empirical and modelled shipment sizes. It is clear that for some commodities, the difference between the two is very big. This is especially the case for commodities 2, 5, 8 and 10. This is likely caused by the fact that these are commodities with a smaller total volume (as shown in section 4.3.2). Due to how the distribution step is currently designed, there are many OD pairs with small flows between them, which causes for small shipments. Naturally, this is enhanced for smaller commodity groups.

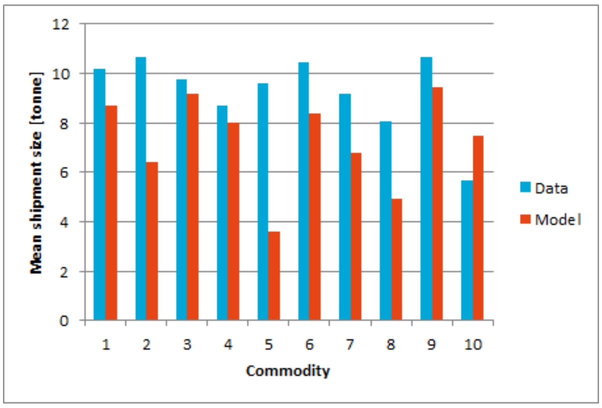



Figure 5.2: Comparison mean shipment size data and model

The last characteristic that is analysed in more detail is the composition of trips: the number of shipments that are transported in the same trip. A comparison between the statistics in the data and the statistics that are model output is shown in figure 5.3. All commodities except for commodity 5 show large disparity between the microdata and the model. In the cases of commodities 3, 4 and 10, the general pattern (the largest percentage is formed by trips with one shipment) is even violated. In future updates of the model, the trips creation procedure should, therefore, be re-evaluated.

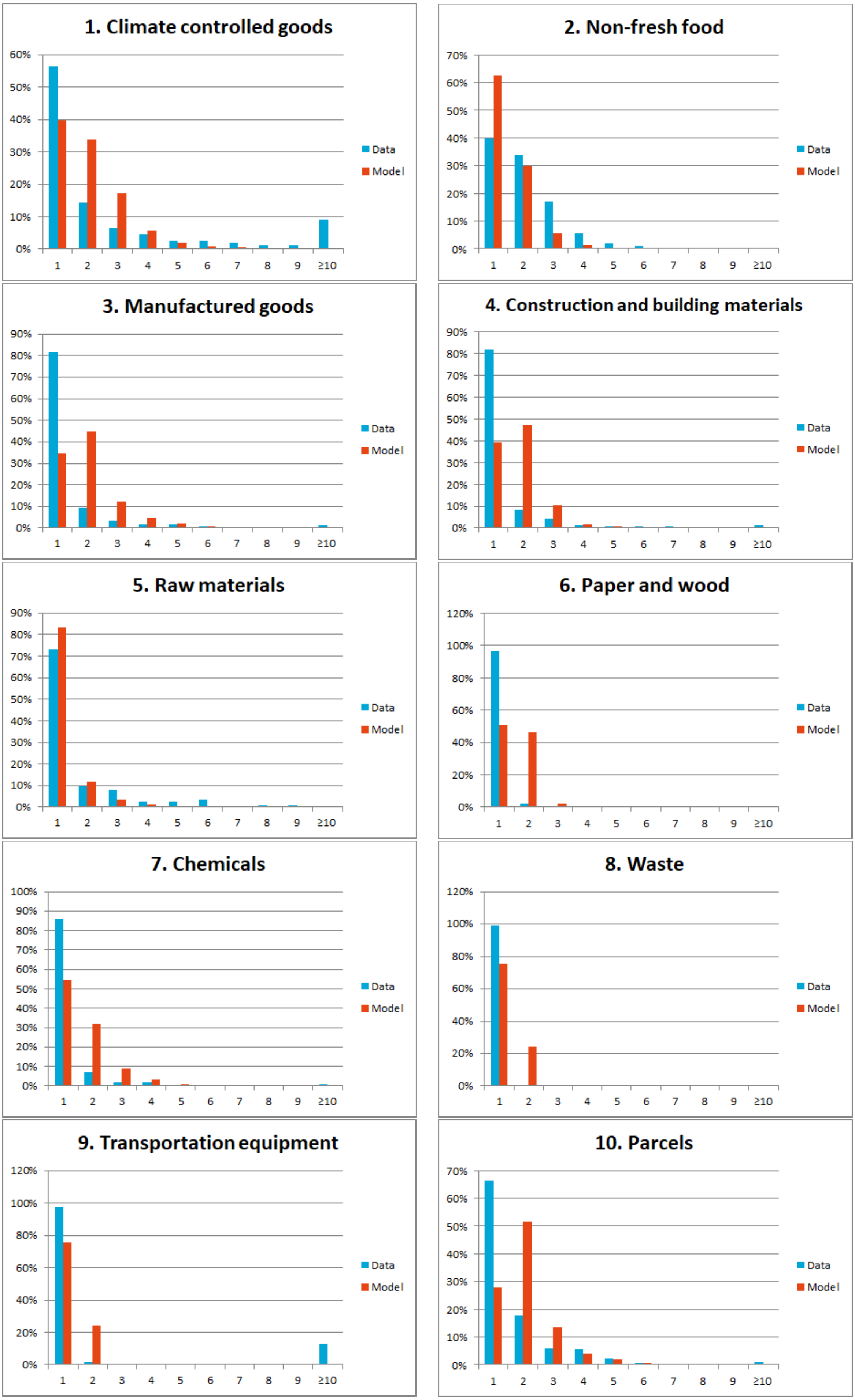



Figure 5.3: Comparison of the number of shipments in a trip

# 6

# Application of the model

This chapter describes the application of the model in seven policy scenarios. First, an explanation of an experimental plan for assessing different scenarios is given in section 6.1. Then, the results of the scenarios in terms of tank-to-wheel emissions are shown in section 6.2. The chapter ends with a discussion of the results in section 6.3.

## 6.1. Description of the tested scenarios

As discussed in section 3.3.2, two main measures/innovations have been assessed using the model. These are the use of zero-emissions vehicles, and the implementation of pricing measures. Three stages of the use of zero-emissions vehicles have been assessed, based on their market share and the type of shipments for which they are used. The pricing measure is implemented as a permanent low emission zone with toll entry. The implementations can be defined as follows:

1. Zero-emissions vehicles
    (a) Electrify all vans
    (b) Electrify all trips with a load <1.5 tonnes
    (c) Electrify all trips with a load <3.5 tonnes
2. Low emission zone (LEZ) with pricing: 10 euros for passing entry and exit points of the LEZ, no differentiation made between vehicle types or time of day

The LEZ has the same spatial definition as the environmental zone that Rotterdam currently has in place. A visual impression of the zone is shown in figure 6.1.

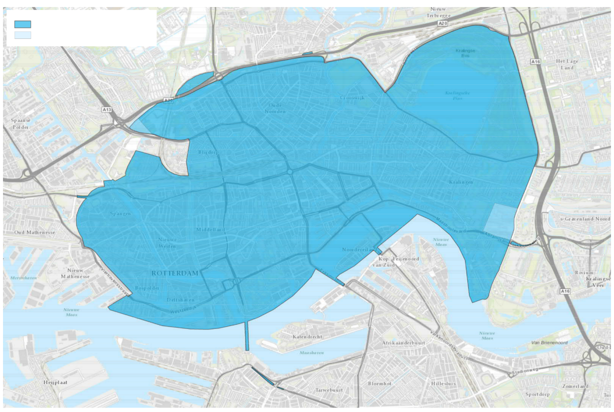


Figure 6.1: Current environmental zone Rotterdam (Gemeente Rotterdam, 2016)

Table 6.1 shows the experimental plan for scenario testing. All combinations of the two measures have been assessed. Different implementations of zero-emissions vehicles have not been combined, as the implementations have some overlap.

Table 6.1: Experimental plan for the assessment of policy scenarios

| | Zero-emissions vehicles | | | Pricing |
|---|---|---|---|---|
| | Electrify vans | Electrify trips <1.5t | Electrify trips <3.5t | |
| Base scenario | 0 | 0 | 0 | 0 |
| Scenario 1 | 1 | 0 | 0 | 0 |
| Scenario 2 | 0 | 1 | 0 | 0 |
| Scenario 3 | 0 | 0 | 1 | 0 |
| Scenario 4 | 0 | 0 | 0 | 1 |
| Scenario 5 | 1 | 0 | 0 | 1 |
| Scenario 6 | 0 | 1 | 0 | 1 |
| Scenario 7 | 0 | 0 | 1 | 1 |

To ensure ease of use of the model, the measures have been added to the code in a way that they can be selected by changing a zero to a one for the inclusion of the respective measure. Figure 6.2 shows how this looks in the R code. The example that is given is for scenario 4, in which no zero-emissions vehicles are used, but in which the LEZ is active. By integrating these measures in other parts of the code, the selection of the measures has been kept very simple and can be done right at the beginning of the code.

```
############################################
# Selection of "measures"
############################################
zev_a = 0
zev_b = 0
zev_c = 0
pricing = 1
```

Figure 6.2: Selection of the measures in the model code, example for scenario 4

## 6.2. Assessment of scenario impacts

The effects of the scenarios on the model outcomes are shown in figure 6.3. Despite this study being set in the context of decarbonisation, impacts on local pollutants are shown as well as these are very relevant in an urban environment. The results are compared to the results of the base scenario, as discussed in section 5.4. Figure 6.3 shows this comparison as a percentage change. Tables 6.2, 6.3, 6.4 and 6.5 show the results of statistical tests of whether the results of the scenarios differ significantly.

The first three scenarios compare the outcomes of different implementations of zero-emissions vehicles. In the first scenario, the only commodities that experience changes are construction materials (commodity 4) and parcels (commodity 10), as these are the only commodities that are transported by vans. Interestingly enough, the $CO_2$ change of scenario 3 (-3.8 percent) is slightly smaller than the $CO_2$ change of scenario 1 (-3.9 percent). This is the same for the other emissions. This can have two causes, the first being that the other commodities simply do not have a lot of light shipments, so not a lot of shipments can be transferred to vans. The second cause could be the fact that the way emissions are calculated (based on tonne-kilometres of the shipments), small shipments already account for a very small share of total emissions. Tables 6.2 to 6.5 support the hypothesis that there is no significant difference in emissions between the two scenarios.

Scenario 2 even shows a small increase in all emissions. This is due to the fact that most shipments weigh over 1.5 tonne, so the relevant number of trips is so small that variance in model outcomes outweighs the impacts of the measure. Moreover, the small size of the emissions reduction of all measures can be caused by how emissions are calculated in the model, as explained previously. Again, the hypothesis that there is no significant difference between the results of the base scenario and the results of scenario 2 can be confirmed (as shown in tables 6.2 to 6.5).

Regarding the scenarios that include zone pricing, an interesting observation can be made. The emissions barely change, compared to scenarios 1, 2 and 3 and the base scenario. This seems to indicate that the implementation of zone pricing does not affect average trip distance. Beforehand, it was expected that pricing would lead to longer distances being driven and thus higher emissions because trips would go around the LEZ. However, the larger generalised costs between some zones also change the outcomes of the distribution model: more volume is transported between zones that are closer to each other. So in the end, the trip lengths remain approximately the same. This was confirmed by the statistical tests as shown in tables 6.2 to 6.5: the average results of the base scenario and scenario 4 do not differ statistically, as well as the results of scenarios 1 and 5, 2 and 6, and 3 and 7.

Figure 6.3: Outcomes of scenarios compared to base scenario

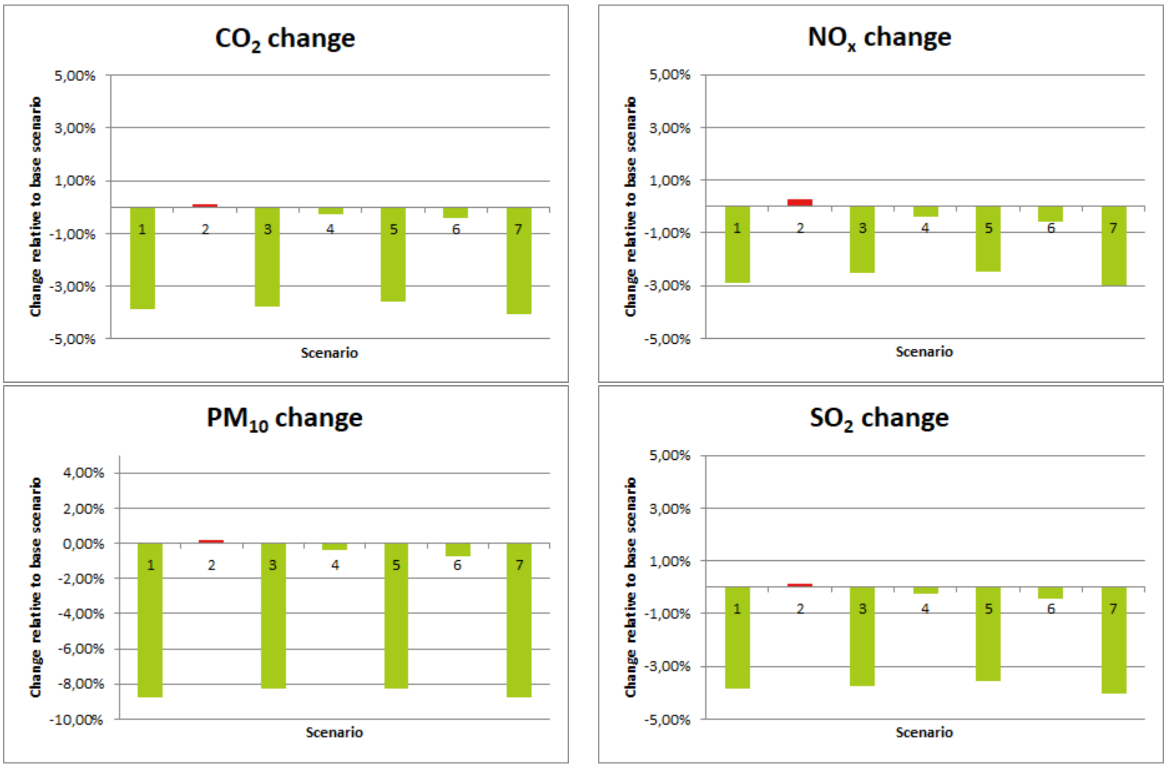


Table 6.2: Two-tailed p-values for a t-test for differences in $CO_2$ between scenarios

| Scenario | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|---|---|
| 0 | - | 0.00 | 0.71 | 0.00 | 0.47 | 0.00 | 0.21 | 0.00 |
| 1 | | - | 0.00 | 0.54 | 0.00 | 0.58 | 0.00 | 0.75 |
| 2 | | | - | 0.00 | 0.40 | 0.00 | 0.26 | 0.00 |
| 3 | | | | - | 0.00 | 0.85 | 0.00 | 0.37 |
| 4 | | | | | - | 0.00 | 0.78 | 0.00 |
| 5 | | | | | | - | 0.00 | 0.45 |
| 6 | | | | | | | - | 0.00 |
| 7 | | | | | | | | - |

Table 6.3: Two-tailed p-values for a t-test for differences in $NO_x$ between scenarios

| Scenario | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|---|---|
| 0 | - | 0.00 | 0.66 | 0.00 | 0.48 | 0.01 | 0.23 | 0.00 |
| 1 | | - | 0.00 | 0.28 | 0.00 | 0.57 | 0.00 | 0.97 |
| 2 | | | - | 0.01 | 0.36 | 0.01 | 0.24 | 0.00 |
| 3 | | | | - | 0.01 | 0.90 | 0.00 | 0.35 |
| 4 | | | | | - | 0.03 | 0.83 | 0.01 |
| 5 | | | | | | - | 0.03 | 0.61 |
| 6 | | | | | | | - | 0.00 |
| 7 | | | | | | | | - |

Table 6.4: Two-tailed p-values for a t-test for differences in $PM_{10}$ between scenarios

| Scenario | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|---|---|
| 0 | - | 0.00 | 0.76 | 0.00 | 0.49 | 0.00 | 0.15 | 0.00 |
| 1 | | - | 0.00 | 0.28 | 0.00 | 0.51 | 0.00 | 0.95 |
| 2 | | | - | 0.00 | 0.44 | 0.00 | 0.24 | 0.00 |
| 3 | | | | - | 0.00 | 0.92 | 0.00 | 0.35 |
| 4 | | | | | - | 0.00 | 0.67 | 0.00 |
| 5 | | | | | | - | 0.00 | 0.56 |
| 6 | | | | | | | - | 0.00 |
| 7 | | | | | | | | - |

Table 6.5: Two-tailed p-values for a t-test for differences in $SO_2$ between scenarios

| Scenario | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|---|---|
| 0 | - | 0.00 | 0.77 | 0.00 | 0.54 | 0.00 | 0.16 | 0.00 |
| 1 | | - | 0.00 | 0.65 | 0.00 | 0.51 | 0.00 | 0.64 |
| 2 | | | - | 0.00 | 0.49 | 0.00 | 0.26 | 0.00 |
| 3 | | | | - | 0.00 | 0.70 | 0.00 | 0.36 |
| 4 | | | | | - | 0.00 | 0.63 | 0.00 |
| 5 | | | | | | - | 0.00 | 0.32 |
| 6 | | | | | | | - | 0.00 |
| 7 | | | | | | | | - |

## 6.3. Discussion of the application results

For a discussion of the results, it is wise to go back to the conceptual model to see where changes have been made. The conceptual model with the inclusion of the policy scenarios is shown in figure 6.4; with the current implementation of measures, the effects on emissions cannot be estimated accurately.

The effects of the LEZ with pricing are currently underestimated, as the model is unable to grasp the effects of different routing due to the design of the distribution model. Since generalised transport cost between zones become higher, the destinations of the shipments change. This leaves the question if it is right to implement this measure in the freight distribution step. Would longer distances truly change the destination of a shipment, considering the fact that carriers have contracts with certain companies with fixed locations? In future updates of the model, this mechanic should be discussed, and perhaps the implementation of pricing measures should only be implemented as late as in the vehicle choice step. A more philosophical remark can be made here: to be able to accurately depict true freight trips, an origin and destination establishment are needed. This is where it becomes noticeable that agent-based models can be more suitable to model freight transportation patterns.

A second consideration that should be made with regards to the effects of a LEZ with pricing, is that the model only considers transportation cost and no warehousing cost (see section 3.2.2). Consequently, all impacts of road pricing are fully charged onto the transportation cost. This could lead to an overestimation of the impacts of road pricing.

With regards to zero-emissions vehicles, the first remark that has to be made is that the current implementation does not match with real-world processes. The growth of the market share of electric vehicles is not exogenously forced by authorities, but is something that occurs as a reaction to endogenous factors, such as LEZs or subsidies. This stresses the need for a better vehicle model that is also based on other factors, e.g. distance. However, the inclusion of an exogenous vehicle change was still interesting to analyse, as it has shown how the model reacted to a change in vehicle type. Even though the model behaved as expected, there is a flaw in the model that causes an overestimation of the effects on emissions. This is not caused by the vehicle model itself, but by the fact that there is an overestimation of very small trips. Since these are the trips that are converted to electric vehicles, too many trips are considered to have zero emissions.

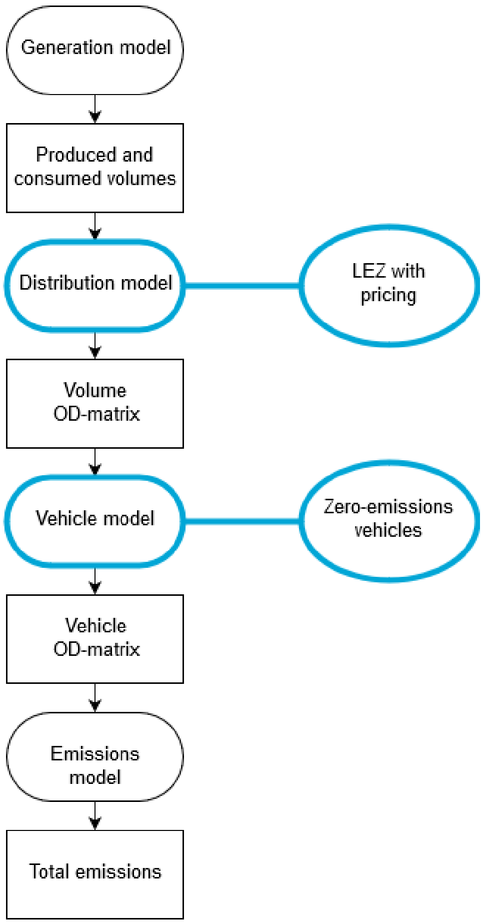



Figure 6.4: Conceptual model with inclusion of measures

# 7

# Conclusions and recommendations

In this chapter, the research is summarised in a set of conclusions and recommendations. First, the main conclusions are presented in section 7.1. Then, recommendations are given for future research and future updates of the model in section 7.2.

## 7.1. Conclusions

This section presents the conclusions that can be drawn from this research. First, the sub research questions are answered one by one. At the end of this section, the main research question is answered. The main research question and sub research questions are as follows:

*How can a model for urban freight transport in the urban region of Rotterdam (Groot-Rijnmond) be created, that allows for estimation of $CO_2$ impacts of policy measures for decarbonisation and that is suitable to be transferred to other European urban areas?*

1. Which existing urban freight models can be taken as a starting point, and what are the lessons that can be learned from these models?
2. Which policy measures should be implemented in the model?
3. Which factors should be taken into account when applying the model to other urban areas in Europe?
4. How can limited data availability in other urban areas be dealt with?
5. How can interoperability with other models in the ITF modelling framework be ensured?
6. Which types of commodities should be considered in a European model for urban freight transport?
7. Generation: How can the volume of freight that is generated in a certain zone be estimated?
8. Distribution: How can freight flows on a regional level be transferred to freight flows on a zonal level?
9. Vehicle trips: How can vehicle split and the creation of vehicle trips be modelled?
10. How can the policy measures that were defined in the context study be implemented?
11. What are the impacts of these policy measures on the expected tank-to-wheel $CO_2$ emissions?

**Research question 1**

Existing models for urban freight transport can be categorised in different ways. In terms of data requirements, models can be roughly categorised into two different types: models that are based on socio-economic data, and models that are based on detailed establishment data. This is a meaningful distinction, since spatial model transferability is largely dependent on the availability of the data sources that are used. In general, socio-economic data is more widely available than establishment data.

Twenty-two models were reviewed. Most of the reviewed sources used traffic surveys for model estimation, which differ a lot in quality and timespan. The most important conclusion is that most models are not suitable to be transferred to other areas, and that very few articles describe the assessment of $CO_2$ mitigation measures. Additionally, when building a model that can be spatially transferable and suitable for assessing decarbonisation measures, a commodity-based adapted four-step model is most suitable.

**Research question 2**
After a detailed review of fifteen data sources, a list of relevant policy measures was established. The following $CO_2$ mitigation measures have been identified:

- Zero/low emissions vehicles
- Restricted access to zones (restriction can be based on different characteristics)
- Pricing measures (on time or location)
- Urban consolidation centres
- Intelligent Transport Systems

In the future, all measures except for ITS should be implemented in the model. For this study, the choice was made to only implement zero-emissions vehicles and a low emission zone based on pricing. Reason for this choice is the fact that implementation of these measures can be done with a simple change in the input of data of the model. This is described in more detail in section 3.3.2.

**Research question 3**
The main factor that hampers spatial transferability is the availability of data in other countries or regions. The detailed CBS microdataset is unique to the Netherlands and is not available for other countries. This makes possible re-estimation of parameters for the freight demand model difficult. According to Holguín-Veras et al. (2013), parameters may be transferable between regions, but it should be investigated if this is possible, due to the large spatial differences between European regions.

**Research question 4**
Limited data availability in other urban areas in Europe can be dealt with by building a model that only uses underlying data that is available for all urban areas. Therefore, the generation model uses only European data from the ITF/OECD as predictors, and the creation of trips is done with empirical statistics that are also available in the Eurostat ERFT database. However, re-estimation of parameters remains a difficult issue because of the lack of useful data for other cities. Moreover, even if useful data were found, shaping these data to the right structure would be time-consuming.

**Research question 5**
Interoperability with other models in the ITF modelling framework can be enabled by three requirements. First, the model has to be written in one of the conventional modelling languages. In this study, this has been done by writing the model in R. Secondly, it should use output from the ITF regional freight model as input for the total volumes entering and exiting the region. This has not been done yet, as the ITF regional model was still under development at the time the model in this study was built. The third requirement is that this model for urban logistics uses the same spatial structure as the ITF regional freight model. This has been done by using a NUTS3 area, which has the same size as the functional urban areas that are established by the ITF.

**Research question 6**
Based on a literature review of commodity types in existing models for urban freight transport and the existing commodity types in the ITF modelling framework, a list of ten commodities for urban freight has been established. The commodities are:

1. Climate-controlled goods
2. Non-fresh food
3. Manufactured goods
4. Construction and building materials
5. Raw materials
6. Paper and wood
7. Chemicals
8. Waste
9. Transportation equipment
10. Parcels

**Research question 7**
The volume of freight that is generated in a zone can be estimated using a GLM with land use, population, GDP, commercial services and a binary variable for logistics hubs as independent variables. Depending on the commodity type, the GLM can either be an OLS model or a Tobit model. In this study, it was decided to use OLS models for all commodities, but for some commodities, the Tobit model would perform better. The $R^2$s of most of these models are quite low, but these values are not out of the ordinary when compared to freight generation models in literature. There is one variable that is included in nineteen of the twenty generation models, which is the binary variable for logistics hubs. Logistics hubs can be derived empirically or using a binary logistic GLM. The inclusion of these hubs can be useful in the future when adding urban consolidation centres to the model.

**Research question 8**
Translating regional freight flows to total freight production and consumption in the region is done in the generation step. This leads to total tonnages of freight production and consumption per year for each zone. Currently, this is done based on the total generated road freight as defined by Eurostat, but two changes will have to be made. First, these volumes should be commodity-specific instead of the shares based on microdata that have been used so far. Secondly, this should be based on the freight volumes that are estimated in the ITF regional freight model, instead of Eurostat data. When total freight production and consumption in the zones are known, OD flows can be calculated based on a doubly constrained gravity model. This gravity model is based on a generalised cost matrix that is calculated based on travel time and travel distance and commodity-specific sensitivity parameters. Using an iterative procedure, total freight OD flows can be calculated between the zones in the region and to and from an external zone. A disadvantage of this method is that a large number of small freight flows is calculated, which causes problems when creating vehicle trips.

**Research question 9**
Starting with OD flows, vehicle trips can be created by applying a shipment creation procedure followed by a trip creation procedure. Shipments are created based on a shipment size distribution from which shipments are drawn until there is no flow left between OD pairs. These shipments are allocated to vehicles based on empirical statistics. Then, trips are created by combining shipments with the same origin, destination and vehicle type. In this trips procedure, an empirical distribution for the number of shipments is used and the maximum load of the vehicle is taken into account.

**Research question 10**
Two policy measures were chosen to be implemented: zero-emissions vehicles and a low emission zone using pricing. Zero-emissions vehicles have been implemented using an adjusted vehicle choice distribution, based on the requirements of the scenario. The low emission zone has been implemented by changing the costs of the links in the road network that lead into the environmental zone, which changes the shortest paths between OD pairs and thus changes total kilometres driven and OD flows. Seven scenarios have been tested, based on all possible combinations of the following implementations:

1. Zero-emissions vehicles
   (a) Electrify all vans
   (b) Electrify all trips with a load <1.5 tonnes
   (c) Electrify all trips with a load <3.5 tonnes
2. Low emission zone with pricing: 10 euros for passing entry and exit points of the low emission zone, no differentiation made between vehicle types or time of day

**Research question 11**
Zero-emissions vehicles reduce total $CO_2$ emissions, based on the level of implementation. Surprisingly, electrifying all trips with a load smaller than 3.5 tonnes does not reduce $CO_2$ emissions significantly more than electrifying all vans. This is probably caused by how emissions are calculated (based on tonne-kilometres): trips with a small load already emit a small volume of emissions. Pricing measures do not cause much of a difference in $CO_2$ emissions, which is due to the mechanics of the freight distribution model. This measure, however, has to be re-applied when vehicle choice is modelled endogenously.

**Main research question**
The modelling methodology that has been created is an adjusted four-step model that is commodity-based. It uses input data that is available for all urban areas in Europe. The only location-specific inputs are parameters of the GLM model for freight generation and sensitivity parameters that are used for freight distribution. These parameters possibly have to be re-estimated for different regions or countries, or can be changed based on aggregate correction factors (see section 7.2.3). The fact that the model only uses input data that is available for all urban areas in Europe is a novelty; it is something that has not been considered in any of the existing models that have been discussed in chapter 2 (section 2.4). This modelling methodology therefore provides a useful first step towards the creation of a European model for urban freight transport.

The model generates output related to general transport statistics (tonne-kilometres, vehicle-kilometres, number of trips) and emissions. Whereas the focus of this study is on $CO_2$ emissions because it is part of the Decarbonising Transport initiative, the model generates output related to the local pollutants $NO_x$, $PM_{10}$ and $SO_2$ as well. The drawback is that because of the iterative creation of shipments and trips, the model takes five hours to run. This does not cause too many problems when performing a case study, but it would be very problematic when applying the model to a larger number of urban areas. Moreover, the five hours is only for one run, and although the model produces quite stable results it is appropriate to perform several runs. Furthermore, the assessment of several policy scenarios would add even more additional time.

The fact that the model as it is, is unsuitable to assess $CO_2$ emissions in a large number of urban areas, raises a more philosophical question. Is a model on a spatial scale that is this small truly needed to estimate $CO_2$ emissions for a whole region? The answer is: probably not. Thus, this model produces interesting results for the assessment of emissions in an urban area, but is most likely only appropriate to perform a smaller number of case studies. If the objective is to estimate $CO_2$ emissions for all urban areas in Europe, it would be easier to use a more aggregate model.

## 7.2. Recommendations

In this section, the recommendations are given that can be defined as a result of this study. They are divided into three categories: data recommendations, practical model recommendations, and recommendations for future research.

### 7.2.1. Data

The vehicles that are specified in the CBS microdata are not that suitable to estimate detailed city logistics patterns, as the microdata do not include vans. Although there is a separate microdataset for vans, the location variables in this dataset have a larger spatial scale than would be practical to convert a to 1 by 1-kilometre grid. Furthermore, having separate datasets means that there is no information about the shares of vans in the total goods distribution. It would be convenient to have more detailed data about shipments by vans and to connect these data to the general freight microdata.

The driven distances that are reported in the CBS microdata are inaccurately recorded. For this study, this meant that a manual connection to an external skim matrix was needed to calculate actual distances. Still, this was difficult because the start and end location of a shipment are reported in different ways for each shipment. Thus, there should be a fixed way of registering the start and end location of a trip, and the reported distance should be automatically calculated from these inputs.

Another issue with the CBS microdata is the fact that the goods types are inaccurately reported. The NST/R goods classification is most of the times reported accurately, but the NST2007 goods types almost seem to be randomly allocated to shipments. This is inconvenient, since the goods classification that is now widely used in Europe is the NST2007 classification, not NST/R. A recommendation to the CBS is to make sure that the NST2007 classification is recorded correctly as well.

The ITF/OECD commercial services data are based on how people report landmarks. This implies that inaccuracies exist. For example, when multiple people report the same store, that store is registered several times. Perhaps there should be a boundary on the number of services that can be reported in a certain area, to control for multiple registrations.

In addition to a better registration of commercial services, it would be very interesting to have a spatial dataset of economic and industrial activity. Thus, to not only register consumer-based landmarks, but also types of manufacturing companies or logistics companies. This would possibly allow for a more accurate freight generation model. Even though the CLC data indicates industrial land use, the surface area of land use does not say much about the number of companies that are active in a certain sector.

### 7.2.2. Model

The distribution modelling step could be improved, as there are too many OD pairs that have tiny volumes transported between them. This leads to an overestimation of small shipments, and thus an overestimation of the number of trips. The distribution model could be improved by adding parameters for GDP, population and a binary variable for logistics hubs in the destination zone, and possibly also by setting a constraint that limits the number of OD pairs with a very small flow. A more accurate distribution model could be established by using actual OD flows for calibration instead of total tonne-kilometres. The OD flows in the microdata are based on postal codes and thus have incomparable zone sizes, so either they would have to be converted to the 1 by 1 kilometre grid, or a parameter for size would have to be added (which turns into a constant when applying it to a 1 by 1 kilometre grid).

Another essential model improvement to the model is to include a better vehicle choice model. Vehicle choice is currently determined by an empirical distribution based on seven shipment size clusters. However, this makes vehicle choice insensitive to changes in transportation cost. Vehicle choice should be based on a deterrence function that has to be estimated. This is essential to be able to assess policy scenarios related to location restrictions, e.g. a zone toll for larger vehicles. Bal (2018) already studied this in a previous master thesis, based on the same microdata as used in this study: the thesis could provide useful insights.

Currently, an OLS model is used to predict freight generation for all commodities, even though a Tobit model has better predictive quality for some commodities. A slight improvement could be made in the freight generation step by replacing the OLS models by Tobit models for freight production of commodities 2, 6, 7, 8 and 10, and freight consumption of commodities 2, 3, 6, 7, 8 and 10.

Future updates of the model should include possibilities to assess all the identified decarbonisation measures. Suggestions for how to implement these measures can be found in section 3.3.1. Especially for the inclusion of urban consolidation centres, some model improvements are still needed in addition to the earlier mentioned improvements. An essential step towards the inclusion of UCCs is to create a tour-based model instead of a trip-based model. For the inclusion of urban consolidation centres inspiration could be taken from the LAMTA model as described by Beagan et al. (2007), or the implementation of UCCs as in De Bok et al. (2020). A previous master thesis by Thoen (2018) can provide guidance for the tour formation procedure.

The run time of the model is an issue, even though parallel processing is used for the most time-consuming procedures. This makes the model unsuitable to be applied to a large number of urban areas. It could be interesting to see if the model performs better when converted to another modelling language that is more efficient with iterative loops than R.

### 7.2.3. Future research

The model should be validated on another urban area. Using the current model but with Eurostat input data, a case study could be done. This can again be done for another Dutch city. Then, the output of the trips by the model can be compared to the trips for that region that are reported in the CBS microdata.

Related to the above-mentioned validation, it would also be appropriate to perform a sensitivity analysis. The model currently outputs stable results with the use of the same input data, but it would be interesting to assess whether this is also the case when small changes in input data are made.

Moreover, a flaw in this study is that the choice of the case study was perhaps not the most suitable. Rotterdam is not the most typical city because of the large volumes that are transported through the port. There is a lot of interregional transport, so in this region, there is possibly not enough emphasis on typical city logistics trips. This could lead to an underestimation of trips that are related to activities in the city. It is recommended to perform a case study for another urban area that does not have such a large port. This can even be a case study for another Dutch city for which the same model estimation procedure with the CBS microdata can be used.

Currently, freight generation is based on the relative shares between commodities in the dataset. This should be improved by linking the commodities in the urban freight model to the commodities in the regional ITF model. It is recommended to establish conversion factors to translate the commodity types that the ITF uses for its regional models to the newly defined urban commodity types from this study.

The land-use types that the freight generation model is currently estimated on, are specific to the Groot-Rijnmond region. Land use patterns are different for different countries in Europe. Therefore, it would be beneficial to re-estimate the freight generation models for different countries or regions, as to include area-specific land-use types.

The policy scenarios to which the model has been applied, have been assessed based on current state spatial data. In future policy studies, it would be worthwhile to see how changes in socio-economics such land use, population and GDP, change freight transportation patterns.

Especially for analysis of transport of parcels, a shortcoming is that trip patterns by vans have not been considered. A separate model for parcels could be estimated based on population and the average number of parcels delivered per household or person. The required data could be requested to postal companies that are willing to participate in this type of study.

Another issue related to vans is that they are currently included in the model as a fixed share for commodities 4 and 10. This is because vans are not connected to the general microdata, as mentioned previously in section 7.2.1. The most meticulous solution would be to estimate a vehicle choice model that includes all vehicle types, based on combined data for larger freight vehicles and vans.

Regarding re-estimation of parameters, it should be investigated if detailed freight transport surveys are available for other countries. The literature that has been reviewed in section 2.4 can be used as a starting point for identifying relevant countries. Then, the model parameters could be re-estimated for one city per country, for example, and then used for all other cities in that country. However, the question remains if comparable datasets to the CBS microdata are available for other countries.

Another simpler procedure for re-estimating freight generation parameters for other regions is inspired by the transferability study by Holguín-Veras et al. (2013). First of all, a correction factor could be applied to the binary land-use variable for ports. This correction factor can be based on the activity in the port. For example, the Port of Rotterdam has very high port activity and thus would have very high freight generation in zones that are defined as port area, while in an inland city, port areas would be multiplied by a lower correction factor. The same could be done based on employment statistics for different sectors: when a higher share of people work in e.g. industry, compared to the Groot-Rijnmond region, the land-use variable for industrial zones would be given a higher correction factor.

The model only includes loaded trips, so no empty trips are included. These, however, are important for estimating $CO_2$ emissions as well. To include empty trips, an additional model could be estimated that treats empty trips as a different type of commodity with its specific freight patterns.

If there is any interest in assessing the effects of freight transport on traffic in urban areas, an additional modelling step should be added that assigns trips to the road network. This also adds the option to feed estimated travel times back into the distribution step and create an iterative model. Moreover, this allows for a more accurate calculation of emissions, since speed and acceleration could be added to the calculation as well. However, this would require drastic changes to the modelling structure. Given the purpose with which this model has been built, such an advanced model would be overly complicated.

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# A

# Interview with local authority

Date: 23 April 2019
Name: Jan Robbert Albrechts

**Wat is je functie bij de gemeente Rotterdam?**
Ik ben coordinator van het cluster goederenvervoer, dat valt onder de afdeling mobiliteit. Ik houd me vooral bezig met beleidsmatige zaken.

**Wat is het beleid waar jullie je nu mee bezighouden?**
Onze hoofddoelstelling is: “efficient en schoon”. Het liefst willen we een emissievrije stad, en we zijn nu ook een van de steden die nog niet voldoet aan Europese emissienormen. We willen daar graag wat aan doen, en denken daarbij na over de midden tot lange termijn, met als doel minder en schonere trips van vrachtvervoer.

**Wat zijn de specifieke beleidsmaatregelen die jullie al hebben geimplementeerd?**
In 2014 zijn we begonnen met de Green Deal zero emission stadslogistiek 010. De Nederlandse doelstelling was om in de binnenstad in 2025 emissievrij te zijn, maar wij hebben dat toen op 2020 gezet. Het doel om in 2020 emissievrije bevoorrading van de binnenstad te hebben blijkt nu te ambitieus. Maar door deze ambitieuze doelstelling is wel een beweging op gang gebracht. Ondernemers komen sneller in actie, in Rotterdam is niet meer het gesprek ’waarom’ maar ’hoe’ gaan we het doen. We hebben een programma met activiteiten opgesteld om vervoerders te stimuleren om hun wagenpark te verduurzamen. Voorbeelden zijn:

- Ecostar: adviseurs gaan langs bij de bedrijven om ze te stimuleren om in hun wagenpark meer emissievrije voertuigen op te nemen. Met een groter aandeel emissievrije voertuigen kunnen bedrijven sterren verdienen waarmee ze privileges krijgen, zoals permissie om op busbanen te rijden of om niet alleen ’s ochtends maar ook ’s avonds gebruik te maken van voetgangersgebieden.
- Platform logistiek 010: een platform dat vooral gericht is op het uitwisselen van kennis. Zo kan hier bijvoorbeeld uit komen dat het nuttig is om subsidies in te stellen.

**Wat zijn de effecten van de geimplementeerde beleidsmaatregelen?**
We hebben geen cijfers om dit te meten. Wat we wel zien is een verschuiving binnen de logistiek. In 2014 was TLN nog terughoudend over de ambitieuze doelstelling van Rotterdam, maar nu roepen ze de lokale overheid om om snel duidelijke kaders te geven zoals invoering van een zero emissie zone voor Stadslogistiek in 2025.

**Hoe nu verder?**
Voorheen richtten we ons vooral op stimuleren, maar nu hebben we ook plannen om te gaan reguleren. Het voornaamste onderdeel daarvan is een vanuit de gemeente vastgestelde zero-emission zone. Daar hebben we nu een nieuwe deal voor in voorbereiding.

**Wat is je mening over de volgende beleidsmaatregelen/innovaties:**

- Emissievrije/alternatieve fuel voertuigen: Wij hebben echt alleen de focus op emissievrije voertuigen, omdat je beter in een keer deze stap kunt zetten. Wel is dit bijvoorbeeld lastig voor grotere/zwaardere trucks.
- Prijsmaatregelen, bijvoorbeeld extra kosten tijdens spitstijden: Voor de algehele verkeersplanning en efficientie is dit natuurlijk heel goed. Maar de vraag is of dit een grote impact heeft op de emissies.
- Trainen van chauffeurs om zuiniger te rijden: Dit is iets waar we in het ecostars project al aan hebben gewerkt. Je zou dit kunnen combineren met intelligente transport systemen. Maar met de omschakeling naar zero emissie voertuigen kan het ook zijn dat de rijstijl weer moet veranderen omdat dat voor zo'n voertuig weer efficienter is.
- Urban consolidation centres: Hier zijn wel wat voorbeelden van waar de overheid dit heeft geprobeerd te implementeren, maar er zijn bijna geen voorbeelden waar dit succesvol is geweest. Wat je ziet is dat de sector het toch vooral zelf wil regelen. Als overheid kunnen wij hier alleen de kaders voor schetsen, bijvoorbeeld door de invoering van een ZE zone. Verder zijn dit soort logistieke hubs alleen interessant voor een klein deel van de bedrijven – voornamelijk kleine bedrijven die baat hebben bij het bundelen van zendingen. Ook verschilt het per logistiek segment.

# B

# Overview of existing commodity classifications

Table B.1: Overview of ITF commodity types

| Name | Transport |
|---|---|
| Chemicals rubber and plastic | 1 |
| Refined Oil | 1 |
| Paper and wood | 1 |
| Public administration | 0 |
| Electricity | 0 |
| Electronic devices | 1 |
| Livestock | 1 |
| Food | 1 |
| Other Metals | 1 |
| Transport Equipment | 1 |
| Transport services | 0 |
| Wholesales retail trade | 0 |
| Other Minerals | 1 |
| Coal | 1 |
| Iron and Steel | 1 |
| Textile | 1 |
| Other Agriculture | 1 |
| Metal products | 1 |
| Business services | 0 |
| Other Services | 0 |
| Crude oil | 1 |
| Other Mining | 1 |
| Rice and crops | 1 |
| Gas | 1 |
| Other Manufacturing | 1 |

Table B.2: Overview of urban commodity types in literature

| | Gentile and Vigo (2013) | Hunt and Stefan (2007) | Muñuzuri et al. (2009) | Nuzzolo and Comi (2014) | Wisetjindawat et al. (2007) | Den Boer et al. (2017) |
|---|---|---|---|---|---|---|
| Clothes and accessories | ✓ | | ✓ | ✓ | | |
| Food (general) | | ✓ | | ✓ | | |
| Fresh food | ✓ | | ✓ | | | |
| Non-fresh food | ✓ | | ✓ | | | |
| Frozen food | ✓ | | | | | |
| Household and electronics | ✓ | | ✓ | ✓ | | |
| Newspapers | ✓ | | | | | |
| Pharmaceuticals | ✓ | | ✓ | | | |
| Wholesale and department stores | ✓ | ✓ | | | ✓ | |
| Other retail | ✓ | ✓ | ✓ | | ✓ | |
| Services | ✓ | ✓ | | ✓ | | |
| Documents | ✓ | | | | | |
| Reverse logistics | ✓ | | | | | |
| Agriculture, forestry, fishing, hunting | | ✓ | | | ✓ | |
| Mining and oil and gas extraction | | ✓ | | | ✓ | |
| Utilities | | ✓ | | | ✓ | ✓ |
| Construction and building materials | | ✓ | ✓ | ✓ | ✓ | ✓ |
| Manufacturing | | ✓ | ✓ | | ✓ | |
| Transportation and warehousing | | ✓ | | | ✓ | |
| Stationery | | | | ✓ | | |
| Personal hygiene | | | | ✓ | | |
| Metal and machinery products | | | | | ✓ | |
| Chemical products | | | | | ✓ | |
| Light industry products | | | | | ✓ | |
| Waste and scrap | | | | | ✓ | ✓ |
| Parcels and express | | | | | | ✓ |
| Temperature-controlled | | | | | | ✓ |

# C

# Principal Component Analysis of services

This appendix gives the output of three different Principal Component Analyses (PCAs) that were conducted to support the decision whether or not to cluster variables of the ITF/OECD commercial services data. The sample data contained random samples of zones of 1 by 1 kilometre in urban areas in Europe. They contained 4528, 4735 and 4668 zones from 133, 140 and 132 functional urban areas respectively. The PCAs were performed in SPSS, and the outcomes were rotated using Varimax rotation. Coefficients with an absolute value below 0.30 were suppressed. The results can be seen in tables C.1, C.2 and C.3. It is clear that the components have different compositions for the different datasets, so it was decided not to use clusters in the freight generation models.

Table C.1: Results of PCA for sample 1

| | Component | | | | | |
|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 |
| restaurant | .761 | .383 | | | | |
| rail | | | | | | .764 |
| post | | .321 | .348 | | .485 | |
| pharmacy | .343 | .523 | .371 | | | |
| parks | | | | .490 | | |
| museum | .637 | | | | | |
| market | | .645 | | | | |
| hospital | | .375 | | .582 | | -.402 |
| health | | .619 | | | | |
| department store | | .636 | | | | |
| cultural centre | | | | | .809 | |
| cinema | | | .611 | | | |
| church | .515 | | | | .378 | |
| cafe | .784 | | .337 | | | |
| bank | | | .830 | | | |
| transit | | | .830 | | | |
| tourist attraction | .894 | | | | | |
| theater | .478 | .399 | | | | |
| stadium | | | | .578 | | .345 |
| other shop | .547 | .590 | .444 | | | |
| food shop | .790 | | | | | |
| school | | .491 | | | | |

Table C.2: Results of PCA for sample 2

| | Component | | | | | |
|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 |
| restaurant | .637 | .468 | | | | |
| rail | | | | .463 | | -.302 |
| post | .399 | | | | | |
| pharmacy | .745 | | | | | |
| parks | | | .828 | | | |
| museum | | .884 | | | | |
| market | .665 | | | | | |
| hospital | .405 | | | -.544 | -.471 | |
| health | .554 | | | | | -.335 |
| department store | | | | .614 | | |
| cultural centre | | | | | .792 | |
| cinema | | .765 | | | | |
| church | | .354 | .575 | | | |
| cafe | .535 | .599 | | | | |
| bank | .796 | .308 | | | | |
| transit | .796 | .308 | | | | |
| tourist attraction | | .897 | | | | |
| theater | | .565 | | | | |
| stadium | | | | | | .855 |
| other shop | .805 | .444 | | | | |
| food shop | .724 | .443 | | | | |
| school | .679 | | | | | |

Table C.3: Results of PCA for sample 3

| | Component | | | | | |
|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 |
| restaurant | .816 | .305 | | | | |
| rail | | | .364 | -.327 | | .321 |
| post | .470 | | | | | |
| pharmacy | .707 | | | | | |
| parks | | | | | | |
| museum | .363 | .536 | | | | |
| market | .599 | | .322 | | | |
| hospital | | | | .399 | | .663 |
| health | .619 | | | | .304 | |
| department store | | | .387 | | -.514 | |
| cultural centre | | | | -.663 | | |
| cinema | .347 | .645 | | | | |
| church | .447 | | | | | |
| cafe | .687 | | | | | |
| bank | .701 | -.323 | -.527 | | | |
| transit | .701 | -.323 | -.527 | | | |
| tourist attraction | .431 | .622 | | | | |
| theater | .357 | .487 | | | | |
| stadium | | | | | .583 | -.466 |
| other shop | .903 | | | | | |
| food shop | .752 | | | | | |
| school | .480 | | | .302 | | |

# D

# GLM models for freight generation

This appendix shows the more detailed results of the OLS, Tobit and ZINB models for freight generation. The following specification can be made regarding significance levels:

- *** = 0 significance level
- ** = 0.001 significance level
- * = 0.01 significance level
- . = 0.05 significance level

## D.1. OLS models

Table D.1: OLS freight production models

| | Commodity | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| constant | 9362.361 | 468.687 | 1211.354. | -422.464** | -238.825. | -678.507 | -1373.508* | 522.362 | 3141.530. | -346.755 |
| logistics hub | 316594.481*** | 11858,978*** | 32114.369*** | 4406.194*** | | 4280.305*** | 16704.341*** | 8901.466* | 107575.804*** | 10811.598*** |
| population | | -0.963** | | 1.266*** | 1.005*** | 1.892*** | 4.862*** | -4.768*** | -6.434*** | |
| GDP | | -0.000*** | 0.000*** | 0.000*** | 0.000*** | 0.000*** | -0.000*** | 0.000*** | 0.000*** | 0.000*** |
| 112: discontinuous urban fabric | | | | | | | | -5507.166. | 12351.687*** | |
| 121: industrial or commercial units | -51160.12. | | 16543.742*** | 1535.422* | 1696.949*** | | 13583.570*** | 11768.949* | | |
| 123: port areas | -252357.700*** | -3077.861** | 46655.757*** | | 4066.312*** | 18245.549*** | 9422.283*** | 18295.791*** | 27863.186*** | -7734.714*** |
| 132: dump sites | | | 43005.953. | | | | | | | |
| 133: construction sites | | | | | | | | | 40709.853* | |
| 141: green urban areas | | | | | | | | | | 15028.335*** |
| 211: non-irrigated arable land | 25913.003** | 1072.263* | | | | | | | | |
| 242: complex cultivation patterns | 48885.613. | | | | | | | | | |
| 243: land principally occupied by agriculture | | | | | | | | | | |
| market | .750. | | | | | | | | | |
| school | | | | | | 283.389* | | | | |
| shop_food | | 302.408** | | | | | | | | |
| shop_other | | | | 3.110*** | | | | | | |
| $R^2$ | 0.232 | 0.200 | 0.471 | 0.254 | 0.118 | 0.190 | 0.252 | 0.071 | 0.464 | 0.138 |

Table D.2: OLS freight consumption models

| | Commodity | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| constant | 11919.074*** | 1084.297*** | 1937.187* | -220.113 | -95.614 | -465.708 | -105.434 | -610.798*** | 3616.370* | 72.614 |
| logistics hub | 168266.124*** | 8834.216*** | 39621.342*** | 3347.457*** | 1431.876*** | 3630.782*** | 9450.750*** | 7024.380*** | 107818.441*** | 20458.906*** |
| population | -9.420 | | | 1.161*** | 0.537*** | 1.681*** | 2.270*** | 1.218*** | -7.868*** | |
| GDP | | -0.000** | 0.000*** | | 0.000*** | 0.000*** | 0.000*** | -0.000*** | 0.000*** | |
| 112: discontinuous urban fabric | | | | | | | | 882.614. | | |
| 121: industrial or commercial units | | | 26668.592*** | 6331.108*** | 1892.781*** | 2473.691. | 6509.865*** | 3453.264*** | | -4733.457. |
| 122: road and rail networks | | | | | | | | | 30270.660* | |
| 123: port areas | -122932.011*** | -3213.213*** | 31966.218*** | 2877.324*** | 2762.933*** | 13980.793*** | 14482.925*** | -1867.811* | 15091.094** | -15299.933*** |
| 132: dump sites | | | | | | | | 13541.702* | | |
| 141: green urban areas | | | | | | | | | | 28386.364*** |
| 242: complex cultivation patterns | 25006.892. | | | | | | | | | |
| 243: land principally occupied by agriculture | | | | | | | | 9337.843*** | | |
| market | 9769.242* | 468.859. | | | | | | | | |
| school | | | | | | 220.756. | | | | |
| shop_other | | | | 4.638*** | | | | | | |
| $R^2$ | 0.212 | 0.186 | 0.473 | 0.334 | 0.250 | 0.185 | 0.233 | 0.251 | | |

## D.2. Tobit models

Table D.3: Tobit freight production models

| | Commodity | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| intercept 1 | -27360*** | -6035*** | -5153*** | -6079*** | -12490*** | -18880*** | -30020*** | -32050*** | -12390*** | -24620*** |
| intercept 2 | 12.060*** | 9.378*** | 10.080*** | 8.670*** | 9.102*** | 9.849*** | 10.210*** | 10.690*** | 10.800*** | 9.818*** |
| logistics hub | 335400*** | 18700*** | 37300*** | 6795*** | 3485*** | 12390*** | 29120*** | 22370*** | 111800*** | 20820*** |
| population | | | | 2864*** | 2841** | 5050*** | 11250*** | | | 3169*** |
| GDP | | -25.320*** | 60.120*** | -11.840*** | -18.420*** | -63.760*** | -86.310*** | 149.300*** | 120.500*** | 30.610* |
| 112: discontinuous urban fabric | | -3821** | | | | | | | 15090*** | 8039** |
| 121: industrial or commercial units | -63530* | | 19130*** | 2465** | 5269*** | 6227* | 18230*** | 16080* | | |
| 123: port areas | -271300*** | | 47530*** | | 9805*** | 23920*** | 13740*** | 27280*** | 28200*** | |
| 133: construction sites | | | | | | | | | 44620** | |
| 141: green urban areas | | | | | | | | | | 21130*** |
| 211: non-irrigated arable land | | 1910** | | | | | | | | 7688*** |
| 242: complex cultivation patterns | 58530* | | | 2047* | | | | | | |
| market | 18700* | | | | | | | | | |
| shop_food | | 704.500*** | | 281.200*** | | | | | | -168.6000*** |
| shop_other | | | | | | | | | | 32.630*** |
| $R^2$ | 0.23 | 0.23 | 0.47 | 0.24 | 0.08 | 0.21 | 0.30 | 0.11 | 0.47 | 0.19 |

Table D.4: Tobit freight consumption models

| | Commodity | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| intercept 1 | -6610* | -1148*** | -411 | -2278*** | -7651*** | -16040*** | -7688*** | -19980*** | -17010*** | -14600*** |
| intercept 2 | 11.440*** | 8.872*** | 10.050*** | 8.508*** | 8.531*** | 9.687*** | 9.683*** | 9.372*** | 10.640*** | 10.040*** |
| logistics hub | 169800*** | 10730*** | 41760*** | 4123*** | 3550*** | 12080*** | 15020*** | 16110*** | 115700*** | 25680*** |
| population | | | | 1594*** | 2246*** | 4780*** | 2609*** | 4701*** | | 2699*** |
| GDP | | -12.850*** | 72.280*** | | -17.720*** | -48.720*** | -20.030* | -28.000*** | 170.600*** | |
| 112: discontinuous urban fabric | | | | | | | | 3732** | | |
| 121: industrial or commercial units | | 2239* | 26080*** | 6924*** | 4107*** | 5652* | 8757*** | 8278*** | | |
| 122: road and rail networks | | -5836 | | | | | | | 30460 | |
| 123: port areas | -128500*** | -2841** | 32250*** | 3321*** | 5416* | 12310*** | 15760*** | | 13010* | -20150*** |
| 132: dump sites | | | | | | | | | -107300 | |
| 133: construction sites | | 6773** | | | | | | | | |
| 141: green urban areas | | | | | | | | 6894* | | 29800*** |
| 211: non-irrigated arable land | | | -2731* | | 936.200*** | | -2946** | 2385* | | |
| 242: complex cultivation patterns | 32730* | -4018** | | | | -15420** | | | | |
| 243: land principally occupied by agriculture | | | | | | | | 15160** | | |
| market | 11680** | | | | | | | | | |
| shop_food | | | -1145* | | | | | | | -1427** |
| shop_other | | | 23.350* | 5.634*** | | | | | | 33.530*** |
| $R^2$ | 0.21 | 0.20 | 0.48 | 0.33 | 0.23 | 0.20 | 0.25 | 0.32 | 0.57 | 0.17 |

## D.3. ZINB models

```
Call:
zeroinfl(formula = A_Climatecontrolledgoods ~ log_hub + gdp_new + land_use_123 + land_use_124 + land_use_132 +
    land_use_211 + land_use_231 + land_use_311 + shop_food | gdp_new + land_use_231, data = cleaned_for_GLM,
    offset = pop_new, dist = "negbin")

Pearson residuals:
     Min       1Q   Median       3Q      Max 
-0.70393 -0.59319 -0.42965 -0.01773 14.68385 

Count model coefficients (negbin with log link):
               Estimate Std. Error z value Pr(>|z|)    
(Intercept)   7.7371295  0.0759535 101.867  < 2e-16 ***
log_hub       3.2397458  0.1143264  28.338  < 2e-16 ***
gdp_new      -0.0037924  0.0006222  -6.096 1.09e-09 ***
land_use_123 -1.4393673  0.1845807  -7.798 6.29e-15 ***
land_use_124 -1.7268327  0.8219882  -2.101 0.035659 *  
land_use_132 -4.5333730  1.4240331  -3.183 0.001455 ** 
land_use_211  0.2471440  0.0874242   2.827 0.004699 ** 
land_use_231 -0.4115374  0.1008935  -4.079 4.52e-05 ***
land_use_311 -0.5884135  0.2678268  -2.197 0.028021 *  
shop_food     0.0713897  0.0190644   3.745 0.000181 ***
Log(theta)   -0.6972463  0.0326465 -21.357  < 2e-16 ***

Zero-inflation model coefficients (binomial with logit link):
              Estimate Std. Error z value Pr(>|z|)    
(Intercept)  -1.865263   0.128933 -14.467  < 2e-16 ***
gdp_new      -0.034477   0.007379  -4.672 2.98e-06 ***
land_use_231  0.866620   0.166771   5.196 2.03e-07 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1 

Theta = 0.498 
Number of iterations in BFGS optimization: 25 
Log-likelihood: -1.722e+04 on 14 Df
```

Figure D.1: ZINB model consumption commodity 1

```
Call:
zeroinfl(formula = P_Manufacturedgoods ~ log_hub + pop_new + land_use_121 + land_use_123 + land_use_142 + land_use_242 +
    land_use_311 + land_use_321 + bank + dep_store + market + post | gdp_new + pop_new + land_use_121 + land_use_231 +
    land_use_242 + healthcare + market + school + shop_other, data = cleaned_for_GLM, offset = pop_new, dist = "negbin")

Pearson residuals:
      Min        1Q    Median        3Q       Max
-0.746926 -0.572015 -0.417477  0.003321 23.358900

Count model coefficients (negbin with log link):
             Estimate Std. Error z value Pr(>|z|)
(Intercept)   7.57613    0.06528 116.049  < 2e-16 ***
log_hub       1.43800    0.11987  11.997  < 2e-16 ***
pop_new      -0.28473    0.04991  -5.705 1.16e-08 ***
land_use_121  0.57042    0.19122   2.983 0.002854 **
land_use_123  1.18117    0.18091   6.529 6.62e-11 ***
land_use_142  0.84338    0.22833   3.694 0.000221 ***
land_use_242 -0.62414    0.25376  -2.460 0.013910 *
land_use_311 -0.64946    0.30643  -2.119 0.034053 *
land_use_321 -0.57639    0.24254  -2.376 0.017478 *
bank          0.24594    0.11385   2.160 0.030755 *
dep_store    -0.56152    0.23768  -2.363 0.018150 *
market       -0.29398    0.06924  -4.246 2.18e-05 ***
post          0.36842    0.15847   2.325 0.020079 *
Log(theta)   -0.56513    0.03515 -16.078  < 2e-16 ***

Zero-inflation model coefficients (binomial with logit link):
              Estimate Std. Error z value Pr(>|z|)
(Intercept)  -0.844875   0.100651  -8.394  < 2e-16 ***
gdp_new       0.005451   0.001567   3.479 0.000502 ***
pop_new      -0.695066   0.113101  -6.146 7.97e-10 ***
land_use_121 -2.338376   1.140979  -2.049 0.040418 *
land_use_231  0.527520   0.124677   4.231 2.33e-05 ***
land_use_242  1.039064   0.295654   3.514 0.000441 ***
healthcare    0.084368   0.027573   3.060 0.002215 **
market       -0.347234   0.131498  -2.641 0.008276 **
school        0.095959   0.031307   3.065 0.002176 **
shop_other   -0.003185   0.001163  -2.738 0.006174 **
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Theta = 0.5683
Number of iterations in BFGS optimization: 33
Log-likelihood: -1.443e+04 on 24 Df
```

Figure D.2: ZINB model production commodity 3

# E

# Generalised cost of goods transport

In the tables in the following three sections, an overview of costs of goods transport by Rijkswaterstaat (2016) can be found. The tables give the total costs per year, the costs per kilometre and the costs per hour. This information was used to calculate a generalised cost function, as explained in section E.4

## E.1. Costs of transporting bulk

Table E.1: Transport costs large-sized bulk (125,000 km; 2,600 hours per year)

| | Annual costs [€] | Distance costs [€ per hour] | Time costs [€ per hour] |
|---|---|---|---|
| Fixed costs | 36505.7 | 0.29 | 14.04 |
| Variable costs | 61487.3 | 0.49 | 23.65 |
| Personnel costs | 81568.6 | 0.65 | 31.37 |
| Specific transport costs | 1149.1 | 0.01 | 0.44 |
| General company costs | 23671.9 | 0.19 | 9.10 |
| Total | 204 382.5 | 1.64 | 78.61 |

## E.2. Costs of transporting general cargo (piece goods)

Table E.2: Transport costs small-sized general cargo (70,000 km; 2,235 hours per year)

| | Annual costs [€] | Distance costs [€ per hour] | Time costs [€ per hour] |
|---|---:|---:|---:|
| Fixed costs | 7,254.4 | 0.10 | 3.25 |
| Variable costs | 10,870.0 | 0.16 | 4.86 |
| Personnel costs | 56,445.9 | 0.81 | 25.26 |
| Specific transport costs | 316.4 | 0.00 | 0.14 |
| General company costs | 10,987.9 | 0.16 | 4.92 |
| Total | 85,874.5 | 1.23 | 38.42 |

Table E.3: Transport costs medium-sized general cargo (85,000 km; 2,235 hours per year)

| | Annual costs [€] | Distance costs [€ per hour] | Time costs [€ per hour] |
|---|---|---|---|
| Fixed costs | 16,502.5 | 0.19 | 7.38 |
| Variable costs | 23,402.5 | 0.28 | 10.47 |
| Personnel costs | 60,568.9 | 0.71 | 27.10 |
| Specific transport costs | 569.5 | 0.01 | 0.25 |
| General company costs | 14,836.2 | 0.17 | 6.64 |
| Total | 115,879.6 | 1.36 | 51.85 |

Table E.4: Transport costs large-sized general cargo (130,000 km; 2,600 hours per year)

| | Annual costs [€] | Distance costs [€ per hour] | Time costs [€ per hour] |
|---|---|---|---|
| Fixed costs | 28,998.2 | 0.22 | 11.15 |
| Variable costs | 58,491.9 | 0.45 | 22.50 |
| Personnel costs | 81,568.6 | 0.63 | 31.37 |
| Specific transport costs | 887.1 | 0.01 | 0.34 |
| General company costs | 22,739.7 | 0.17 | 8.75 |
| Total | 192,685.5 | 1.48 | 74.11 |

## E.3. Costs of transporting containers

Table E.5: Transport costs medium-sized containers (105,000 km; 2,525 hours per year)

| | Annual costs [€] | Distance costs [€ per hour] | Time costs [€ per hour] |
|---|---|---|---|
| Fixed costs | 18077.2 | 0.17 | 7.16 |
| Variable costs | 28581.2 | 0.27 | 11.32 |
| Personnel costs | 69098.0 | 0.66 | 27.37 |
| Specific transport costs | 569.5 | 0.01 | 0.23 |
| General company costs | 10993.4 | 0.10 | 4.35 |
| Total | 127 319.3 | 1.21 | 50.42 |

Table E.6: Transport costs large-sized containers (135,000 km; 2,600 hours per year)

| | Annual costs [€] | Distance costs [€ per hour] | Time costs [€ per hour] |
|---|---|---|---|
| Fixed costs | 28998.2 | 0.21 | 11.15 |
| Variable costs | 60743.1 | 0.45 | 23.36 |
| Personnel costs | 81568.6 | 0.60 | 31.37 |
| Specific transport costs | 887.1 | 0.01 | 0.34 |
| General company costs | 16112.9 | 0.12 | 6.20 |
| Total | 188 309.9 | 1.39 | 72.43 |

## E.4. Calculation of a general generalised cost function

Since the choice was made to build an aggregate model, it was decided to choose one general cost function for all different commodities. The function is based on a weighted average of three cargo types, based on their share of the total volume of goods transport in the Groot-Rijnmond region. The relevant values are given in table E.7. It can be seen that for the calculation of the distance, the variable costs as given in the previous sections are taken, while the cost of time is based on the remaining costs. This leads to the following function:

$$c_{ij} = 0.322 * distance_{ij} + 43.520 * traveltime_{ij}$$

Table E.7: Calculation of generalised cost function

| **Cargo type** | | **Distance [km]** | **Time [h]** | **Share** |
|---|---|---|---|---|
| General cargo | Small | 0.16 | 33.56 | 0.72 |
| | Medium | 0.28 | 41.38 | |
| | Large | 0.45 | 51.61 | |
| | Average | 0.29 | 42.18 | |
| Containers | Medium | 0.27 | 39.10 | 0.20 |
| | Large | 0.45 | 49.06 | |
| | Average | 0.36 | 44.08 | |
| Bulk | Large | 0.49 | 54.96 | 0.07 |
| Total | | 0.322 | 43.520 | |

# F

# Vehicle type choice and clustering of weight groups

Tables F.1 to F.10 show the vehicle choice probabilities for different shipment size clusters. The clusters were determined based on k-means clustering for the entire set of shipments of the Groot-Rijnmond region. This analysis showed that the clusters performed best starting at seven clusters, which is why this number was chosen. Furthermore, the bounding numbers were rounded to multiples of 500, as to make the clusters easily comprehensible. The vehicle type references in the tables are the following:

1. Van
2. Truck/lorry without trailer
3. Truck/lorry with trailer
4. Tractor without trailer
5. Tractor with trailer
6. "Other" vehicle without trailer
7. "Other" vehicle with trailer

Table F.1: Vehicle type probability per shipment size cluster commodity 1

| | vehicle type probability | | | | | | |
|---|---|---|---|---|---|---|---|
| shipment size [kg] | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| <500 | 0% | 5% | 28% | 0% | 67% | 0% | 0% |
| 500-1,500 | 0% | 2% | 42% | 0% | 56% | 0% | 0% |
| 1,500-3,500 | 0% | 4% | 27% | 0% | 69% | 0% | 0% |
| 3,500-6,500 | 0% | 2% | 25% | 0% | 73% | 0% | 0% |
| 6,500-10,000 | 0% | 5% | 28% | 0% | 67% | 0% | 0% |
| 10,000-15,000 | 0% | 3% | 29% | 0% | 68% | 0% | 0% |
| >15,000 | 0% | 2% | 32% | 0% | 66% | 0% | 0% |

Table F.2: Vehicle type probability per shipment size cluster commodity 2

| | vehicle type probability | | | | | | |
|---|---|---|---|---|---|---|---|
| shipment size [kg] | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| <500 | 0% | 15% | 36% | 0% | 48% | 0% | 0% |
| 500-1,500 | 0% | 11% | 33% | 0% | 56% | 0% | 0% |
| 1,500-3,500 | 0% | 20% | 34% | 0% | 46% | 0% | 0% |
| 3,500-6,500 | 0% | 10% | 33% | 0% | 57% | 0% | 0% |
| 6,500-10,000 | 0% | 0% | 31% | 0% | 69% | 0% | 0% |
| 10,000-15,000 | 0% | 4% | 20% | 0% | 76% | 0% | 0% |
| >15,000 | 0% | 1% | 23% | 0% | 76% | 0% | 0% |

Table F.3: Vehicle type probability per shipment size cluster commodity 3

| | vehicle type probability | | | | | | |
|---|---|---|---|---|---|---|---|
| shipment size [kg] | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| <500 | 0% | 18% | 2% | 0% | 78% | 1% | 0% |
| 500-1,500 | 0% | 9% | 6% | 1% | 84% | 0% | 0% |
| 1,500-3,500 | 0% | 14% | 6% | 1% | 77% | 1% | 1% |
| 3,500-6,500 | 0% | 9% | 11% | 0% | 68% | 3% | 8% |
| 6,500-10,000 | 0% | 8% | 7% | 1% | 85% | 0% | 0% |
| 10,000-15,000 | 0% | 14% | 11% | 2% | 69% | 1% | 2% |
| >15,000 | 0% | 11% | 9% | 1% | 76% | 1% | 1% |

Table F.4: Vehicle type probability per shipment size cluster commodity 4

| | vehicle type probability | | | | | | |
|---|---|---|---|---|---|---|---|
| shipment size [kg] | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| <500 | 100% | 0% | 0% | 0% | 0% | 0% | 0% |
| 500-1,500 | 100% | 0% | 0% | 0% | 0% | 0% | 0% |
| 1,500-3,500 | 100% | 0% | 0% | 0% | 0% | 0% | 0% |
| 3,500-6,500 | 0% | 32% | 18% | 0% | 50% | 0% | 0% |
| 6,500-10,000 | 0% | 11% | 71% | 0% | 18% | 0% | 0% |
| 10,000-15,000 | 0% | 10% | 35% | 0% | 55% | 0% | 0% |
| >15,000 | 0% | 25% | 24% | 0% | 51% | 0% | 0% |

Table F.5: Vehicle type probability per shipment size cluster commodity 5

| | vehicle type probability | | | | | | |
|---|---|---|---|---|---|---|---|
| shipment size [kg] | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| <500 | 0% | 0% | 0% | 0% | 100% | 0% | 0% |
| 500-1,500 | 0% | 83% | 0% | 0% | 17% | 0% | 0% |
| 1,500-3,500 | 0% | 29% | 5% | 0% | 67% | 0% | 0% |
| 3,500-6,500 | 0% | 6% | 59% | 0% | 35% | 0% | 0% |
| 6,500-10,000 | 0% | 22% | 4% | 0% | 73% | 0% | 0% |
| 10,000-15,000 | 0% | 5% | 13% | 0% | 82% | 0% | 0% |
| >15,000 | 0% | 0% | 3% | 0% | 97% | 0% | 0% |

Table F.6: Vehicle type probability per shipment size cluster commodity 6

| | vehicle type probability | | | | | | |
|---|---|---|---|---|---|---|---|
| shipment size [kg] | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| <500 | 0% | 63% | 13% | 0% | 25% | 0% | 0% |
| 500-1,500 | 0% | 33% | 44% | 0% | 22% | 0% | 0% |
| 1,500-3,500 | 0% | 11% | 47% | 0% | 42% | 0% | 0% |
| 3,500-6,500 | 0% | 16% | 54% | 0% | 30% | 0% | 0% |
| 6,500-10,000 | 0% | 6% | 61% | 0% | 33% | 0% | 0% |
| 10,000-15,000 | 0% | 24% | 24% | 0% | 53% | 0% | 0% |
| >15,000 | 0% | 6% | 1% | 0% | 93% | 0% | 0% |

Table F.7: Vehicle type probability per shipment size cluster commodity 7

| | vehicle type probability | | | | | | |
|---|---|---|---|---|---|---|---|
| shipment size [kg] | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| <500 | 0% | 33% | 0% | 0% | 67% | 0% | 0% |
| 500-1,500 | 0% | 8% | 8% | 0% | 84% | 0% | 0% |
| 1,500-3,500 | 0% | 13% | 3% | 0% | 84% | 0% | 0% |
| 3,500-6,500 | 0% | 22% | 2% | 0% | 76% | 0% | 0% |
| 6,500-10,000 | 0% | 1% | 1% | 0% | 98% | 0% | 0% |
| 10,000-15,000 | 0% | 11% | 2% | 0% | 87% | 0% | 0% |
| >15,000 | 0% | 25% | 4% | 0% | 71% | 0% | 0% |

Table F.8: Vehicle type probability per shipment size cluster commodity 8

| | vehicle type probability | | | | | | |
|---|---|---|---|---|---|---|---|
| shipment size [kg] | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| <500 | 0% | 100% | 0% | 0% | 0% | 0% | 0% |
| 500-1,500 | 0% | 44% | 53% | 0% | 2% | 0% | 0% |
| 1,500-3,500 | 0% | 51% | 46% | 0% | 3% | 0% | 0% |
| 3,500-6,500 | 0% | 47% | 46% | 0% | 7% | 0% | 0% |
| 6,500-10,000 | 0% | 55% | 31% | 0% | 14% | 0% | 0% |
| 10,000-15,000 | 0% | 52% | 35% | 0% | 13% | 0% | 0% |
| >15,000 | 0% | 74% | 15% | 0% | 11% | 0% | 0% |

Table F.9: Vehicle type probability per shipment size cluster commodity 9

| | vehicle type probability | | | | | | |
|---|---|---|---|---|---|---|---|
| shipment size [kg] | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| <500 | 0% | 12% | 23% | 14% | 51% | 0% | 0% |
| 500-1,500 | 0% | 0% | 14% | 0% | 86% | 0% | 0% |
| 1,500-3,500 | 0% | 4% | 12% | 0% | 83% | 0% | 0% |
| 3,500-6,500 | 0% | 4% | 10% | 0% | 86% | 0% | 0% |
| 6,500-10,000 | 0% | 18% | 8% | 0% | 73% | 0% | 0% |
| 10,000-15,000 | 0% | 2% | 4% | 2% | 92% | 0% | 0% |
| >15,000 | 0% | 9% | 14% | 0% | 77% | 0% | 0% |

Table F.10: Vehicle type probability per shipment size cluster commodity 10

| | vehicle type probability | | | | | | |
|---|---|---|---|---|---|---|---|
| shipment size [kg] | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| <500 | 100% | 0% | 0% | 0% | 0% | 0% | 0% |
| 500-1,500 | 100% | 0% | 0% | 0% | 0% | 0% | 0% |
| 1,500-3,500 | 100% | 0% | 0% | 0% | 0% | 0% | 0% |
| 3,500-6,500 | 0% | 11% | 46% | 0% | 43% | 0% | 0% |
| 6,500-10,000 | 0% | 5% | 37% | 0% | 58% | 0% | 0% |
| 10,000-15,000 | 0% | 12% | 29% | 0% | 59% | 0% | 0% |
| >15,000 | 0% | 5% | 19% | 0% | 76% | 0% | 0% |

# G
# Calculation of emissions

This appendix explains the emissions classes that were used to calculate total emissions. Tables G.1 and G.2 show tank-to-wheel emissions for a larger set of vehicle types, based on the report by Otten et al. (2017). In the report, different density classes of cargo are defined. However, in the model of this study these densities have not been defined. Therefore, averages of the different density classes were used. Furthermore, the values of emissions classes for goods transport in cities were taken. The model vehicle references in the tables are as follows:

1. Van
2. Truck/lorry without trailer
3. Truck/lorry with trailer
4. Tractor without trailer
5. Tractor with trailer
6. ”Other” vehicle without trailer
7. ”Other” vehicle with trailer

Table G.1: Emissions table bulk and general cargo

| Vehicle reference (Otten et al., 2017) | Vehicle reference model | Emissions light bulk/ general cargo [g/tkm] co2 | so2 | pm10 | nox | Emissions medium bulk/ general cargo [g/tkm] co2 | so2 | pm10 | nox | Emissions heavy bulk/ general cargo [g/tkm] co2 | so2 | pm10 | nox |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Kleine bestelauto GVW <2 ton | 1 | 1537 | 0.010 | 0.895 | 6.6 | 1321 | 0.008 | 0.777 | 5.7 | | | | |
| Grote bestelauto GVW >2 ton | 1 | 1256 | 0.008 | 0.36 | 6.8 | 1079 | 0.007 | 0.322 | 5.9 | | | | |
| Vrachtauto <10 ton | 2 | 666 | 0.004 | 0.238 | 7.5 | 454 | 0.003 | 0.163 | 5.1 | | | | |
| Vrachtauto 10-20 ton | 2 | 457 | 0.003 | 0.102 | 4.5 | 306 | 0.002 | 0.068 | 3 | 189 | 0.001 | 0.036 | 1.6 |
| Vrachtauto >20 ton | 2 | 381 | 0.002 | 0.07 | 3.4 | 256 | 0.002 | 0.04 | 2.3 | 242 | 0.001 | 0.039 | 2.1 |
| Vrachtauto 10-20 ton + aanhanger | 3 | 237 | 0.001 | 0.041 | 1.9 | 162 | 0.001 | 0.034 | 1.3 | 153 | 0.001 | 0.033 | 1.2 |
| Vrachtauto >20 ton + aanhanger | 3 | 201 | 0.001 | 0.037 | 1.5 | 139 | 0.001 | 0.021 | 1 | 132 | 0.001 | 0.021 | 1 |
| Trekker-oplegger Licht | 4 | 242 | 0.001 | 0.027 | 2 | 242 | 0.001 | 0.027 | 2 | 233 | 0.001 | 0.027 | 1.9 |
| Trekker-oplegger Zwaar | 5 | 133 | 0.001 | 0.017 | 0.7 | 133 | 0.001 | 0.017 | 0.7 | 128 | 0.001 | 0.017 | 0.7 |
| Overig | 6 | 381 | 0.002 | 0.07 | 3.4 | 256 | 0.002 | 0.04 | 2.3 | 242 | 0.001 | 0.039 | 2.1 |
| Overig met aanhanger | 7 | 201 | 0.001 | 0.037 | 1.5 | 139 | 0.001 | 0.021 | 1 | 132 | 0.001 | 0.021 | 1 |

Table G.2: Emissions table container

| Vehicle reference (Otten et al., 2017) | Vehicle reference model | Emissions light container [g/tkm] co2 | so2 | pm10 | nox | Emissions medium container [g/tkm] co2 | so2 | pm10 | nox | Emissions heavy container [g/tkm] co2 | so2 | pm10 | nox |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Kleine bestelauto GVW <2 ton | 1 | | | | | | | | | | | | |
| Grote bestelauto GVW >2 ton | 1 | | | | | | | | | | | | |
| Vrachtauto <10 ton | 2 | | | | | | | | | | | | |
| Vrachtauto 10-20 ton | 2 | | | | | | | | | | | | |
| Vrachtauto >20 ton | 2 | 423 | 0.003 | 0.072 | 3.8 | 251 | 0.002 | 0.042 | 2.2 | 187 | 0.001 | 0.031 | 1.6 |
| Vrachtauto 10-20 ton + aanhanger | 3 | | | | | | | | | | | | |
| Vrachtauto >20 ton + aanhanger | 3 | 242 | 0.001 | 0.039 | 1.8 | 147 | 0.001 | 0.024 | 1.1 | 113 | 0.001 | 0.018 | 0.8 |
| Trekker-oplegger Licht | 4 | | | | | | | | | | | | |
| Trekker-oplegger Zwaar | 5 | 271 | 0.002 | 0.029 | 1.5 | 167 | 0.001 | 0.018 | 0.9 | 128 | 0.001 | 0.014 | 0.7 |
| Overig | 6 | 423 | 0.003 | 0.072 | 3.8 | 251 | 0.002 | 0.042 | 2.2 | 187 | 0.001 | 0.031 | 1.6 |
| Overig met aanhanger | 7 | 242 | 0.001 | 0.039 | 1.8 | 147 | 0.001 | 0.024 | 1.1 | 113 | 0.001 | 0.018 | 0.8 |

Tables G.3 and G.4 show the final $CO_2$, $SO_2$, $PM_{10}$ and $NO_x$ emissions per tonne-km for the different vehicle types in the model. In case of multiple emissions values of one vehicle type in tables G.1 and G.2, the average of the two is taken. For most commodities, the emissions table for bulk is used. For commodities 6 and 9 however, the commodity table for containers is used. The vans category is missing in this table, as containers are not transported by vans.

Table G.3: Emissions for bulk and general cargo transport per vehicle type

| Vehicle type | co2 [g/tkm] | so2[g/tkm] | pm10[g/tkm] | nox[g/tkm] |
|---|---|---|---|---|
| 1 | 1298.25 | 0.00825 | 0.5885 | 6.25 |
| 2 | 390.1111 | 0.002389 | 0.106278 | 3.977778 |
| 3 | 170.6667 | 0.001 | 0.031167 | 1.316667 |
| 4 | 239 | 0.001 | 0.027 | 1.966667 |
| 5 | 131.3333 | 0.001 | 0.017 | 0.7 |
| 6 | 293 | 0.001667 | 0.049667 | 2.6 |
| 7 | 157.3333 | 0.001 | 0.026333 | 1.166667 |

Table G.4: Emissions for container transport per vehicle type

| Vehicle type | co2 [g/tkm] | so2[g/tkm] | pm10[g/tkm] | nox[g/tkm] |
|---|---|---|---|---|
| 1 | NA | NA | NA | NA |
| 2 | 287 | 0.002 | 0.048333 | 2.533333 |
| 3 | 167 | 0.001 | 0.027 | 1.233333 |
| 4 | 189 | 0.001333 | 0.020333 | 1.033333 |
| 5 | 189 | 0.001333 | 0.020333 | 1.033333 |
| 6 | 287 | 0.002 | 0.048333 | 2.533333 |
| 7 | 167 | 0.001 | 0.027 | 1.233333 |

# H

# Draft scientific paper

# A modelling methodology to assess $CO_2$ mitigation measures for urban freight transport in Europe: case study with possibilities for transferability

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ABSTRACT

Freight transport is a significant cause of $CO_2$ emissions in the European Union. This creates the need to implement $CO_2$ mitigation measures for freight transport in European cities. Assessing these measures before implementation can give an indication of their effects. However, no spatially transferable modelling methodology exists that would facilitate quick ex-ante policy assessment for all European urban areas. This study explains the creation of a transferable modelling methodology for Europe, based on lessons learned from existing urban freight models and literature discussing transferability of models. The modelling methodology has been proven to work and provides plausible results. However, for accurate assessment of the effects on $CO_2$ emissions of some policy measures, further model improvements are needed.

## 1. Introduction

Climate change affects the entire world population, and is largely caused by the emission of $CO_2$. Transportation is a significant cause of these $CO_2$ emissions. When considering $CO_2$ emissions from transport in Europe, freight transport is essential, because compared to passenger transport, it emits significantly more $CO_2$ (Coulombel, Dablanc, Gardrat and Koning, 2018). This is due to the fact that in Europe most inland freight transport is conducted by road (Jonkeren, Francke and Visser, 2019) and vans and heavy goods vehicles (HGVs) are the largest emitters in terms of $CO_2$ per tonne-km (McKinnon, 2007). This emphasises the need for models for freight transport to support assessment of decarbonisation measures: to be able to select the right policy measures for decarbonisation, assessing the effectiveness of the measures before implementation is essential (Comi, Delle Site, Filippi and Nuzzolo, 2012). The European Commission supports the creation of these types of models with the introduction of Horizon 2020: a research and innovation programme with which a sustainable future of Europe is promoted (European Commission, n.d.). Especially urban freight transport is a point of interest, since over 70 percent of the European population lives in urban areas. With the population in urban areas only expected to grow (Eurostat, 2016), impacts of freight transport on the sustainability of urban establishments are important to evaluate (Aditjandra, Galatioto, Bell and Zunder, 2016; Comi, Donnelly and Russo, 2014). While some case studies of urban freight transport models have been conducted, there is no spatially transferable model for urban freight transport in Europe. This is a clear gap that can be observed in literature.

This study is aimed at partly closing the scientific gap: there is no generally transferable model for urban freight transport in Europe. The research objective is to establish a modelling methodology that is transferable to all other urban areas in Europe. The transferability requirements are based on data availability for urban areas in Europe. The first step towards closing the knowledge gap is taken by creating an example model (proof of concept) for urban freight transport for the case of Groot-Rijnmond (the urban area around Rotterdam), which is suitable to assess effects of policy measures in different scenarios. This study contains a description of the modelling methodology, with a first proof of concept for Groot-Rijnmond. The emphasis of the estimated model is on freight generation; the further modelling steps are simplified to be able to calculate final outcomes in terms of $CO_2$ emissions within the given time frame for this study. Incremental improvement of the model will thus still be needed to improve the reliability of the results, and to be able to assess a larger set of mitigation measures.

The outline of the rest of this paper follows the order of the steps that have been taken in this study. First, the results of the literature review are discussed in section 2. These results give an even clearer view of the scientific gap with regards to urban freight models, and where this research fits in. Subsequently, the identified data sources that are suitable to use in a transferable European modelling methodology for urban freight are discussed in more detail in section 3. Based on the lessons learned from the literature review, and the identified data sources, a methodology has been established, which is discussed in section 4. This section also elaborates on the methods that are used for the different modelling steps. Then, the results of the first proof of concept are discussed in section 5. In this section, detailed model estimations are explained for the freight generation model and a calibration of the sensitivity parameters of the distribution model. Furthermore, the validity of the total outcomes of the model is discussed, followed by an example of the application of the model for some policy scenarios. Finally, section 6 gives the conclusions of this study, and discusses recommendations for the further incremental development path to improve the model.

## 2. Literature review

A literature review of existing models for urban logistics has been done, in which twenty-two models have been identified. These models have been critically reviewed on two main requirements: inclusion of policy measures and ease of spatial transferability. Ease of transferability is assessed based on the availability of the underlying data of the models. Table 1 shows the results of the literature review, including an identification of the models regarding the focus, the category (according to Comi et al. (2012)) and the modelling structure (according to González-Feliu, Cedillo-Campo and García-Alcaraz (2014)).

In the review of models in as is summarised in table 1, a lack of models that are both suitable for policy testing and that can be transferred to other areas can be observed. There are only two models that have accomplished this: Freturb by Routhier and Toilier (2007), and Hunt and Stefan (2007)'s model for Calgary, which has been transferred to Toronto by Ferguson, Maoh, Ryan, Kanaroglou and Rashidi (2012). However, in the latter case, Ferguson et al. (2012) state that the adaptation was not simple. The model had to be re-estimated, and the authors had some challenges with the re-estimation of location-specific model parameters. Moreover, the tour generation approach is fundamentally different from the approach of Hunt and Stefan (2007). In terms of transferability, the Freturb model is the most appropriate example that has been found, since it has already proven its worth in a large number of French cities. However, since the models need a detailed database of the establishments in the city, the question remains if this model can be used for all cities in Europe, since it is not clear if these cities all have easily accessible databases of their firms.

Concluding: no models have been found that are easily transferable, appropriate to assess policy measures, and that are solely based on easily accessible data. Moreover, policy assessment seems to be hardly existent in more recent models, with only three of the fifteen reviewed articles from the past ten years describing the assessed effects of policy measures. The other articles all seem to focus on modelling efforts rather than the societal impact of these models. One can see that there is a clear need for a generalised, aggregate model for urban logistics, which is based on publicly available data.

Table 1: Existing models for urban freight transport

| Reference | Urban area(s) | Focus | Category | Modelling structure | Underlying data | Policies tested? | Easy spatial transferability? |
|---|---|---|---|---|---|---|---|
| Visser and Maat (1996) | Delft (NL) | Environment | Vehicle | Combined | Establishment | N | N |
| Boerkamps and Van Binsbergen (1999) | Groningen (NL) | Environment | Commodity | Adapted four-step | Socio-economic, establishment | Y | N |
| Russo and Comi (2002) | Calabria (IT) | Policy | Commodity | Adapted four-step | Socio-economic, establishment | N | N |
| Friedrich, Haupt and Nökel (2003) | DE cities | Unclear | Vehicle | Classical four-step | Establishment | N | Y |
| Hosoya, Sano, Ieda, Kato and Fukuda (2003); Wisetjindawat and Sano (2003); Wisetjindawat, Sano, Matsumoto and Raothanachonkun (2007) | Tokyo (JP) | Emissions | Commodity | Adapted four-step | Establishment | Y | N |
| Yannis, Golias and Antoniou (2006) | Athens (GR) | Policy, Environment | Vehicle | Combined | Socio-economic | Y | N |
| Beagan, Fischer and Kuppam (2007) | Los Angeles (US) | Policy | Vehicle, commodity | Adapted four-step | Socio-economic, establishment | Y | N |
| Beagan et al. (2007); Donnelly, Wigan and Thompson (2010) | US cities | Policy | Commodity | Combined | Establishment | Y | Y |
| Hunt and Stefan (2007) | Calgary (CA) | Policy | Commodity | Combined | Socio-economic, establishment | Y | Y |
| Routhier and Toilier (2007), Toilier, Gardrat, Routhier and Bonnafous (2018) | FR cities | Policy | Delivery | Combined | Establishment | Y | Y |
| Kanaroglou and Buliung (2008) | Hamilton (CA) | Emissions | Vehicle | Combined | Socio-economic | N | Y |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Muñuzuri, Cortés, Onieva and Guadix (2009, 2010, 2011) | Seville (ES) | Policy | Delivery | Adapted four-step | Establishment | N | N |
| Russo and Comi (2010) | Calabria, Palermo (IT) | Policy | Delivery | Adapted four-step | Socio-economic, establishment | N | N |
| Urban, Beagan and Fischer (2012) | Chicago (US) | Policy | Commodity | Combined | Socio-economic | N | N |
| Ferguson et al. (2012) | Toronto (CA) | Policy | Commodity | Adapted four-step | Socio-economic, establishment | N | N |
| Lawson, Holguín-Veras, Sánchez-Díaz, Jaller, Campbell and Powers (2012) | New York (US) | Unclear | Vehicle | Classical four-step | Socio-economic, establishment | N | N |
| Nuzzolo, Crisalli and Comi (2012); Nuzzolo and Comi (2014); Nuzzolo, Comi, Ibeas and Moura (2016) | Rome (IT) | Policy | Mixed: vehicle, commodity, delivery | Adapted four-step | Establishment | N | Y |
| Gentile and Vigo (2013) | Emilia-Romagna (UT) | Policy | Delivery | Adapted four-step | Establishment | N | N |
| Alho and Silva (2014) | Lisbon (PT) | Unclear | Delivery | Combined | Socio-economic, establishment | N | N |
| Aditjandra et al. (2016) | Newcastle (UK) | Emissions | Vehicle | Combined | Establishment | Y | N |
| Anand, van Duin and Tavasszy (2014) | Rotterdam (NL) | Policy | Delivery | Combined | Establishment | Y | N |
| De Bok and Tavasszy (2018) | Rotterdam (NL) | Policy | Vehicle | Combined | Establishment | Y | N |

**Table 2**
Overview of data sources

| Organisation | Data source name | Data |
|---|---|---|
| CBS | XML microdata freight transport survey | Detailed freight patterns |
| ITF/OECD | Services in urban areas | Grid of 1 x 1km with number of commercial services |
| ITF/OECD | ITF regional freight model | Freight volumes entering and exiting the urban region |
| ITF/OECD | OECD population and GDP | Data on population and GDP |
| EU | CORINE land cover | Spatial land use characteristics |
| EU | European Road Freight Transport survey | Regional freight statistics |

## 3. Data

From the literature review, it can be concluded that the main requirement for establishing a transferable model is that the underlying data are available for all study areas to which the model should be transferred. Therefore, an identification of data sources for the EU has been done before establishing a modelling methodology. These data sources are shown in table 2. One outlier is the XML microdataset of the CBS (Statistics Netherlands): this is a dataset that is only available for the Netherlands, but that is needed to estimate model parameters for the first proof of concept of the modelling methodology.

All data sources by the ITF/OECD and the EU are available for all functional urban areas in the EU. The ITF/OECD services in urban areas data source contains data on the number and type of commercial services per zone. The data are based on area data by TomTom, and contain for example the number of supermarkets, the number of healthcare services, the number of shops etc. The second data source from the ITF/OECD is output from the regional freight model of the ITF, which can be used to calibrate the freight flows that are estimated with the urban model. The first publicly available data source by the EU that is used is the Corine Land Cover (CLC) by Copernicus (Copernicus, 2018). The CLC provides small-scale data on the land use of specific areas, which are publicly available as shapefiles on the website of Copernicus. The second European data source that is used is the European Road Freight Transport (ERFT) survey by Eurostat (Eurostat, n.d.). The survey offers anonymised freight transport statistics on the NUTS3 level, differentiated per commodity. This includes statistics on average shipment size, type of vehicle used and the load factor, and is useful to use as a replacement for the statistics from the CBS microdata for the Netherlands.

The identified data had to be converted to the same spatial structure, as to establish a uniform dataset that could be used for model estimation and application. All data have been transferred to a uniform spatial structure of 1 by 1 kilometre. This has lead to a dataset of 1892 zones inside the Groot-Rijnmond region, that have characteristics about the number of commercial services, the population and GDP, and the predominant type of land use (binary variable), and the production and consumption of freight in the zone.

## 4. Methodology

To be able to transfer the model to other urban areas in Europe, the underlying data of the demand model should come from datasets that are available for the entire European Union. Thus, only the data sources that have been mentioned in section 3 are used as input for the model. This is where this model differs from existing models for urban freight transport. Moreover, the modelling structure is commodity-based, as this the modelling structure that causes the fewest issues with regards to transferability of the freight generation model. Additionally, being commodity-based enables the estimated demand-model to be calibrated on the ITF regional freight model or Eurostat freight statistics on the NUTS3-level.

Figure 1 shows the logic of the model as a flowchart. The model has the structure of an adapted four-step model, with an additional step for calculating emissions but without assignment to the network. The transferability framework is indicated by a red line, which shows that all the data sources that are located within the line are available for all of Europe. The steps in the modelling structure are performed separately for each of the following commodity types:

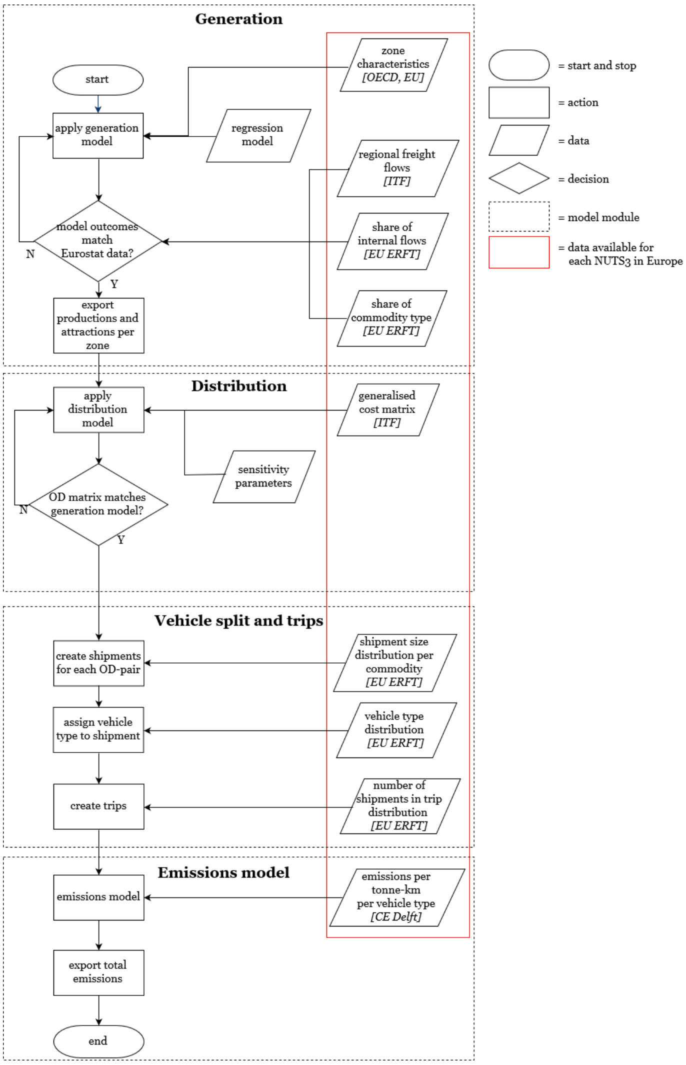


**Figure 1:** Technical flowchart of the modelling structure

1. Climate-controlled goods
2. Non-fresh food
3. Manufactured goods
4. Construction and building materials
5. Raw materials
6. Paper and wood
7. Chemicals
8. Waste
9. Transportation equipment
10. Parcels

The first step of the model is freight generation, in which production and consumption of freight in all zones are predicted with the use of spatial data. A generalised linear model (GLM) is used to estimate freight shares of the zones. These shares are then converted to total tonnes based on the total goods volumes that are produced and consumed in the whole urban area. The second modelling step, freight distribution, outputs an OD-matrix with goods volumes that are transported between zones. These volumes are calculated based on an accessibility function for OD-pair, which is based on the generalised transportation cost. The generalised transportation cost is based on distance and travel time, which are calculated with a shortest path algorithm that determines travel times based on an average speed of 80 percent of the maximum speed. The calibration of the distribution model is based on an uncongested network, since most freight is transported during off-peak hours.

The last two modelling steps, the creation of vehicle trips and the emissions model, use empirical statistics. These statistics are available in the Eurostat ERFT survey data. To calculate total emissions from OD-volumes, the following steps have to be taken. First, the volume between each OD-pair is converted into shipments based on a commodity-specific empirical shipment size distribution. Then, these shipments are allocated to vehicles according to a vehicle type distribution that depends on the weight of the shipment and the commodity type. Included vehicle types are vans, trucks (with or without trailer), tractors (with or without trailer and "other" vehicles. Subsequently, shipments are grouped into trips using an empirical trip composition distribution that indicates a commodity-specific probability for a certain number of shipments to be grouped in a trip. Based on the weight, the vehicle type and the distance of the trip, emissions can be calculated.

## 5. Results

Using the data as described in section 3 and the methodology as defined in section 4, a model for the urban area Groot-Rijnmond has been estimated and calibrated. This section elaborates on the results of the creation of this first proof of concept. The results show a first working model, but further adjustments have to be made to create a complete model that fully complies to the policy scenario testing requirements.

### 5.1. Freight generation results

Three types of GLMs have been tested on their performance to predict freight generation: an ordinary least squares (OLS) model, a Tobit model, and a zero-inflated negative binomial (ZINB) model. In a first iteration, these models were used to predict the consumption of climate-controlled goods (commodity 1) and the production of manufactured goods (commodity 3). The performance of the ZINB model was of such bad quality that it was decided to only assess the performance of OLS and Tobit models for the other commodities.

The OLS models and Tobit models showed similar performance. It has been decided to use the OLS models to estimate freight generation because their interpretation is the easiest. Table 3 shows the standardised results of the model. The $R^2$s of the generation models seem low at first sight, but it is important to view them in context of other freight models. Several examples have been examined to compare the results of the generation model. Ducret and Gonzalez-Feliu (2015) report $R^2$s for their generation model of deliveries to establishments based on the number of employees from as low as 0.0000187 to craftsmen, to 0.81 for deliveries to stores. The average $R^2$ for the eight establishment types equals 0.186. González-Feliu et al. (2014) also report a large range of values for an establishment-based freight trip production model, based on the number of employees and a class variable. Their adjusted $R^2$s take values from 0.009 to 0.81, averaging 0.254 over eleven establishment types. Hunt and Stefan (2007) estimate tour generation for five types of establishments, with a minimum and maximum $R^2$ of 0.087 and 0.590, the average being 0.263. Gonzalez-Feliu and Peris-Pla (2017) also estimate freight attraction based on number of employees, and report the most constantly well-performing $R^2$s of all literature regarding the topic: between 0.35 and 0.78 with an average of 0.539 for fifteen establishment types. The final article that has been found, by Sánchez-Díaz, Holguín-Veras and Wang (2016), reports adjusted $R^2$s for weekly deliveries to establishments between 0.20 and 0.94, averaging 0.72. Unfortunately, no reported results have been found for models that use spatial data as freight predictors. However, as the model in this study shows a comparable performance to those in related studies, and considering that this model uses limited data, it can be concluded that the results are promising.

**Table 3**
Betas and $R^2$ of the freight production model, *** = 0 significance level, ** = 0.001 significance level, * = 0.01 significance level, . = 0.05 significance level

| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Production | Logistics hub | 0.595*** | 0.462*** | 0.382*** | 0.343*** | | 0.119*** | 0.309*** | 0.092** | 0.606*** | 0.314*** |
| | Population | -0.080*** | 0.109** | | 0.287*** | 0.262*** | 0.153*** | 0.262*** | -0.144*** | -0.105*** | |
| | GDP | | -0.193*** | 0.125*** | -0.141*** | -0.129*** | -0.171*** | -0.234*** | 0.285*** | 0.174*** | 0.149*** |
| | LU: Discontinuous urban fabric | | | | | | | | -0.062. | 0.076*** | |
| | LU: Industrial or commercial units | -0.049. | | 0.100*** | 0.061* | 0.078*** | | 0.128*** | 0.062* | | |
| | LU: Port areas | -0.295*** | -0.074* | 0.345*** | | 0.226*** | 0.314*** | 0.108*** | 0.118*** | 0.097*** | -0.139*** |
| | LU: Dump sites | | | 0.036. | | | | | | | |
| | LU: Construction sites | | | | | | | | | 0.048* | |
| | LU: Green urban areas | | | | | | | | | | 0.135*** |
| | LU: Non-irrigated arable land | 0.071** | 0.061* | | | | | | | | |
| | LU: Complex cultivation patterns | 0.046. | | | | | | | | | |
| | LU: Land principally occupied by agriculture | | | | | | | | | | |
| | Market | 0.043. | | | | | | | | | |
| | School | | | | | | 0.053* | | | | |
| | Shop food | | 0.082** | | | | | | | | |
| | Shop other | | | | 0.098*** | | | | | | |
| | $R^2$ | 0.25 | 0.21 | 0.47 | 0.26 | 0.12 | 0.20 | 0.26 | 0.08 | 0.47 | 0.14 |
| Consumption | Logistics hub | 0.595*** | 0.462*** | 0.382*** | 0.343*** | | 0.119*** | 0.309*** | 0.092** | 0.606*** | 0.314*** |
| | Population | -0.080*** | 0.109** | | 0.287*** | 0.262*** | 0.153*** | 0.262*** | -0.144*** | -0.105*** | |
| | GDP | | -0.193*** | 0.125*** | -0.141*** | -0.129*** | -0.171*** | -0.234*** | 0.285*** | 0.174*** | 0.149*** |
| | LU: Discontinuous urban fabric | | | | | | | | -0.062. | 0.076*** | |
| | LU: Industrial or commercial units | -0.049. | | 0.100*** | 0.061* | 0.078*** | | 0.128*** | 0.062* | | |
| | LU: Port areas | -0.295*** | -0.074* | 0.345*** | | 0.226*** | 0.314*** | 0.108*** | 0.118*** | 0.097*** | -0.139*** |
| | LU: Dump sites | | | 0.036. | | | | | | | |
| | LU: Construction sites | | | | | | | | | 0.048* | |
| | LU: Green urban areas | | | | | | | | | | 0.135*** |
| | LU: Non-irrigated arable land | 0.071** | 0.061* | | | | | | | | |
| | LU: Complex cultivation patterns | 0.046. | | | | | | | | | |
| | LU: Land principally occupied by agriculture | | | | | | | | | | |
| | Market | 0.043. | | | | | | | | | |
| | School | | | | | | 0.053* | | | | |
| | Shop food | | 0.082** | | | | | | | | |
| | Shop other | | | | 0.098*** | | | | | | |
| | $R^2$ | 0.25 | 0.21 | 0.47 | 0.26 | 0.12 | 0.20 | 0.26 | 0.08 | 0.47 | 0.14 |

**Table 4**
Sensitivity parameters of the distribution model

| Commodity | Av. distance per tonne | $\beta$ |
|---|---|---|
| 1. Climate-controlled goods | 2.37 | -0.41 |
| 2. Non-fresh food | 1.30 | -0.64 |
| 3. Manufactured goods | 1.51 | -0.60 |
| 4. Construction and building materials | 1.50 | -0.64 |
| 5. Raw materials | 1.47 | -0.60 |
| 6. Paper and wood | 0.60 | -0.79 |
| 7. Chemicals | 1.30 | -0.62 |
| 8. Waste | 2.59 | -0.61 |
| 9. Transportation equipment | 2.00 | -0.49 |
| 10. Parcels | 1.56 | -0.57 |

## 5.2. Freight distribution results

With the use of travel time and distance OD-matrices, the sensitivity parameters of the cost function that is used to calculate generalised cost have been calibrated. Unfortunately, it was not possible to use the exact OD-flows as input for the calibration of the model. This was caused by the fact that the spatial scale that is used to describe shipments in the CBS microdata is very different from the scale of this model. To overcome this, an aggregate approach has been used, based on total tonne-kilometres. The average distance per tonne for each commodity can be seen in table 4. Using these values, total tonne-kilometres have been calculated for freight transport within the Groot-Rijnmond region. Based on an iterative calibration minimises the difference between the estimated tonne-kilometres and the empirical tonne-kilometres, the sensitivity parameters as shown in table 4 have been derived. These parameters can be used to calculate the volume of goods that is transported between two zones:

$$V_{ij} = p_i * P_i * q_j * C_j * f(c_{ij})$$

In this equation, $V_{ij}$ denotes the transported freight from zone $i$ to zone $j$, while $P_i$ and $C_j$ are the reported production and consumption of freight in the corresponding zones, multiplied by zone-specific multiplication factors $p_i$ and $q_i$. These are multiplied by function $f$ that determines the accessibility of the destination zone based on the travel cost between zones $c_{ij}$. In this function, $\beta$ is a sensitivity parameter, while $c_{ij}$ is based on the generalised transportation cost between zones:

$$f(c_{ij}) = e^{-\beta c_{ij}}$$

Table 4 shows that most commodities have sensitivity parameters that fluctuate between -0.55 and -0.65. Two clear outliers can be observed: commodity 1 and commodity 6. Commodity 1 is not as sensitive to higher transportation cost as the other commodities, which intuitively seems right as the goods are climate-controlled and can, therefore, be kept fresh for a longer time. As for commodity 6, paper and wood, it is not as clear why these goods are more sensitive to transportation cost, but it can be observed that the average distance per tonne is also very low. There is a third commodity that does not fall within the -0.55 to -0.65 range, although not as far as the other two: transportation equipment. There is no clear explanation as to why this commodity is less sensitive to transportation cost.

## 5.3. Total outcomes of the model

Table 5 shows the final results of the model in terms of the main variables. Internal statistics refer to trips with their origin and destination inside the Groot-Rijnmond region, while external statistics refer to trips that have their origin or their destination in the Groot-Rijnmond region, but not both. A positive remark is that the outcomes of the model are quite stable, even though some probabilistic functions were used to draw numbers from empirical distributions. Over five model runs, the standard deviation of the main model outcomes is less than one percent of the mean for all main variables.

No regional statistics were found to compare these values with. Therefore, the outcomes (total values, so internal as well as external trips) have been compared to total Dutch transport statistics. The last column of table 5 shows the percentage to which the Groot-Rijnmond region contributes to the total numbers of the Netherlands. Although Groot-Rijnmond is only one of forty NUTS3 regions in the Netherlands, it makes sense that this region contributes to a

**Table 5**
Summary of model outcomes

| | Model outcome | Total in NL | Percentage of GR |
|---|---|---|---|
| Weight [Mtonne] | 110.11 | 535.52 | 20.6% |
| Trips [x mln] | 7.21 | 39.26 | 23.9% |
| Tonne-km internal [x mln] | 38.42 | 59,226 | 8.6% |
| Tonne-km external [x mln] | 5,080.72 | | |
| Vehicle-km internal [x mln] | 28.65 | 4,415 | 6.1% |
| Vehicle-km external [x mln] | 240.68 | | |
| $CO_2$ internal [ktonne] | 4.45 | 8,728 | 5.9% |
| $CO_2$ external [ktonne] | 511.30 | | |
| $NO_x$ internal [ktonne] | 0.03 | 42.82 | 8.7% |
| $NO_x$ external [ktonne] | 3.68 | | |
| $PM_{10}$ internal [tonne] | 0.82 | 930 | 10.6% |
| $PM_{10}$ external [tonne] | 97.94 | | |
| $SO_2$ internal [tonne] | 0.03 | 60 | 5.8% |
| $SO_2$ external [tonne] | 3.47 | | |

relatively sizeable share of emissions. Around 20 percent of the volume of goods that are transported in the Netherlands has Groot-Rijnmond as origin or destination, which is plausible because this is where the Port of Rotterdam is located.

### 5.4. Application of the model

Seven policy scenarios have been assessed with the model, based on different implementations of zero-emissions vehicles and a low emission zone based on pricing that is geographically the same as the current environmental zone in Rotterdam. The implementations can be defined as follows:

1. Zero emissions vehicles
   (a) Electrify all vans
   (b) Electrify all trips with a load <1.5 tonnes
   (c) Electrify all trips with a load <3.5 tonnes
2. Low emission zone with pricing: 10 euros for passing entry and exit points of the low emission zone, no differentiation made between vehicle types or time of day

The experimental plan for the policy scenarios and the $CO_2$ effects of the scenarios are shown in table 6. The first three scenarios compare the outcomes of different implementations of zero-emissions vehicles, and show a decline in $CO_2$ emissions. However, the results indicate limited change between only electrifying vans, or electrifying all trips with a load smaller than 3.5 tonnes.

The implementation of a low emission zone based on pricing does not cause a significant change compared to the base scenario due to the current mechanics of the model. Beforehand, it was expected that pricing would lead to longer distances being driven and thus higher $CO_2$ emissions, because trips would go around the low emission zone. However, the larger generalised costs between some zones also change the outcomes of the distribution model: more volume will be transported between zones that are closer to each other. Thus, the trip lengths will remain approximately the same. In future updates of the model, this mechanic should be changed, and a later implementation of pricing measures, e.g. in the vehicle choice step, should be considered.

## 6. Conclusion

In this study, a modelling methodology has been created that can be transferred to all urban areas in Europe, which is something that has not been established on such a large scale before. It is an adjusted four-step model (without network assignment) that is commodity-based. It uses input data that is available for all urban areas in Europe. The only location-specific inputs are parameters of the GLM for freight generation and sensitivity parameters that are used for freight distribution. These parameters possibly have to be re-estimated for different regions or countries.

The modelling methodology that has been established in this research is innovative because it uses only input data that is available for all European urban areas, and because of its uniform spatial structure. This way, a first step towards a useful tool to give guidance in the effectiveness of certain measures for European urban areas is provided.

**Table 6**
Policy scenarios summary

| | Zero-emissions vehicles | | | Pricing | $CO_2$ change |
|---|---|---|---|---|---|
| | Electrify vans | Electrify trips <1.5t | Electrify trips <3.5t | | |
| Base scenario | 0 | 0 | 0 | 0 | |
| Scenario 1 | 1 | 0 | 0 | 0 | -3.86% |
| Scenario 2 | 0 | 1 | 0 | 0 | 0.12% |
| Scenario 3 | 0 | 0 | 1 | 0 | -3.77% |
| Scenario 4 | 0 | 0 | 0 | 1 | -0.26% |
| Scenario 5 | 1 | 0 | 0 | 1 | -3.58% |
| Scenario 6 | 0 | 1 | 0 | 1 | -0.42% |
| Scenario 7 | 0 | 0 | 1 | 1 | -4.06% |

The modelling methodology has been used in a case study for the Groot-Rijnmond urban area, and proves to generate stable and plausible output related to emissions and general transport statistics (tonne-kilometres, vehicle-kilometres, number of trips). However, the model is not finished yet. The freight generation model is currently performing sufficiently well, but the subsequent modelling steps need more attention to improve their performance. This is essential, since the current model is not good enough to provide reliable assessment of policy scenarios. Moreover, validation is needed to prove the model's suitability to be applied to other urban areas. An incremental process is needed for further model development, for which several recommendations can be done.

First, the distribution modelling step should be improved by adding parameters for GDP, population, and logistics hubs in the destination zone, and possibly also by setting a constraint that limits the number of OD-pairs with a very small flow. A more accurate distribution model could be established by basing the estimation on actual OD-flows instead of total tonne-kilometres. The OD-flows in the microdata are based on zip codes and thus have incomparable zone sizes, so a conversion factor would have to be established.

Another vital improvement to the model is to include a better vehicle choice model. Vehicle choice is currently based on a commodity-specific empirical distribution based on shipment size clusters. However, this makes vehicle choice insensitive to changes in transportation cost. Vehicle choice could be based on a deterrence function or a logit model that has to be estimated. This is essential to be able to assess policy scenarios related to location restrictions, e.g. a zone toll for larger vehicles.

Additionally, the model should be validated on another urban area. Using current model but with Eurostat input data, another case study can be done. This can again be done for another Dutch city, making use of the CBS microdata. Related to this: one flaw in this study is that the choice of the case study was perhaps not the most suitable. Rotterdam is a typical city because of the large volumes that are transported through the port. There is a lot of interregional transport, so in this region there is probably not enough emphasis on typical city logistics trips. It is recommended to perform a case study for another urban area that does not have such a large port.

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