Intermodal Freight Transport on the Right Track?

Environmental and economic performances and their trade-off

Nam Seok Kim

Delft University of Technology

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Intermodal Freight Transport on the Right Track?
Environmental and economic performances and their trade-off

Proefschrift

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Nam Seok KIM

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Prof. dr. G.P. van Wee

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Prof. dr. G.P. van Wee	Technische Universiteit Delft, Promotor
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TRAIL Research School
PO Box 5017
2600 GA Delft
The Netherlands
T: +31 (0) 15 278 6046
F: +31 (0) 15 278 4333
E: info@rsTRAIL.nl

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Contents

Preface

This dissertation aims to evaluate environmental and economic performances of an intermodal freight transport system and to estimate the trade-off between CO_2 emissions, which is represented as an indicator of environmental performance, and freight costs, which indicate the economic performance of the intermodal freight system. The truck-only system is always regarded as the counterpart of the intermodal freight system in this dissertation.

To examine the environmental performance of the intermodal freight system, CO_2 emissions generated from all the processes in the intermodal chain, such as pre- and post-haulage, long-distance haulage, and transshipment, are estimated considering different sources that generate electricity and transmission loss of electricity (Chapters 3 and 4). To examine the economic performance of the system, two approaches are considered: (1) finding the intermodal break-even distance for which the intermodal system is more competitive than the truck-only system (Chapter 5); (2) examining the economies of scale in the intermodal network and finding the route/system choice that minimizes the total freight transportation costs (Chapter 6). Finally, this dissertation attempts to find the trade-off between CO_2 emissions (representing the environmental performance) and freight transportation cost (representing the economic performance) (Chapter 7).

Except Chapter 6, all the chapters were written in the Department of Transport and Infrastructure, OTB Research Institute for Housing, Urban and Mobility Studies at Delft University of Technology between 2006 and 2010. Chapter 6 is the result of a visiting scholar program at the Center for Transportation Studies at the University of Virginia for about 5 months in 2009. On the one hand, I wrote this dissertation as a member of the Netherlands TRAIL Research School for Transport, Infrastructure and Logistics. On the other hand, I have been a PhD student advised by Prof. Dr. Bert Van Wee, the Dean of Transport and Logistics, Faculty of Technology, Policy and Management, at Delft University of Technology.

Although the majority of this dissertation can be regarded as the outcome of my 4 years studying at TU-Delft in the Netherlands, I believe this dissertation can be considered the comprehensive outcome of the 7 years I spent studying abroad, including my 3 years at the

University of Maryland in the United States. While I pursued these two scholarly degrees, a 27-year-old *boy* became a 34-year-old *man*.

I believed that sacrificing "some period" of one's life for a worthwhile goal could be meaningful in the future, even though a better future can never be easily defined. Thus, I had thought that the period during which I concentrated on this PhD dissertation would be a sort of sacrifice for my future until I realized that 7 years is not that short of a time to be sacrificed for such an uncertain target. This thought was a turning point. What I realized is that pursuing advanced degrees is not a target for a better life in the future but just a part of one's life in itself. As "tomorrow" quickly becomes today, the "future" must be a piece of my current life; I shouldn't focus on the things that could be sacrificed for the upcoming future. Thus, since I realized this, I have not thought that I sacrificed my young life for a better future anymore. I have rather simply enjoyed this bloody research job.

The main contributor to this dissertation is undoubtedly my promoter, Prof. Dr. Bert Van Wee. This dissertation consists of two published, one accepted, and two submitted journal articles to which he substantially contributed. He is an open-minded scholar who respects his PhD students and makes every effort to understand and reflect the students' initial ideas, methodologies, and philosophies, which are often very naïve. Thanks to his open-heartedness, I have had excellent opportunities to learn how to mature a premature idea/philosophy in academic articles. Needless to say, the journal article would not be published without his effort.

Prof. Dr. Milan Janic, who advised me as a daily supervisor, is also one of the main contributors to the conception and execution of this dissertation. If I had to choose one or two things that I have learned from him in particular, they would be "how to become a good researcher" and "the attitude of a good researcher". I would like to acknowledge that his previous works on the relationship between transport and environment inspired me to write and eventually publish Chapter 8. These innumerable formal and informal discussions are present in this dissertation.

I cannot fail to mention associate Prof. Dr. Byung-Kyu (Brian) Park who temporarily advised me on Chapter 6 while I stay at the University of Virginia in the United State for 5 months in 2009. From him, I gained academic knowledge/technique, specifically genetic algorithm and its application to logistics, as well as social skills: "how to harmonize work with family life". In other words, he taught me how to obtain "Pareto optimal between academic life and social/family life". During my short time in U.S., I met Dr. Joyoung Lee who supported me academically as well as socially. Needless to say, meeting him was a stroke of luck.

Next, my gratitude must go to my colleagues of V&I (Department of Transport and Infrastructure). Dr. Bart Wiegmans, the coordinator of the V&I section, was always willing to discuss several issues, such as my research ambitions/concerns, as well as other miscellaneous issues even though he was very busy. The relationship between Dr. Rob Konings and myself could be described as "crocodile and crocodile bird". He needed my assistance when he had some trouble using some weird (advanced) techniques in Microsoft Word, while I needed him whenever I received seemingly important letters written in Dutch. Since he mentioned me as a *personal ICT assistant* in his dissertation, I would like to refer to him here as a *personal Dutch assistant*. Dr. Dimitris Potoglou, Dr. Koichi Sintani, and Ms. Mo Zhang shared an office with me for 18, 6, and 18 months respectively. I was very lucky to have these nice,

silent, knowledgeable and decent office-mates during my PhD studies. I cannot fail to acknowledge Dr. Jaap Vleugel, who translated “Summary and Conclusion” into “Samenvatting en conclusies”. I sincerely appreciate his time and effort in doing this. In addition, two professors who were supposed to be the committee members, Prof. René B.M. de Koster at Erasmus University and Prof. Cathy Macharis at the Free University of Brussels, gave valuable comments that obviously make improve the quality of this dissertation.

Dr. Hugo Ledux, Ms. Janneke Toussaint, Dr. Yusak Susilo, Ms. Eva Heinen, Dr. Richard Ronald, and Mr. Kyung Ho Choe were my OTB colleagues in different sections. I would like to acknowledge these open-minded international friends since I never felt lonely at OTB thanks to them. I also would like to acknowledge my lovely Korean friends, Dr. Ki Taek Lim, Mr. Sung Hun Oh, Mr. Han Sol Moon, Mr. Hyung Soo Kim, Mr. Byung Joon Kim, Mr. Hyung Joon Noh, Mr. Hyun Bo Shin and Mr. Chang Ho Yeo. If I could stack the number of Belgian beer bottles that we accumulated, it would be taller than the Delft New Church. We talked a lot about innumerable issues. The happy hours I spent with them certainly relieved the stress that came from my PhD studies.

I am very lucky because I haven’t suffered the stress of economic hardship during my 7 years in graduate school, including 3 years in U.S. The OTB research institute at TU-Delft, the National Center for Smart Growth at Univ. of Maryland, and the Korean Science and Engineering Foundation have provided 4 years of salary (120,000 Euro, 2006-2010) and tuition exemption, 2 years of salary (25,000 US dollars, 2003-2005) and tuition exemption, and a scholarship (60,000 US dollars, 2003-2005), respectively. It would have been impossible to finish my study if I had not received this financial support.

My two sisters, Ho Jung Kim and Eun Jung Kim, and their husbands, Jun Seok Lee and Eun Hong Joo, have also played an important role in driving me to finish my study. I also owe gratitude my three nieces, Hye In Lee (13 years old), Yeon Woo Joo (7 years old), and Ga In Lee (5 years old). They were born either just before I left for the U.S. or while I was abroad. I have hardly played the role of uncle, yet they have made me realize that there is another beautiful and important life outside of academia.

As mentioned above, I owe a lot to several persons. However, my largest debt, which I may never be able to repay in my biological lifetime, is to my parents. My mother, who passed away 7 years ago, was undoubtedly my greatest supporter. I still find myself with wet eyes whenever I think of her. No words can describe how much I love her. My father, who has lived a lonely life for these past 7 years, is the strongest presence in my life. His existence has been a driving force in helping me to finish my studies and the main reason that I go back to Korea.

Without your love, I would never have finished this dissertation. I sincerely appreciate all your love and support.

Nam Seok Kim
2010 summer in Delft, the Netherlands and Il-san, Korea

Chapter 1
Introduction

"By doubting we come at truth."

Marcus Tullius Cicero (106 BC-43 BC)

1.1 Background

1.1.1 Concerns on global warming and other externalities in transport field

When some symptoms of global warming were discovered in the 1970s, the United Nation began to identify the relationship between man-made carbon dioxide (CO_2) and global warming (IPCC, 2008). In 1992, at the Earth Summit, in Rio De Janeiro, several developed and developing countries signed an agreement to reduce anthropogenic CO_2 (IPCC, 2008). Later in the third Conference of the Parties of the United Nations Framework Convention on Climate Change (UNFCCC), at Kyoto, in 1997, the so-called Kyoto protocol was agreed upon. This protocol explicitly indicates that countries classified as Annex I countries (this was 36 developed countries in 1998, and had grown to 41 developed countries by 2004, including the EU as one country) are required to reduce greenhouse gas emissions to the level indicated in the UNFCCC and Kyoto protocol (UNFCCC, 2006, 2008, UN, 1998). The protocol includes a mandatory CO_2 emissions reduction for clusters of countries. Despite efforts, the European Environment Agency (EEA) shows that the European Union has not yet achieved the reduction target agreed in the Kyoto Protocol. More specifically, the total Greenhouse Gas Emissions equivalent in Europe, expressed in million tonnes (Mt) of CO_2, and the achieved reduction as of 2004 are as follows
(UNFCCC, 2008, EEA, 2006, EC/Eurostat, 2007):

- EU-15 : 4279.0 Mt (1990: base year) and 4227.0 Mt (2004), - 1.2 % (*Changes in emissions)*
- EU-25 : 5429.4 Mt (1990: base year) and 5258.2 Mt (2004) , - 3.2 % (*Changes in emissions)*
- EU-27 : 5796.0 Mt (1990: base year) and 5487.9 Mt (2004), - 5.3 % (*Changes in emissions)*

It is notable that the 8% target reduction rate of the Kyoto protocol has not been achieved in any of the groups. The rationale that the EU could count the mass of CO_2 in these groups is based on the Burden Share Agreement in Europe made in 1998 (EC, 1999). This agreement aims to consider various national circumstances such as energy sources, dependency on fossil fuel, and industry. As a result, the adjusted reduction targets for CO_2 emissions are assigned to European countries (EC, 2006a). Accordingly, European commissions, as well as each individual European country, have established strategies to reduce CO_2 emissions and have attempted to identify the most severe CO_2 contributors, according to the trend of CO_2 emissions by sectors. The European Union recognizes that of the greenhouse gas emissions it is the emission of CO_2 from transport that has increased at the fastest rate compared with any other sector over the last 15 years, as shown in Figure 1.1.

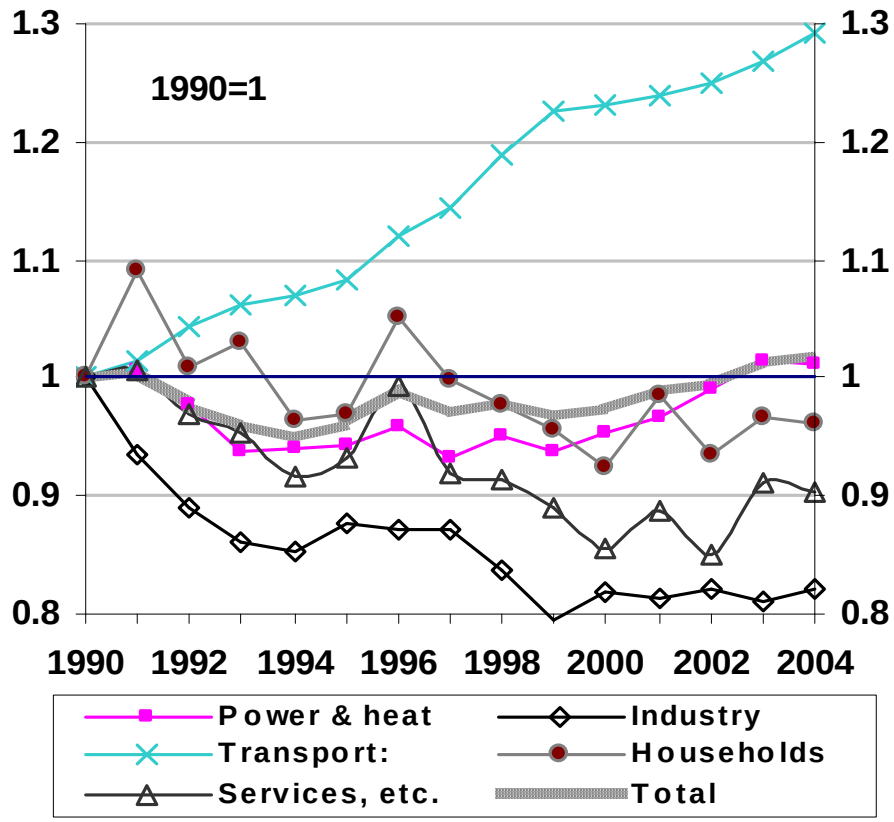

Figure 1.1 Trend of CO_2 emissions in Europe by sector, 1999-2004 (Source: Euro Stat (EC/Eurostat, 2007))

In addition to the CO_2 emissions, it is notable that concerns about other externalities are also growing these days. Most of them are directly related to the increasing share of road usage that increases (a) air pollutants such as SO_2, NO_x, CO, VOC, and PM_{10} and accordingly has an adverse impact on human health (b) traffic noise, (c) accidents, and (d) traffic congestion

and the accordingly adverse effects on the economy. Note, this dissertation only considers CO_2 emissions among these externalities.

1.1.2 Intermodal freight system as an alternative to the truck-only system

The European Union has been concerned about the increasing CO_2 emissions and other externalities from transport and is trying to mitigate it. Among the several mitigating strategies, encouraging non-road transport modes such as trains and waterborne vessels has been regarded as one of the most feasible action plans (EC, 2001b). In the freight transport sector, an intermodal freight transportation system has been considered as (a) satisfying the door-to-door delivery requirement, (b) being more environmentally friendly for long-distance haulage, and (c) being even more economically beneficial than a truck-only freight system. In addition, it was also expected (d) to reduce other externalities, such as traffic congestion, road accidents, noise, and adverse health impacts).

The European Conference of the Ministers of Transport defined the intermodal freight transport system as either

> "*Intermodal transport is the movement of goods (in one and the same loading unit or vehicle), which uses successfully several modes of transport without handling of the goods themselves in transhipment between the modes*" (ECMT, 1998),
>
> "*Combined transport is a transport in which the major part of the European journey is carried out by rail inland waterways or sea and in which any initial and/or final leg carried out by road are as short as possible* " (ECMT, 1997), or
>
> "*Multi-modal transport is a carriage of goods by at least two different transport modes*" (ECMT, 1998)

The definitions above are all slightly different from each other (Janic and Reggiani, 2001). The key point of the first definition is "without handling of the goods themselves". It means the loading units used in the intermodal system should be standard, such as a container and a swap body. The second definition emphasizes the role of the truck in the intermodal chain. Trucks must be used for as short a drayage as possible. In the third definition, the intermodal (multimodal) freight system is broadly defined without any other constraints. This dissertation does not choose one of them but respects all of them. In this dissertation, the first two definitions are combined: "*Intermodal transport is the movement of goods (in one and the same loading unit or vehicle), which successfully uses several modes of transport without the handling of the goods themselves in transhipment between the modes, and in which any initial and/or final leg carried out by road is as short as possible*"

Figure 1.2 illustrates the concept of the intermodal freight system comparing it with the truck-only system. In many cases the intermodal system is operated in a hub-and-spoke network. The disadvantage of such a hub-and-spoke network in general is that loading units need to be transshipped more than twice at terminals. The transshipment, which never happens in a truck-only system, is a time-consuming and expensive process. In addition, the unit cost (rate) short-distance collection/distribution by truck (drayage or pre- and post-haulage) in the intermodal chain is often more expensive then long-distance trucking. Moreover, the

intermodal system in general has a less-flexible schedule. Due to these disadvantages, shippers (or receivers) who are not seriously concerned about the CO_2 emissions mitigation do not actively use the intermodal system. The modal split of goods transport in billion tonne-kilometres for the EU-27 is 45.6% by road, 37.3% by sea (domestic and intra-EU-27 transport only), 10.5% by rail and 6.5% by inland waterways and pipelines (EC/Eurostat, 2007). Since non-road transport modes are a main part of the intermodal freight system, the relatively lower modal share of rail and inland waterway is a strong indicator of the low market share of intermodal transport.

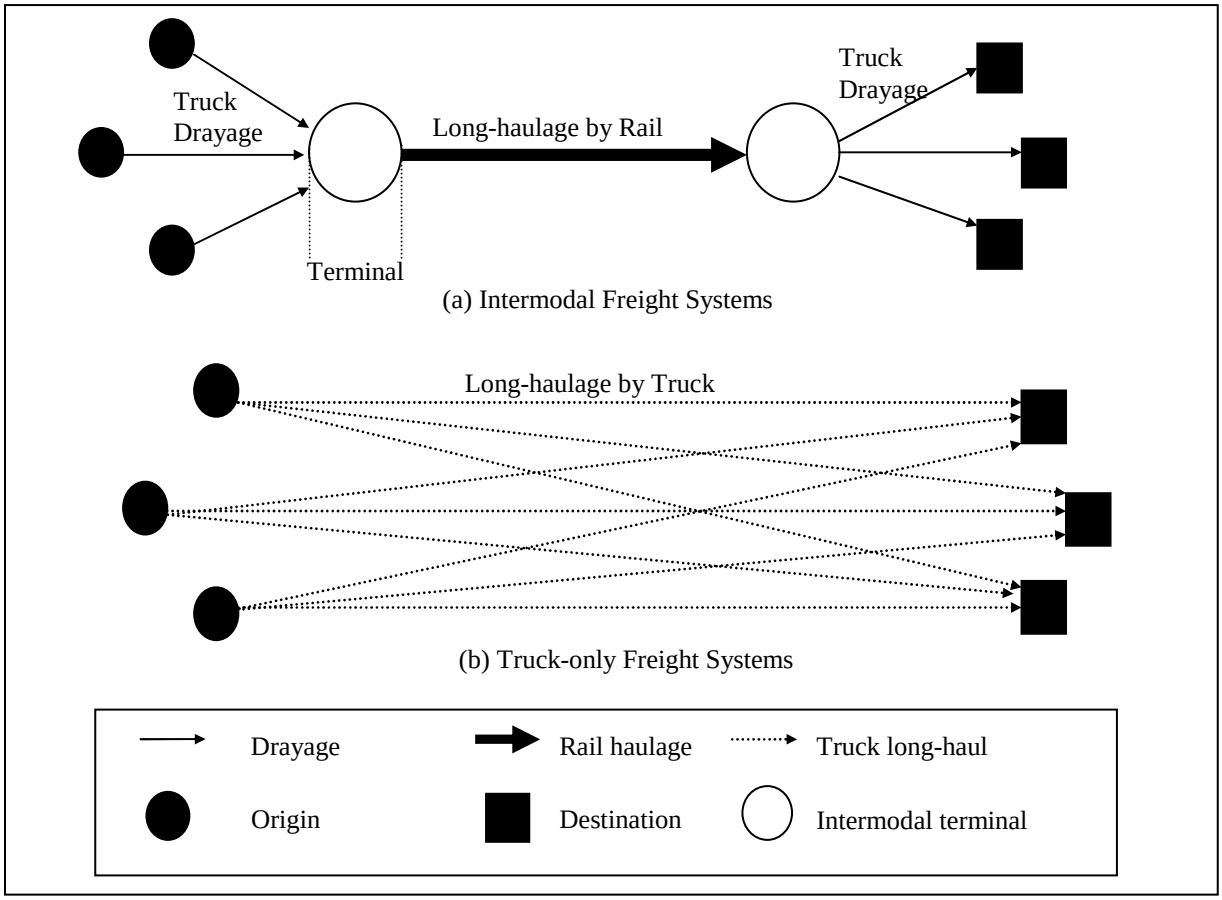

Figure 1.2 Conceptualization of intermodal freight transport systems and truck-only systems

The rationale that the EU has encouraged the intermodal freight system does not seem to be based on strong scientific evidence with respect to the benefits for the environment or the economy, nor on business analyses. It has been encouraged simply because the EU thinks it is needed, even though the EU also recognizes the disadvantages of such a system. It is notable that encouraging the intermodal system does not only happen in Europe but also in other countries such as the United States, where the Intermodal Surface Transportation Efficiency Act (ISTEA) was launched in 1991. The Federal Highway Administration (FHWA) in the U.S. described developing and implementing the intermodal system as an “ambitious goal” (1994).

1.2 Research overview, questions, and scope

1.2.1 Global research question

Despite the policy desire to increase the intermodal share, to date no clear evidence exists that shows its economic and environmental superiority compared to the truck-only system. The question of whether intermodal transport is superior depends on several factors and their interactions. The factors, for example, are drayage distances, drayage rates, type of locomotives, long-distance truck speed and so on. It is important to understand the conditions that make the intermodal systems competitive in order to be able to successfully encourage it. Therefore, the purpose of this dissertation is to answer the question: *Under what conditions is the intermodal system more competitive than the truck-only system in economic and environmental terms?* Furthermore, this dissertation is also an attempt to answer the questions: *What is the relationship between CO_2 emissions generated in the logistics chain and logistics cost? In order to decrease one unit of CO_2 emissions through shifting freight mode (system), how much is the shifting cost?*

Ideally this research would include all the factors affecting the intermodal system as well as the logistic decision-making process. However, this dissertation only includes two important aspects of the intermodal system: economic feasibility and environmental sustainability. The author is aware that there are several other aspects crucially influencing logistics decision-making in general. Temporal factors such as travel time and JIT (Just-In-Time), for example, are often key factors in freight mode choice. However, according to LOGIQ, an EU research project into the decision making-process in intermodal transport, “the cost is the most important criterion in the decision making process” (EC, 2000, EC, 2006b). Even if other factors were more important than the cost, evaluating the economic competitiveness is certainly applicable to the cost saving-oriented shipper (or receivers).

Instead, in order to achieve the global research question mentioned above, emphasis is put on the estimation of trade-offs between CO_2 emissions and specific (freight) costs. Although the unit of cost of CO_2 per ton is examined in this dissertation, in this case it expresses the cost to reduce one unit of CO_2 following the modal shift from truck-only system to intermodal system. In other words, the unit of cost of CO_2 per ton estimated in environmental economics, taking into account environmental damage and the adverse effects of climate change is not the key issue in this dissertation.

1.2.2 Specific research questions by chapters

Apart from Chapters 1, 2, and 8 this dissertation contains three parts; Part 1 includes the environmental aspects (mainly CO_2 emissions) of the intermodal system (Chapter 3 and 4); Part 2 includes the economic aspects of the intermodal system (Chapter 5 and 6); and Part 3 focuses on the relationship between the two aspects (Chapter 7). Two appendices are attached at the end of the dissertation in order to supplement the literature review (Appendix A) and to suggest a policy option to control CO_2 emission in the freight transport field (Appendix B). Note, Appendix A also provides a background to Chapter 6. Figure 1.3 gives an overview of this dissertation.

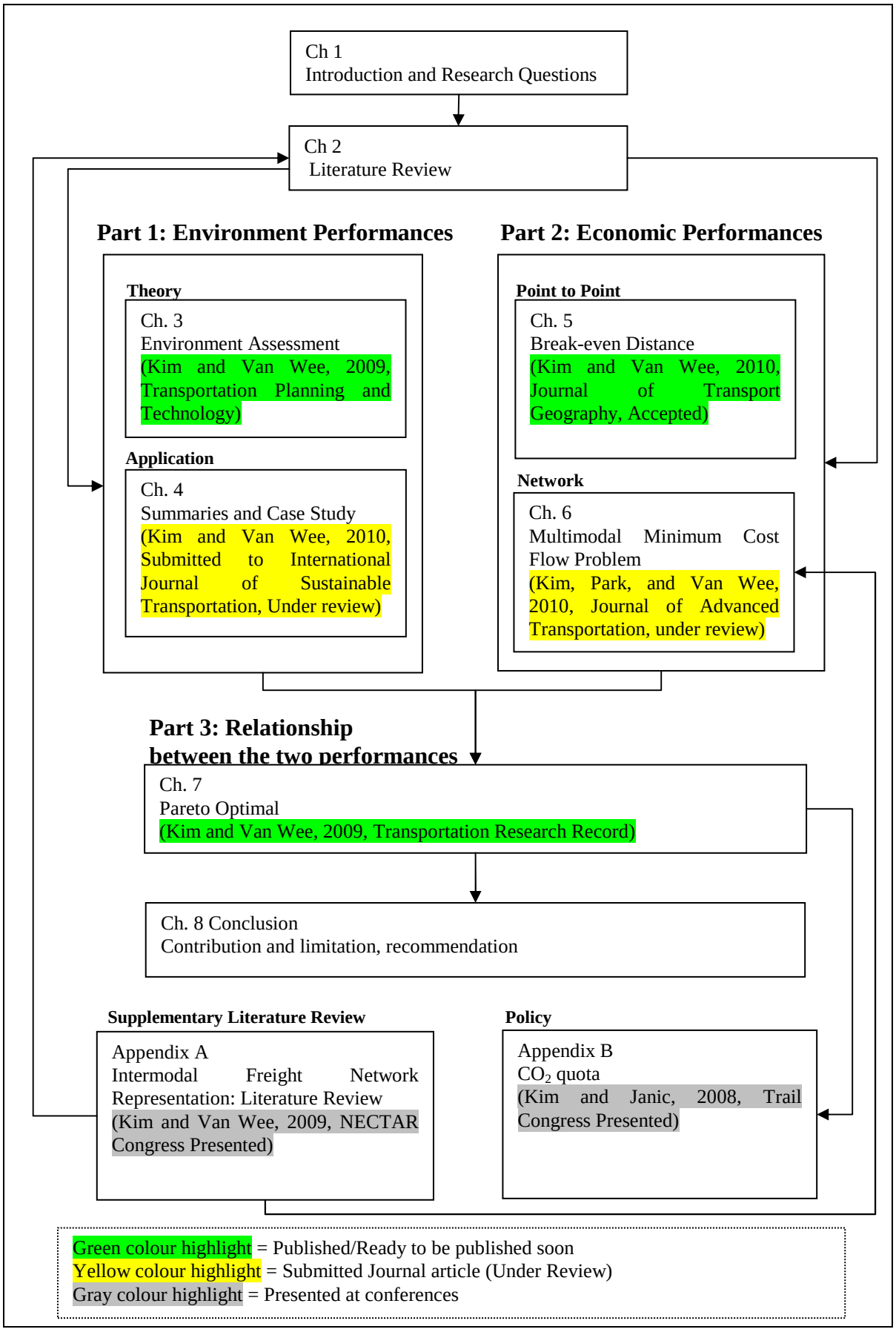

Figure 1.3 Overview of the dissertation

In Part 1, Chapter 3 is based on the paper "Assessment of CO_2 emissions for truck-only and rail-based intermodal freight systems in Europe" (Kim and Van Wee, 2009). This Chapter examines whether the intermodal freight system really does emit less CO_2 than its road-based counterparts. Chapter 4 provides a summary of some caveats and points for attention when CO_2 emissions from the intermodal system are assessed and compared with those from the truck-only system. In addition, three freight transport systems with *nine* scenarios including short sea shipping based intermodal systems are compared in Chapter 4 while two transport systems with *five* scenarios are compared in Chapter 3. Chapter 3 focuses on the framework, assessment method and data needs whereas Chapter 4 examines the case study.

In Part 2, economies of scale, which is a crucial advantage of the intermodal freight system, are highlighted. In general, three types of economies of scale are considered: Economies of scale in terms of quantity, distance, and vehicle size. The estimation of break-even distances between two markets with several shipper-receiver pairs and two intermodal terminals is discussed in Chapter 5 since the intermodal break-even distance can be a measurement for working out the economic feasibility of intermodal systems. In Chapter 6, the economic feasibility is examined at the network level (i.e. more than two markets). Throughout developing a minimum cost flow problem, the near-optimal route/system is chosen.

Part 3 shows the trade-off between economic feasibility and environmental sustainability in the logistics chain. Specifically, Chapter 7 develops a model estimating Pareto optimal solutions potentially indicating CO_2 price (Euro/ton) in logistics.

Although there are some additional findings in each Part and Chapter, the most important research question for each Chapter is summarized as follows :

Part 1: Is the intermodal freight system more environmentally sustainable than the truck-only system?

- Chapter 3
  Are diesel/electric powered rail-based intermodal freight systems really more sustainable than truck-only freight systems in terms of CO_2 emissions?
- Chapter 4
  If a waterborne based intermodal freight system (e.g. short sea shipping) is included in the comparison, which system is less CO_2 emitting in a case study (Rotterdam – Gdansk)?

Part 2: Is an intermodal freight system economically more feasible than the truck-only system?

- Chapter 5
  Under what circumstances do intermodal systems shorten the break-even distance (i.e. more competitive than the truck-only system)?
- Chapter 6
  What are the impacts of several types of economies of scale on intermodal freight route/system choice?

Part 3: What relationships can be found between minimizing the logistic total cost and minimizing the environmental impact in the intermodal network?

- Chapter 7

How can a freight mode/system be selected in order to satisfy both economical feasibility and environmental sustainability?

1.2.3 Theme, scope and position of this study

Transportation is a complex multi-disciplinary research area. European Commissions have funded numerous research projects. Some of them are closely related to the topics of this dissertation. The thematic research summaries published by TRKC (Transport Research Knowledge Centre) (EC, 2009) are very useful for identifying where this dissertation lies in the field of transport study in general. It classifies transport researches with the five dimensions consisting of the detailed subdivisions. Table 1.1 shows the selected TRKC's classifications (dimensions) and subdivisions, and the relations to this dissertation (EC, 2009). The entire themes are shown in Appendix 1A.

Table 1.1 Diverse transport research dimensions and the relation to this dissertation

Dim-ension	Theme	Sub-Theme	Relative Chapter in this Dissertation
Dim1	Passenger transport		Not included
	Freight transport	Logistics and supply chain management tools Intermodal transport	Ch 7 All
	Regional transport		All
Dim2	Rail transport		All
	Road transport		All
	Waterborne transport		Ch 4, Ch 7
	Intermodal freight transport	Intermodal Modelling and planning Market-oriented strategy and socio-economic scenarios	Ch 4, 5, 7 Ch 7
Dim3	Economic aspects	Costs in relation to pricing Socio-economic impacts of transport investment and policies	Ch 5, Ch 6, Ch 7
	Environmental aspects		Ch 3, Ch 4, Ch7
Dim4	Decision support tools		All
	Infrastructure provision including TEN-T		Ch 6
	Integration and policy development		Ch 5 Appendix B
	Regulation/deregulation		Appendix B
	Pricing and taxation		Ch 7 Appendix B

Source: EC (2009)

Dimension 1 can be subdivided into *sectors* (passenger and freight transport) and *geographical area* (urban, rural, regional, EU accession issue). Dimensions 2, 3, and 4 relate to the *transport mode*/*system*, *policy*, and *tools* respectively (EC, 2009). Therefore, as indicated in Table 1.1, this dissertation is about freight transport system at the regional to international level focusing on intermodal chains including rail and waterborne transport modes, examining the economic and environmental aspects and developing decision-making tools.

Those themes are prepared by the European Commission, one of the largest public sector parties. The important related question is: *Why is the public sector interested in freight transport, despite its private sector character?* The rationale for the public sector's involvement, as summarized in Morlok et al. (1997), is justified mainly due to two reasons; In many countries, railway and terminals/ports are owned and managed by governments, and freight transport generates externalities influencing society (i.e. air pollution, noise, accident).

There are several actors in the private sector: shippers and receivers (manufacturers/producers and purchasers in many cases, respectively), transport operators (trucks, rail, inland waterway, short sea, and sea-going vessels), terminal operators, and intermodal operators (also often called intermodal brokers). The objective of each actor in the private sector is undoubtedly to maximize its profit. This incomplete management often results in the inefficiency of the system, which is often called "market failure" (Bator, 1958). However, the concern of the public sector is not necessarily the same as the private sectors. From an economic point of view, the public sector's goal is to make the *entire* logistic chain more efficient. In other words, the public sector pursues "system optimum" while the private sectors pursue "user equilibrium" (Sheffi, 1985). When environmental issues are considered, the different positions are also clearly expressed. It is necessary for the public sector to consider the environmental issues although it is not yet compulsory for the private sector. However, it is notable that the private sector has recently begun to take the environmental burdens into account and their impact on the success of their business (e.g. IBM, 2010).

This dissertation has been written with the focus on the public sector. However, it has also attempted to reflect the interests of the private sector. More specifically, Chapter 3 takes the perspective of the public sector while Chapter 4 takes that of the private sector. For example, Chapter 3 focuses only on the quantity of CO_2 emissions assuming that equivalent distances are travelled by each transport mode but Chapter 4 examines the CO_2 emissions considering the different distances, speeds, and travel times of the transport modes. Chapters 5 and 6 examine the results of both solving the private sector's concerns (locations of shippers/receivers and transport prices offered) and the public sectors concerns (locations of intermodal terminals and the boundary of the market area especially if the intermodal terminal is operated by a governmental body). Of course, the decisions of the two sectors closely interact. Chapter 7 examines the conflict between the private sector (minimization of total logistics costs) and the public sector (minimization of CO_2 emissions generated from the logistics chain).

As far as environmental issues are concerned this dissertation is limited to CO_2 emissions. However, the methods developed could also include other air pollutants/greenhouse gases as well as the other externalities such as noise, land contamination, water pollution as so on (EC, 2001a).

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Appendix 1A

		Transport Theme
Dimension1	1.1	Passenger Transport
	1.2	Freight Transport
	1.3	Urban Transport
	1.4	Rural Transport
	1.5	Regional Transport
	1.6	EU Accession Issues
Dimension 2	2.1	Air Transport
	2.2	Rail Transport
	2.3	Road Transport
	2.4	waterborne Transport
	2.5	Other Modes
	2.6	**Intermodal Transport**
Dimension 3	3.1	Economic Aspects
	3.2	Efficiency
	3.3	Equity and Accessibility
	3.4	Environmental Aspects
	3.5	User Aspects (incl. ergonomics, Quality, choice and rights)
	3.6	Safety and Security
Dimension 4	4.1	Decision-support Tools
	4.2	Information and Awareness
	4.3	Infrastructure Provision (incl. TENs)
	4.4	Integration
	4.5	Intelligent Transport Systems
	4.6	Regulation/ Deregulation
	4.7	Land Use Planning
	4.8	Transport Management
	4.9	Pricing, Taxation and Financing Tools
	4.10	Vehicle Technology

(Source: EC, 2009)

Chapter 2
Key determinants for the environmental and economic performance of intermodal freight system: an overview

"A Fool thinks himself to be wise, but a wise man knows himself to be a fool."

William Shakespeare (1564-1616)

2.1 Introduction

In the previous Chapter, the scope and position of this dissertation were identified: *"this dissertation is about freight transport system at the regional to international level focusing on intermodal chains including rail and waterborne transport modes, examining the economic and environmental aspects and developing decision-making tools"*. In this chapter, the intermodal freight transport studies addressing this issue as well as the related unimodal freight transport studies are explored. Note that, as each chapter consists of an independent article, a brief literature review addressing the corresponding topic is also included in each chapter. This chapter presents a rather general literature overview.

This chapter consists of four Sections:

- Section 2.1: Overview of intermodal studies (for all the later chapters),
- Section 2.2: Environmental Competitiveness (CO_2 emissions) of intermodal system (for Chapters 3, 4, and 7)
- Section 2.3: Economic Competitiveness of intermodal system (for Chapters 5, 6, and 7)

- Section 2.4: The relationship between the cost of logistics and CO_2 emissions

Note, Appendix A attached at the end of this dissertation is regarded as a part of this Chapter: OR (Operations Research) applications for intermodal freight system.

2.2 Overview of intermodal studies

The research questions addressed by the intermodal related literature are very varied. Bontekoning et al. (2004) reviewed about 90 scientific/practical publications and demonstrated that the field of intermodal freight study had become a new field of applied transport study. They categorized all the intermodal transport related studies into eight subcategories: *drayage, rail haul, transshipment, standardisation, multi-actor chain management and control, mode choice and pricing strategies, intermodal transportation policy and planning, and miscellaneous* (Bontekoning et al., 2004). The first three subcategories are related to the physical decomposition of the intermodal chain. The rest relates to mainstream research and intermodal practice. They found that more than half of the studies reviewed were related (i.e. cited each other). Macharis and Bontekoning (2004) and Crainic and Kim (2005) reviewed many OR (Operations Research) studies dealing with a part or whole intermodal system.

An "intermodal freight study" cannot be distinguished as a "specialized" freight research field but rather as a "comprehensive" freight research field. This is the rationale to review and include the general freight studies in the following Sections, even though the focus of this dissertation is on the intermodal freight system. The operations of the intermodal chain can be distinguished into drayage, long-haulage, and terminal operation. Each disjointed process can be studied as a unimodal study. For example, the *drayage* can be an independent unimodal optimization problem covering short and medium distance trucking. In the intermodal case, one end of a trip is represented as an intermodal terminal/port. Similarly, the algorithm to solve LTL (Less-Than-Truckload) trucking problems can be applied for drayage problems (Crainic and Roy, 1990, 1992, Morlok et al, 1990). In addition, the *transshipment* has also not been limited to a part of the intermodal system (Kim, 2005). The intermodal transshipment problem could be considered as the conventional general port/terminal operation problem. The *long-haulage* part in the intermodal system is obviously the unimodal (mostly non-road modes) operation problem such as rail, inland waterway, and even international sea-going optimization problem. For an excellent review and overview of rail transport optimization, see Assad (1977a, 1977b), and Cordeau et al. (1998); for general logistics/network problems in freight transportation, See Bianco (1987), Crainic and Laporte (1997), Crainic (2000), Ghiani et al. (2004).

2.3 Environmental competitiveness (CO_2 emissions) of intermodal system

Throughout this dissertation, it is assumed that the intermodal system emits less CO_2 than the truck-only system if the CO_2 emission generated from all the processes of the intermodal chain is less than from the truck-only system. Thus, the key issue associated with environmental competitiveness was rather straightforward: *How to assess CO_2 emissions from all related transport modes/operations in the intermodal chain?*

To date, several models have been developed to assess CO_2 emissions from transport in general. When it is assessed, they should be categorized based on four characteristics indicated *(a)* to *(d)*. The first is by *(a) transport mode*. It is obvious that the method for assessing CO_2 emissions (basically, fuel consumption) for trucks is different to that for rail since the mechanical mechanisms for combustion are different. The second category is *(b) passenger versus freight transport* (EC, 1999b, USEPA, 2003, McKinnon, 2007). The two characteristics can be combined (e.g. rail-freight, rail-passenger, car-passenger, truck-freight, vessel-passenger, vessel-freight) and each combination can furthermore be subdivided by *(c) the vehicle specification*. Specifically, if the transport mode is truck (and therefore freight), the specification is subdivided by engine type such as Euro 1 to Euro 5, the year of manufacturing, mileage, and GVW (Gross Vehicle Weight[1]) (EC, (1999b, 2006), Barlow and McCrae, 2001). In the case of freight trains, it is subdivided by locomotive type such as diesel- and electric-powered and gross weight (Kentrail, 2008). Note, in this dissertation, air transport is not considered and passenger transport modes such as passenger cars, SUV (Sport Utility Vehicles), and pick-up trucks, passenger trains, and excursion ships are also excluded. Once it is subdivided into the categories of specific freight/passenger transport modes and specifications, *(d) operation cycles* are often taken into account (EC, 2006). The variables to be determined by the diverse operating conditions are, for example, payload (weight loaded), speed, utilization factor, loading factor, empty back-haul, the number of stops due to either truck drivers resting stops according to the regulations or the train's intermediate stops, peak or off-peak hours, urban or non-urban, and types of commodity (Kolb and Wacker, 1995, Vanek and Morlok, 1998, Jørgensen and Sorenson, 1998, EC, 1999b, 2000, 2006, Van Wee et al., 2005, McKinnon, 2007, Tarancon and del Rio Gonzalez, 2007).

More specifically, for trucks, Barlow and McCrae (2001) examined the drive cycle consisting of 13 steady engine speed and load operating conditions. It is notable that the so-called FIGE cycle (also referred to as ETC: European Transient Cycle) is used to test the different driving conditions (Barlow and McCrae, 2001, DieselNet, 2009). Jorgensen (1996) includes the transport demand in a Danish case study for emission assessment and Tarancon and Del Rio Gonzalez (2007) examine the impact of the transport demand on CO_2 emissions in a European case study. It is notable that, when assessing emissions, considering transport demand and traffic conditions is only justified in a confined area such as the country level since the circumstances are not comparable (Van Wee et al., 2005). Van Wee et al. (2005) also pointed out that using emission factors obtained from the literature or from another country/region might lead to serious miscalculations. For the train, Jørgensen and Sorenson (1998) showed three different operations affecting fuel consumption and emission rates. They categorized the train operations into shunting, running with loads, and running without loads (i.e. empty back-haul). For waterborne vessels, Trozzi and Vaccaro (1999) classified into cruising, maneuvering in the harbor area, and hotelling at the dockside. It is obvious that each of these three phases emits a different amount of emissions for the same distance. Also note that the assessment methods are varied, according to different types of ships, engines, and fuels.

MEET (Methodology for Calculating Transport Emissions and Energy Consumption), a European project finalized in 1999, takes into account the diverse conditions mentioned above (EC, 1999b). This project is the prototype model of the assessment method of this dissertation.

[1] Heavy duty vehicles are often categorized as less than 14 tons, 14– 20, 20– 28, 28 – 34, 34 – 40, 40 – 50, 50 – 60, more than 60 tons in Table 14 in EC (2006).

This project includes the methodologies to assess several air pollutants as well as greenhouse gases including CO_2 emissions from trucks, rails, and waterborne vessels (EC, 1999b). In addition, this report considers air pollution and fuel consumption issues based on Life Cycle Assessment (LCA). The LCA is very useful for assessing air pollutants from either electricity-based transport modes (e.g. electric powered train) or terminal operations. In general (not limited to the MEET project), this technique makes it possible to compare freight transport systems (EC, 1999b, Lewis et al., 2001, Facanha and Horvath, 2006, Spielmann and Scholz, 2005). Jørgensen and Sorenson (1998) pointed out that special attention should be paid to the degree of electrification of the railway systems when it is applied at the country level. (Also see the website presenting the European Train List for the details of the distribution of rail electrification by country in Europe)

Technically, the MEET model is based on regression models that are obtained from many experiments in several situations. The situations consist of different types of engines/vehicles, speed, weight, slope of terrain (i.e. gradient), and even ambient temperature. Some representative situations (i.e. combination of several of the above factors) are designed and the corresponding regression equations are developed. Until the recent development of the COST model (see below), the MEET model had been the most advanced air pollution assessment technique in Europe. (Note, air pollution was assessed in several European projects by using the MEET model. See RECORDIT (EC, 2000) and REALISE (EC, 2004) for example).

Even though the emissions assessment part in this dissertation relies on the MEET model, emissions models are still evolving in Europe. The MEET model consists of all transport modes (truck, rail, and waterborne vessel) for both passenger and freight while the COST (346) project, a new European project started in 1999, focused on heavy duty vehicles (EC, 2006). In the COST 346 project, more specifications including engine types and detailed GWV (?) categorizations are considered as well as the gear shift model[2] and the driving cycle which have been more recently added (EC, 2006).

However, all the research mentioned above are limited to the assessment of air pollution for individual transport modes rather than the combination of modes, so-called “freight system”. Chapters 3 and 4 in this dissertation are dedicated to filling out the gap combining more than two modes and taking into account some other issues such as air pollution in terminals and transmission loss of electricity.

2.4 Economic competitiveness of intermodal system

Traditionally, the economic competitiveness of freight transport has been evaluated, comparing the total cost for individual transport modes (e.g. rail vs. truck) rather than combined modes. In the case of intermodal (combined) freight systems, it is similar: the total cost of the intermodal system is compared to its counterpart, the truck-only system. Thus, estimating the total freight cost that can be decomposed into individual freight transport modes plays a crucial role in the evaluation of the economic competitiveness of intermodal systems (Subsection 2.3.1). This Section also includes some other approaches: Freight mode choice based on the utility maximization approach (Subsection 2.3.2), based on the Operation Research technique (Appendix A), and the geographical approach (Subsection 2.3.2).

[2] It produces different levels of emissions according to shifting gears.

2.4.1 Freight transport cost structure

Previously the intermodal cost was simplified as a combination of linear functions as shown in Figure 2.1. (See Section 5.2 in Chapter 5, for a detailed description of Figure 2.1). The actual cost structure/function of an intermodal freight transport system is more complicated (i.e. non-linear). Since the intermodal freight system is constructed by individual freight transport modes/processes, exploring generic characteristics of cost structure and function for freight transport modes is of interest. Thus, this subsection is designed to explore general freight transport rather than focusing on the intermodal freight system.

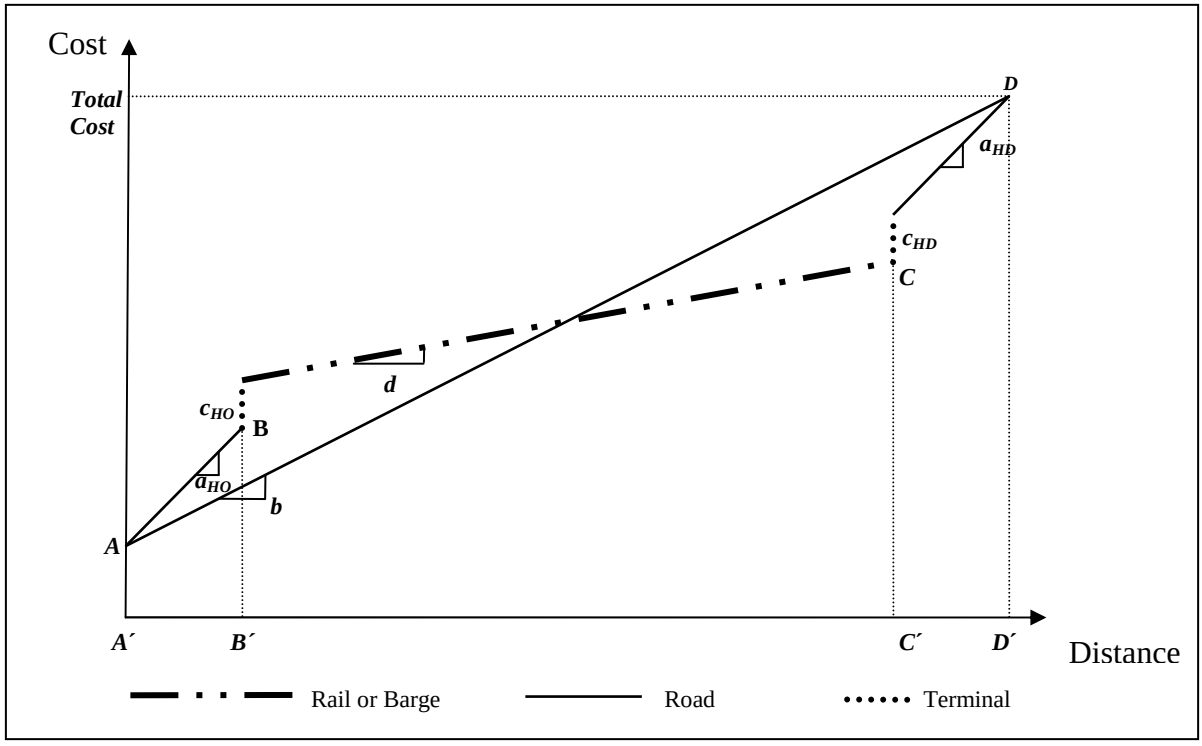

Figure 2.1 Cost structure for the intermodal system and the truck-only system (Similar figures are found in Mcginnis (1989), Rutten (1995), Konings (1996), Macharis et al. (2002), United Nations (2006), Macharis and Pekin (2009))

In general, there are many ways to represent freight costs. The form of cost functions are determined mainly by (1) the scope of the total cost, (2) the complexity of the freight transport units and unit costs (i.e. freight rate), and (3) other specific issues.

First, the scope of the total cost is a key issue in determining the form of freight cost function. The decision as to what process should be included in the freight cost function should be made based on: *transportation costs* (often referred to as direct costs; including crew wage, maintenance costs, fuel costs, facility/equipment costs and so on), *inventory costs*, *handling costs*, and *their combinations*. Harris of Westinghouse Corporation first formulated the inventory costs such as warehousing costs, holding costs, and order processing costs in 1915 and included them in the total freight cost (Winston, 1994, De Jong and Ben-Akiva, 2007). Several variants are found, such as the EOQ (Economic Order Quantity) model (Baumol and Vinod, 1970, Blumenfeld et al., 1985, Burns et al., 1985, Hall, 1985, Hall, 1987, Abdelwahab and Sargious, 1990, Daganzo and Newell, 1993, Higginson, 1993, Daganzo, 1998, Hsu and Tasi, 1999, De Jong and Ben-Akiva, 2007). In general, the purpose of the EOQ model is to

find the optimal shipment size/frequency, clarifying the trade-off between decreased transport cost and increased inventory costs as quantity increases. In the field of waterborne transport, handling costs are emphasized rather than inventory costs (Kendall, 1972, Jansson and Shneerson, 1982, Charles, 2008). However, it is worth noting that specifying inventory and handling costs is beyond the scope of this dissertation.

Secondly, when the scope is limited to the transport costs only, there are several cost components with different units: distance-based costs such as fuel (e.g. €/km), time-based costs such as labour costs (e.g. €/hour), and quantity-based costs such as transshipment costs (e.g. € /TEU[3]) (De Jong and Ben-Akiva, 2007). Thus, depending on what cost components are considered, how to express such units, how to aggregate/simplify the units, the form of (transport) cost function varies. Furthermore, costs increase in a non-linear way if the quantity shipped, the size of the lot, the distance travelled, or size of vessels/vehicles (i.e. capacity of vehicles) increases. This is called economies of scale (also referred to as returns of scale and often expressed as price discount). The nature of economies of scale is to save the fixed costs[4] such as labour costs (e.g. €/hour) for a certain amount of quantity and distance since in many cases the variable costs such as fuel costs proportionally increase as quantity and distance increase. For example, regardless of the quantity (transporting 1 TEU and 2 TEU in the case of trucks), the same wage should be paid for the truck driver. To sum up, the total cost (€) in freight transport system is an outcome of the interaction between those cost components with different units (e.g. €/km, €/TEU, €/ship, and €/day). In many cases, it has been expressed as one of the following:

$T_1 = f(Q) * Q;$
$T_2 = f(D) * D;$
$T_3 = f(Q,D) * Q*D$
$T_4 = F(Q,D)$

Where,
T is the total cost (€)
Q is quantity shipped (tonne or TEU)
D is distance travelled
$f(Q)$ is unit cost function of flow (€/tonne or €/TEU)
$f(D)$ is unit cost function of distance (€/km)
$f(Q,D)$ is unit cost function of quantity-distance (€/tonne-km)
$F(Q,D)$ is total cost function of quantity-distance (€)

If $f(Q)$ is a constant, T_1 becomes a linear equation. Then, as Q increases, T_1 increases linearly. In this case, the marginal cost is equal to the average cost. If $f(Q)$ is a linear function, T_1 becomes a quadratic equation which is a non-linear equation. In some previous studies, log functions were often used for $f(Q)$ (Samuelson, 1977, Higginson, 1993). In this Chapter, the constant unit costs are excluded. This Chapter only presents the cases that either $f(Q)$, $f(D)$, $f(Q,D)$, or $F(Q,D)$ is a nonlinear function. The cases of the constant unit costs are shown in Figure 2.1 and also found in (EC, 2000). Specifically, the unit cost could be either weight/quantity-based such as €/tonne and €/TEU, distance-based such as €/km, or could be

[3] Twenty-Foot Equivalent
[4] The total cost consists of fixed and variable costs (Rutten, 1995, Daganzo, 1998)

based on a composite form such as €/tonne-km and or €/TEU-km as shown in equations (T_1 to T_4) above (Higginson, 1993):

- T_1 : The unit cost in €/tonne (or €/TEU) could be a function of
  a) quantity/weight (Samuelson, 1977, Daughety et al., 1983, Abdelwahab and Sargious, 1990, Perl and Daskin, 1985, Perl and Sirisoponslip, 1988, Xu et al., 1994, Hall, 1987):
  b) both quantity/weight and vehicle size (Kendall, 1972, Cullinane and Khanna, 2000, Kreutzberger, 2008, McCann, 2001, Cullinane and Khanna, 1999)

In the case of b) above,
$T_1 = f(VS,Q) * Q$
Where, VS is vehicle size (capacity of vehicle). The unit of VS such as TEU or tonne should be same as Q.

- T_2 : The unit cost in €/km could be a function of
  a) distance (Perl and Daskin, 1985, Xu et al., 1994)
- T_3 : The unit cost in €/tonne-km (€/TEU-km) could be a function of
  - both distance and quantity (Ballou, 1990)
  - both distance, quantity, and vehicle size altogether (Rutten, 1995, Hsu and Tasi, 1999)
- T_4: : Total cost is a function of
  - Both distance and quantity (Boyer, 1977, McFadden et al., 1986)

Note, other units could be useful in certain cases: €/vehicle-km (Janic, 2007, 2008), €/locomotive-horsepower-mile (Bereskin, 2001).

It is also of interest to clarify the relationship between marginal costs and economies of scale. The marginal cost that is the first derivative of the total cost can be regarded as the outcome influenced by economies of scale. If the marginal cost is equal to the average cost, the economies of scale is a constant (Charles, 2008). Thus, the form of marginal cost functions is not necessarily non-linear.

Finally, the other issues also influence the form of cost functions. Depending on transport mode, the form should be different even though the basic structure consisting of fixed and variable costs is not significantly different. The empty back haul issue also leads to complicated cost functions (Daughety et al., 1983). In addition, some factors can completely change the form of the cost function, for example, the shape of the market area (Fetter, 1924, Hsu and Tasi, 1999) and travel speed (Hsu and Tasi, 1999), multiple type of vehicles (McCann, 2001), multi-commodity (Oum, 1979), inclusion of external costs (Janic, 2007)).

2.4.2 Freight mode/system choice

From a shipper´s perspective the purpose of examining the economic competitiveness of intermodal freight systems is to decide whether or not to choose it. There are only a few

previous studies focusing on the intermodal freight system choice[5]. This subsection explores the general mode choice and then links it with the intermodal system choice.
There are largely two approaches to studying freight mode choice in general: utility maximization approach (also referred to as random utility model) and OR (Operational Research) method-based network equilibrium models. Some examples of the former are discrete choice models (e.g logit, probit) while examples of the latter are the minimum cost flow problem, the route-mode choice problem, and the network design problem. The former can consider several decision variables in the decision/making process in freight transport while the focus of the latter is freight costs. Obviously, the former has a limitation in fully considering the costs components (i.e. linear cost functions are assumed in many cases) while the latter has difficulty taking non-cost variables such as preference of shippers into account. To the best of my knowledge, the latter has been used as a method of mode choice after Dial (1979) incorporated mode choice in the scheme of route choice. He explicitly called his model "non-logit" mode choice model.

Since the utility maximization approach is beyond the scope of this dissertation, some demerits of this approach are briefly discussed here. As Cascetta et al. (2009) pointed out, the conventional passenger mode choice models based on the utility maximization approach is not a good enough fit to model freight mode choice. The main differences are that freight transport has some additional dimensions to passenger transport such as multiple decision makers in freight transports, service rather than mode, and time constraints (i.e. departure/arrival time). However, the second approach, OR method-based network equilibrium models, are relatively more flexible and well-fit for freight decision makers since it is capable of optimizing a service-oriented network, of incorporating the time constraints, and to model, at least potentially, any types of multimodal network accommodating all actors involved in the system.

The second approach is considered in Chapters 6 and 7. There are many OR problems to evaluate the competitiveness of intermodal freight system and improve it. More than 100 publications handling either a part of or entire intermodal freight systems were found (Macharis and Bontekoning, 2004, Crainic and Kim, 2005). An extensive review of this literature can be found in the Appendix (See, Appendix A).

2.4.3 Geographic approach

When economic competitiveness for the intermodal freight system is examined, geographical issues are crucial. Nierat (1997) finds the market area that makes the intermodal freight system more competitive than the truck-only system. Fowkes et al., (1989, 1991) estimates the break-even distances for different sized containers. The key issues in these approaches are to find locations of shipper-receiver, terminals, and market areas where an intermodal system is more economical and accordingly also the distances between shipper and receiver, between shipper/receiver and a terminal, and between two terminals. Since the mid-1990s, GIS(Geographic Information System) based models have received attention (for example, Jourquin and Beuthe (1996), Jourquin et al. (1999), Beuthe et al. (2001), Macharis and Pekin (2009)). These studies either find locations or select a route for which multimodal systems are

[5] "System" choice is more appropriate than "mode" choice in the context of this dissertation. Note, Cascetta et al. (2009) uses "service" choice instead of "mode" choice and "system" choice.

competitive in the more complicated real freight networks. However, it is obvious that cost functions still play an important role although the focus is on the geographical issues.

Chapter 5 incorporates the two issues: geographic and cost issues. Chapter 6 specifies the non-Logit mode choice incorporating mode choice and flow assignment and using the unit cost in €/tonne-km (€/TEU-km) (T_3 in subsection 2.3.1).

2.5 Relationship between logistics cost and CO_2 emissions

The straightforward outcome of the relationship between logistics costs and CO_2 emissions is CO_2 cost (or CO_2 tax) which is the answer to the question – *How much do we need to pay for reducing CO_2 emission in logistics chain?* Two different approaches to handling this issue were recognized: traditional external cost concept and the proposed shifting cost concept. Firstly, in general external costs include air pollution, noise, and traffic accident (EC, 2002b). When CO_2 is only taken into account as the external cost, the main task to estimate it is to identify the global warming effects and express them in monetary value (EC (1999a), Mayeres et al. (2001), Int Panis et al.(2000)). Some factors being taken into account are for example the impact on mortality, morbidity, public health, agriculture, energy demand, water supply, rise in the sea level, extreme weather events (EC, 1999a, 2003). However, there is no consensus for a single external cost or even a range of costs (EC, 1999a, Mayeres et al., 2001). Tol (2005) clearly showed how wide the range is. Despite the uncertainty of the CO_2 cost, several studies internalize such externalities because there seems to be no feasible alternative which can appropriately consider them (EC, 2000, 2002a, Janic, 2007, Maibach et al., 2008). The second approach, which will be specified in Chapter 7, is to estimate the per ton CO_2 cost through shifting freight systems from a more CO_2 emitting one such as a truck-only system to a less CO_2 emitting one such as a rail/based intermodal system. When CO_2 cost is estimated using multi-objective optimization, the CO_2 cost based on environmental economics (i.e. first approach) can be used as a weight. In other words, CO_2 emissions are converted into money. However, the second approach is the outcome (i.e. Pareto optimal) in the multi-objective optimization problem. The difference will be clarified in Chapter 7.

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Chapter 3
Assessment of CO_2 emissions for truck-only and rail-based intermodal freight system in Europe: data needs, methodology, and research framework

Nam Seok Kim and Bert Van Wee
Delft University of Technology

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Abstract
Rail-based intermodal freight transportation systems in EU have been regarded as being more environmentally friendly than truck-only freight systems, particularly for long-distance haulage and in terms of CO_2 emissions. However, to date, there has been no clear comparison of CO_2 emissions between different freight systems. Therefore, this research aims at demonstrating whether the intermodal freight system really does emit less CO_2 than their road-based counterparts. A research framework was established in which the methods and data of earlier studies were assessed. Based on a conceptualisation of intermodal and truck-only systems, the semi life-cycle assessment technique, which is excluding emissions from infrastructures and vehicle manufacturing and including emissions from production of fuel and definitely direct emission, was used in order to examine the short- and medium-term environmental impact of different freight systems. The main conclusion is that in general rail-based intermodal freight systems emit less CO_2 than truck-only systems, regardless type of locomotives. In case of electrical locomotives the electricity power-generating source is the definitive factor in deciding which type of train in an intermodal freight system offers the most environmentally friendly alternative: if power plants use coal or oil only intermodal systems using electrical trains might even emit more CO_2 than their competitors

3.1 Introduction

Although in Europe rail-based intermodal systems, at least potentially, are more economically feasible and environmentally sustainable under certain conditions than unimodal freight systems (i.e. truck-only freight systems), the statistics for freight transportation in the EU show that between 1980 and 2004 the share of road usage expressed in tonne-kilometres increased (+12.2%), and that of rail usage decreased (-8.5%) (ECMT, 2006). The increasing share of road usage has raised concerns about air pollutants (mainly SO_2, NO_x, CO, VOC, and PM_{10}), and greenhouse gases (mainly CO_2 and CH_4), because road transport is regarded as being one of the major contributors to air pollution (EC, 1999, EC, 2002a, EC, 2003). As a result, in order to try to reduce air pollution, international organisations, and national and local governments have tried to increase the proportion of freight transported by non-road freight modes, focussing on intermodal freight systems to satisfy door-to-door demands (EC, 2002b). However, substantial achievements have not been made because the freight industry focuses mainly on profits, irrespective of environmental concerns about truck-only freight transportation. In addition, it has not been clearly demonstrated that intermodal freight systems are more environmentally friendly than long-distance truck-only systems. Although some statistics and earlier studies have reported that rail transportation emits fewer pollutants than road transportation, these have not been comparable because truck-only systems are based on door-to-door trip, whereas rail systems are based on terminal-to-terminal trip only (EC, 1999, EC, 2002a, EC, 2003). Therefore the concept combining two modes is required to assess the environmental impacts and compare rail-based intermodal freight system with truck-only freight. However, the techniques to assess emissions from transport modes have been developed only focusing on an individual transport mode (EC, 1999). The other requirement for assessing environmental impact is to clarify the relationship between different types of energy and corresponding emissions. For the electric powered trains, the source of generating electricity (e.g. coal, oil, nuclear, and windmill) should be considered because it might be the key factor for the comparison of CO_2 emissions at the system level.

To assess emissions from the freight transport systems and appropriately compare them, this research aims to *identify* the factors that influence emissions for both freight systems (i.e. the clarification of data requirements), *estimate* greenhouse gas emissions - especially CO_2 – in the entire door-to-door logistics chain, and *compare* the emission levels from intermodal systems with the emission levels of road-based counterparts. Specifically, the paper begins by exploring the input and output of emissions for three types of different freight transport modes rather than for the entire systems: trucks, diesel powered trains, and electric powered trains. In this research, Life Cycle Assessment (LCA) modelling is partially used to estimate specific transportation emissions (ECMT, 2000), making comparisons at the system level possible. The focus of the paper is on the effects of modal choice and related modal shift policies within the current infrastructure networks, and thus in the short and medium term. The focus is not on assessments in case of network extensions; in that case a full LCA is needed including also infrastructure (see next section). In addition, the focus is on container transport since especially in the container marketed opportunities for modal changes exist. Emissions for producing vehicles are also relevant. At the level of individual vehicle categories some methodologies and data are available (e.g Van Wee et al. (2000)). However, currently no comprehensive methodology is available to include these emissions (see also the section ‘conclusions and further research’).

The remainder part of this paper is organized as follows. In Section 2, more details of scope and a conceptual model including the description of the semi-LCA model are discussed.

Section 3 describes the methodology and data need to assess emissions from individual transport modes: truck, diesel powered train, and electric powered train. In addition, emissions from transshipment process at the intermodal terminal and transmission loss are also discussed. Using the methodologies and the conceptualisation of both freight systems, Section 4 presents the comprehensive emission model combining individual processes (i.e. drayage by trucks, transshipment at the terminal, and long-haulage by different types of trains) into 3 freight systems: truck-only system, diesel powered train based intermodal system, and electric powered train based intermodal system. Through a numerical example with an emphasis of source of fuel for transport modes, CO_2 mass for these three freight systems is assessed. Finally, the authors attempts to answer a question: *"Are intermodal freight systems really more sustainable than truck-only freight systems in terms of CO_2 emissions?"*

3.2 Scope and conceptual model

In recent years, increasing attention has been paid to life cycle assessment (LCA) in the field of energy consumption and emissions from freight transportation (Facanha and Horvath, 2006, Spielmann and Scholz, 2005). However, since LCA is an attempt to assess environmentally harmful effects over long-term periods, it is not always appropriate in medium- or short-term analysis. As one of the main factors of LCA, the pollution from infrastructure construction should not be included in medium- or short-term analysis, but in long-term analysis only. This study includes emissions from exhaust and production, but excludes emissions from the construction of infrastructure and vehicle manufacturing, and attempts to define it as "Semi-LCA". This kind of issue is still open to debate (Hellweg and Frischknecht, 2004). The semi-LCA is appropriate when two freight transport systems are compared by using the same criteria, in especially the short or medium term. For example, since electric powered trains do not emit CO_2 during operation at the vehicle level, emissions produced during operation could not be compared with other modes. Thus, to compare them, emission from generation of electricity, so-called 'production emission', should be considered. Definitely, the production emissions from extracting, refining, and transporting diesel oil should be considered at the same time.

As mentioned previously, in the context of rail-truck intermodal freight transport system, the scope of this study is the door-to-door trip. Intermodal freight systems are commonly defined as freight transport systems consisting of two or more modes of transport used in door-to-door trips for consolidated loads (i.e. containers, swap bodies, and trailers or semi-trailers) (EC, 2001, Janic, 2007, Bontekoning et al., 2004). Figure 3.1 represents a conceptualisation of intermodal freight systems and truck-only systems. Intermodal freight systems have three main stages: drayage, terminal operation (transshipment), and long-hauling. Drayage is the movement of loads to or from an intermodal terminal for collecting from shippers and distributing to consignees by trucks. At an intermodal terminal, loads are transhipped from truck to wagons, and vice versa. Long-hauling is the transportation of loads from the intermodal terminal of origin to the destination intermodal terminal.

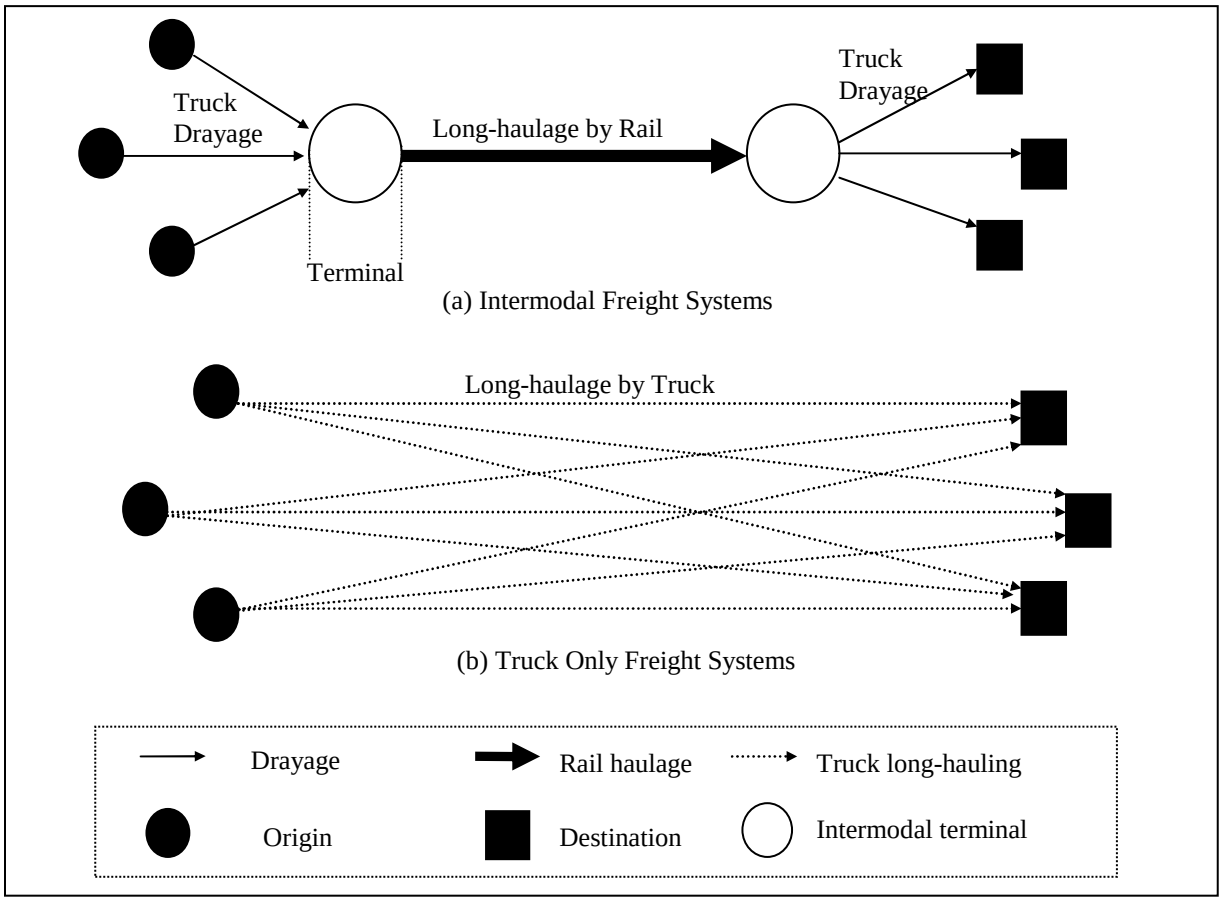


Figure 3.1 The conceptualisation of intermodal freight transport systems and truck-only systems

Once the inputs (e.g. fuel, distance travelled, weight of load, gradient, and so on) and outputs (e.g. mass of CO_2) for emissions are recognised, the relationship between inputs and outputs is clarified by using equations estimated by the European Commission (EC, 1999). Then, CO_2 mass for three different freight modes (i.e. truck, diesel locomotive, and electric locomotive) are separately estimated. The Procedural diagram for estimating CO_2 emission presented in Figures 3.2 and 3.3 might lead to a better understanding of the overview of the research. When considering the characteristics of each freight system, the first step is to identify the type of emission (i.e. direct emission and production emission) and estimate fuel consumption. As shown in Figure 3.2 in the case of trucks, direct (exhaust) emissions consist of hot and cold emissions. Following the EC methodology the amount of the direct emission is the input of carbon balance method to estimate fuel consumption. Then, production emissions, which include the emissions generated during the processes of extraction, crude oil transportation, and refinery, are considered. Finally, adding two types of emissions, the total emissions from trucks are estimated. For intermodal freight systems as shown in Figure 3.3 shows that there are three processes (i.e. drayage, long-hauling, and terminal operation), each resulting in emission (i.e. direct emission and production emission). In the long-haulage process two types of locomotive are considered: diesel and electric. Electric vehicles generally emit pollutants in different ways to diesel vehicles: direct emissions (i.e. at the vehicle level) do not exist. In stead the emissions are at the power plant level (i.e. production emissions). Emissions from energy used in drayage and transmission are estimated separately. It is notable that the emission factor of truck-only systems is used in the drayage part of intermodal freight systems. Furthermore, for intermodal systems using electric powered trains, some power source

scenarios are considered to estimate different production emission rates (e.g. 100% nuclear, 100% coal/oil, and 50% nuclear and 50% coal and oil). More detailed description will be discussed step by step with respect to the freight system, process of the system, and the types of emission in the next Section.

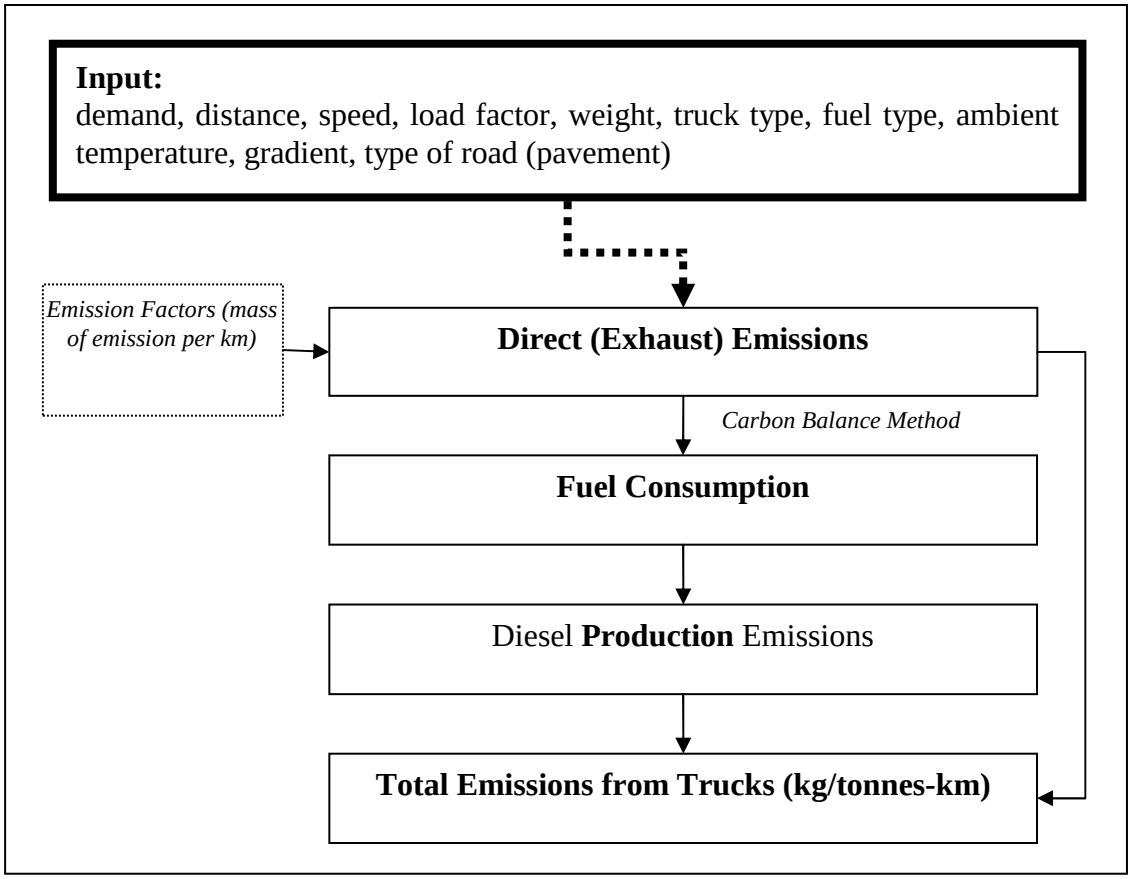


Figure 3.2 Procedural diagram for estimating for truck-only system

3.3 Methodology and data need

Generally, two methods estimating emissions from transports are used in current practice: top-down and bottom-up method (Van Wee et al., 2005). The former is based on aggregate statistics for emissions and freight volumes while the latter is focused on physics and engineering techniques. The latter is more appropriate to examine the mechanism of pollutions from transport while the former is more appropriate to calculate overall averages of emission factors or emissions per speed, per distance, and per weight loaded implicitly including all relevant determinants. Therefore, with respect to the purpose of this research, the top-down approach is more appropriate to be applied.

The basic equation for estimating emissions from transport using the top-down approach is a function of transport activity and fuel consumption (EC, 1999). If fuel consumption is unknown, it is estimated by empirical measurements. In other words, a lot of the data needed for the assessment of air-pollution does not depend on theoretical methodology, but on empirical measurements. The European Commission has suggested the most reliable measurements to be used for every separate mode in Europe so far (for a thorough description, see (EC, 1999)). In this Section, emissions from separate mode (i.e. trucks, diesel powered

trains, and electric powered trains) and other processes (transshipment of loads and transmission of electricity) are decomposed and specified with respect to characteristic of freight mode.

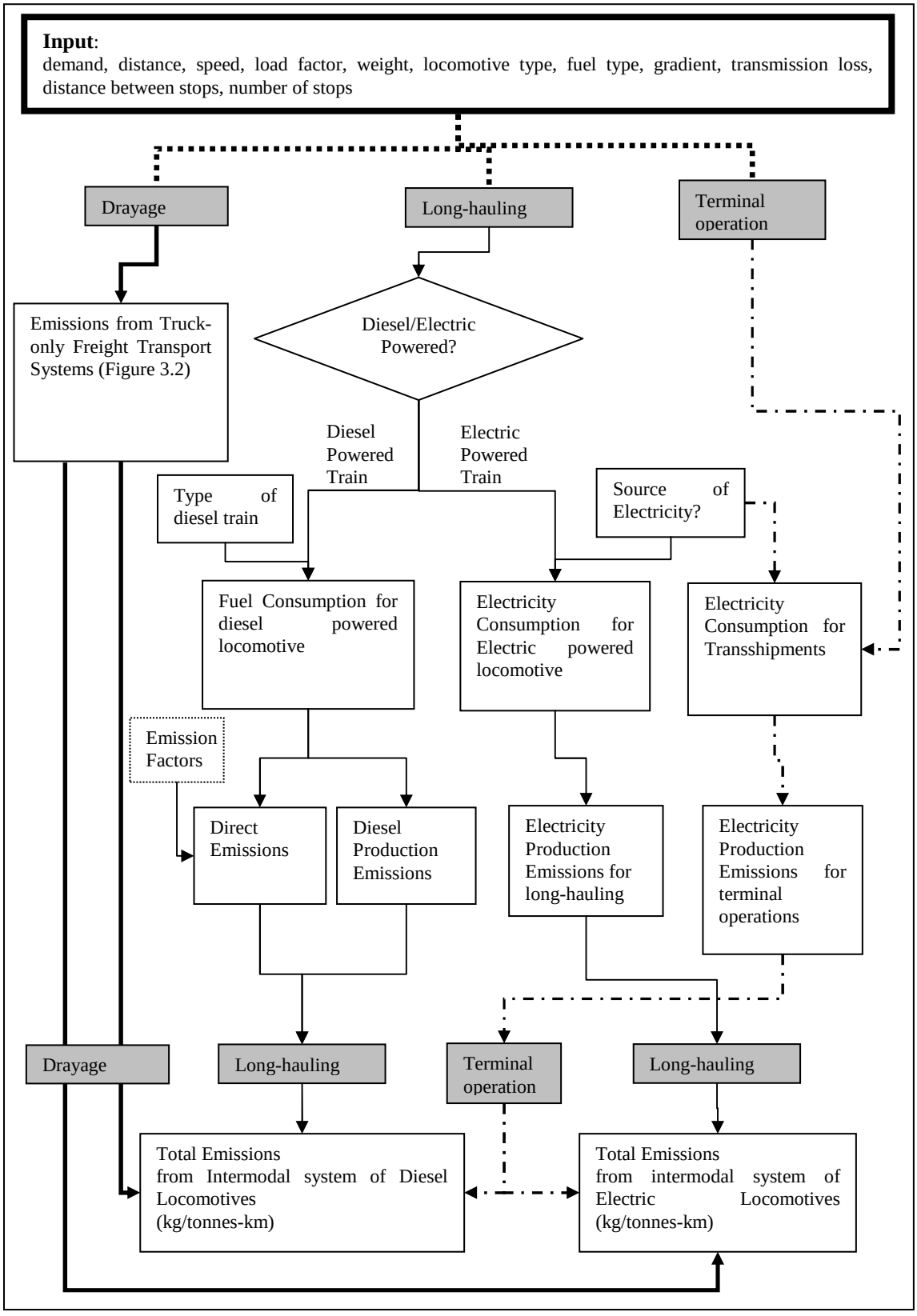


Figure 3.3 Procedural diagram for estimating for rail-based intermodal Systems

3.3.1 Trucks

Direct Emissions from Trucks

For road transport, emissions vary in accordance with the temperature of engines. This leads to the basic calculation as follows (EC, 1999):

$TE_{truck} = (TE_{Hot} + TE_{Cold} + TE_{Evaporative})$

Where,

TE_{truck}	is the total of exhaust emissions (kg/tonne-km)
TE_{Hot}	is emissions produced when engines are hot
TE_{Cold}	is emissions produced when engines are cold (including starting)
$TE_{Evaporative}$	is evaporative emissions

Table 3.1 shows the summary of specific methodology of direct emissions and corresponding data needs for trucks.

Table 3.1 Data needs and methodology for exhaust emissions from diesel engine trucks

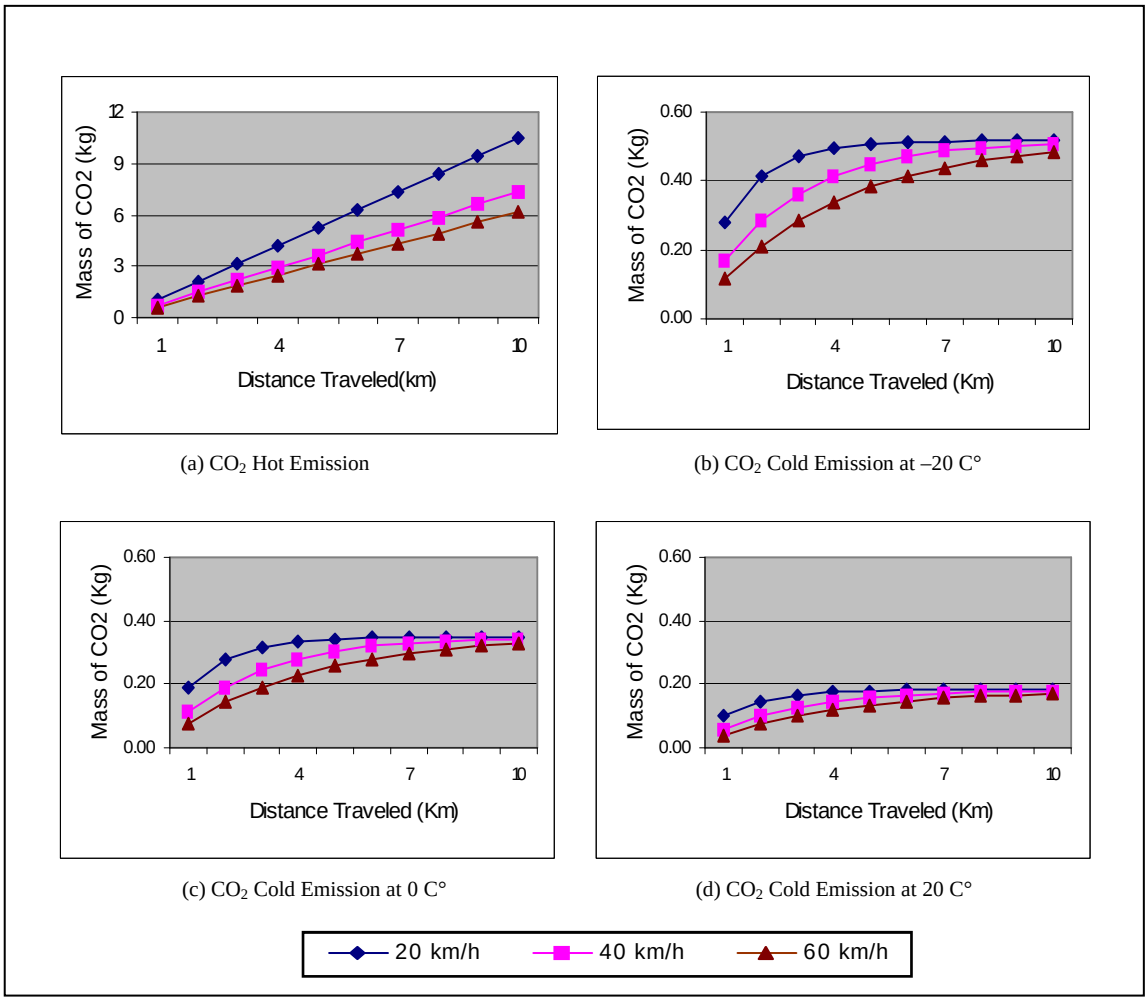
	Hot (TE_{Hot})	Cold (TE_{Cold})
Equation	$TE_{Hot} = \sum_{i=1}^{vehicle\_type} n_i * l_i * \sum_{j=1}^{road\_type} p_{i,j} * e_{i,j,k}$	$TE_{Cold} = w*[f(v) + g(t) - 1]*h(d)$
Where (Data Needs)	k= type of the pollutant i = the truck category j = the type of the road n_i = the number of vehicles in category i l_i = the average annual distance travelled by the vehicles of category i (km/time) $p_{i,j}$ = the percentage of the annual distance travelled by the vehicles of category i $e_{i,j,k}$ = the emission factor of pollutant k corresponding to the average speed on road type j, for vehicle category i (g/km) related to the average speed, the road gradient factor, load weight, vehicle mileage, and ambient temperature	v, f(v) = the average speed and the function of speed and emissions respectively t, g(t) = the temperature of engine in °C and the regression equation of temperature and emissions respectively d, h(d) = the distance travelled and the regression equation of distance and emissions respectively w = the reference excess emissions (at 20°C and 20 km/h)

Source: EC (1999)

To be able to compare truck-only systems with intermodal systems, only trucks which are able to load containers/swap bodies are considered. In most of EU countries the total weight of trucks should be less than 44 metric tonnes. We selected two of the vehicle categories of the MEET-project: heavy goods vehicles with Gross Vehicle Weights (GVW) of 16 to 32 tonnes. Thus, the vehicle type in the equation of E_{Hot} is not a multi-class vehicle, but a unique type of truck in this study (i.e. i = 1 in the Table 3.1). The last factor ($e_{i,j,k}$) in Table 3.1 is defined as a function of the average speed, gradient, load weight, vehicle mileage, and ambient temperature. Some factors for the total direct emissions are simplified and assumed. Specifically, the type of road, gradient, and ambient temperature is assumed as highway, 0%, and 20°C respectively. The factor of average speed and distance travelled is considered as constants in 10 km/h and 100km intervals respectively in the later analysis of this paper.

Cold emissions, CO_2 in this study, are estimated at 1 km intervals and regarded as a constant (e.g. 0.52 kg at –20°C, 0.35 at 0°C, and 0.18 at +20°C) regardless of the distance travelled and temperature, because, in general, they converge at around 10 km as shown in Figure 3.4 and the distance covered by long-haulage trucks is per definition much longer than 10 km. In addition, since cold emissions are only a negligible fraction of hot CO_2 emissions, they are considered as 'excessive emissions' (EC, 1999). In other words, the cold emission does not significantly affect the total CO_2 mass. This makes sense because they are a one-time emission and the engine will be hot after around 10 km has been travelled. For reasons of completeness we include them in our methodology (see Table 3.1).

The techniques to evaluate evaporation emissions, while vehicles are operated, have only been developed for gasoline-based vehicles because diesel oil has no significant evaporation emissions. An EPA report concludes that the reason is the low volatility of diesel fuel compared to gasoline (EPA, 1994). The detailed and thorough description and method used to estimate emissions from distribution can be found in the EPA report (EPA, 1994). To conclude, the evaporative emissions directly generated by trucks are excluded from this study.



(a) CO_2 Hot Emission

(b) CO_2 Cold Emission at –20 C°

(c) CO_2 Cold Emission at 0 C°

(d) CO_2 Cold Emission at 20 C°

Figure 3.4 Comparisons between Hot and Cold Emissions

Fuel consumption from trucks and production emissions of crude oil

As mentioned previously, production emissions are also considered in this study. Before estimating them, fuel consumption should be estimated because production emission is

linearly linked to the fuel consumption. We use the so called "carbon balance' method (EC, 1999), with which the total fuel consumption of trucks can be estimated. Specifically, since fuel consumption is based on the combustion of a hydrocarbon fuel such as petrol or diesel, the mass of fuel can be calculated from the mass of estimated emissions. Production emissions are fuel consumption multiplied by the production emission factor (PE). It turns out that emissions related to the production of fuel account for approximately 10% the total of direct and fuel emissions together. This value is more or less in line with a research carried out by Facanha and Horvath (2006). They carried out a full LCA and found fuel production to be responsible for around 10% of total CO_2 emissions (other emissions: approximately 70% direct emission, 10% infrastructure, and 10% of vehicle manufacturing) (Facanha and Horvath, 2006). This implies that the production emission of fuel in this study was approximately 12.5% of the sum of direct emissions and fuel emissions (excluding emission from infrastructure and vehicle manufacturing). It is notable that, to consider production emissions as discussed above, the unit of litres/1,000 km can be converted to kg/MJ (or kg/GJ), which is the common unit used for the measurement of production emissions. The energy content in diesel is 38.6 MJ/litre (2006). The estimation of fuel production with respect to the semi-LCA method needs a variety of data at several stages (e.g. energy and emission related to crude oil extraction and transportation, refining process, and refined oil distribution). This research uses the factors estimated by Lewis (2001). Specifically, 6.96 kg of CO_2 is generated for 1 GJ on average of EU countries. This factor will be used for fuel consumption for diesel trucks as well as for diesel locomotives in the next Section.

3.3.2 Diesel powered trains

Jørgensen and Sorenson (1997) estimated two main factors (i.e. the power specific emission factor ($BSEF_i$) and the brake specific fuel consumption ($BSFC_i$)) using measurements and regression as shown in Table 3.2. Specifically, the two factors are estimated by empirical measurements of several types of diesel trains (e.g. IC3 in Denmark, Austrian diesel trains, and British trains). The 3.180 g CO_2 /kg indicated in Table 3.2 is the weighted average value of those trains. As explained above for the fuel consumption (i.e. energy consumption) specifically, there are two approaches to estimate fuel consumption: the physics based approach and the empirical data approach (i.e. bottom-up and top-down approach, respectively). The former approach based on physics is complicated since it concerns several experimental factors influencing energy consumption and emission factors. In other words, it is difficult to generalize without several assumptions such as elevations, type of fuel, and the number of stops. On the other hand, the latter approach suggested by Jørgensen and Sorenson (1997) can overcome this roadblock. Specifically, the rolling stock's properties (e.g. the weight, stop spacing, and speed) play an important role to estimate fuel consumption in the latter approach. Other factors, such as curvature, gravity, air friction, and rail friction, are considered in the curve fitting of several trains. Thus, the constants (i.e. k and c in Table 3.2) can be different for each type of train (e.g. For ICE trains: k = 0.007 and C = 74; for TGV trains: k = 0.0097 and C = 70; for Swedish RC trains: k = 0.015 and C = 81 (for thorough description, see Jørgensen and Sorenson (1997)). The estimated fuel consumption and some value of factors (weight, distance, load factor, $BSEF_i$) are used for estimating the direct emissions from diesel powered locomotives.

Diesel powered trains also have production emissions as mentioned previously. It is worth mentioning the slight difference between the diesel oil used for diesel powered trains and the one for trucks. The one for diesel powered train is called 'red diesel', which is dyed for

taxation, or sometimes called ‘gas oil’ in Europe, while the other for trucks is called ‘white diesel’. The energy content of red and white diesel is almost same at least in Europe: 38.6 MJ/litre (=138,000 BTU/gallon) (Commonwealth of Australia, 2004, Queensland Transport Facts, 2006, Discussion with Zoetmulder, 2007). Therefore, production emissions can be calculated by using the same production emission factor (PE) (kg/GJ) as described in the truck section.

Table 3.2 data needs and methodology for direct emissions from diesel powered trains and fuel consumption

	Direct Emissions	Fuel consumption	Production Emissions
Equation	$TE_{\text{intermodal Dloco}}$ = Fuel specific emission factor	$F = k \times \frac{v_{ave}^2}{in(x)} + C$	
Where (Data Needs)	Fuel specific emission factor = (BSEFi/BSFC) $BSEF_i$ is the power specific emission factors BSFC is the brake specific fuel consumption	F = the energy consumption of locomotives (KJ/tonne-km) k and C = train dependent constants: k= 0.019 and C = 63 for large freight trains (600 tonne empty mass) x = distance between stops in km: 80km $\leq$ x $\leq$ 200km V_{ave} = average speed	6.96 kg of CO_2/1GJ
Assumption	Fuel Specific in average (g/kg) is 3.180	x = 120 km V_{ave} = 10 to 110 km/h in 10km/h interval (constant)	

3.3.3 Electric powered trains

The emissions for electric powered trains are mainly emitted at electric power plants, when electricity is generated (EC, 1999). In other words, unlike emissions from diesel-based freight modes, operational emissions - at least in terms of air pollution while trains are being operated - are not generated. Thus, electric locomotives are free of direct emissions. As shown in Figure 3.3 the production emission is the only contributor of long-hauling of electric locomotives. Electricity use and the type of power generation is the main issue in case of emissions from electric powered trains. We used the top down approach since the development of bottom up approaches for energy use of trains is still under development (Jong and Chang, 2005). Contrary to diesel powered trains, a break down in categories, in particular with respect to of power plants is needed. We assume that the energy required to pull an electrical train can be calculated using the methodology as presented in Table 3.2. Combined with the fuel efficiency of power plants, the energy needed for an electrical train can now be calculated, The difference between diesel and electric powered train is the fuel efficiency (i.e. the energy content): 38.6 MJ/litre for diesel powered trains and 3.6 MJ/Kwh

for electric powered trains (Queens Transport Fact, 2006, Fuel and Energy Conversion and Equivalence Chart, 2007).

Once the fuel consumption is estimated, the source of electricity generation should be considered. Lewis et al. (2001) specified CO_2 emissions in terms of power sources: coal-fired power stations (959.2 g/kWh), oil-fired power stations (818.6 g/kWh), combined cycle gas turbines (447.5 g/kWh), and nuclear power stations (4 g/kWh). Nuclear electricity shows the lowest CO_2 mass per unit kWh when viewed against other power generation sources. As in the case of diesel production mentioned previously, the emission factors estimated above include emissions generated from all pre-combustion processes such as the transport of raw materials, processing, and extraction. The difference of electricity production emissions over the countries in EU is much higher than the one of oil production emissions. Norway, for example, emits very low CO_2 (1.7 kg/GJ) when compared to other EU countries: 296.0 kg/GJ in Greece, 257.3 kg/GJ in Denmark, 212.0 kg/GJ in Ireland, with an EU average overall of 130.6 kg/GJ. For more detailed information, see (Lewis et al., 2001). This discrepancy in the production emission factors for different countries mainly reflects the type of electric power generation used (i.e. nuclear, coal/oil, and renewable resources).

3.3.4 Transshipment and transmission loss

Electricity consumed for loading/unloading and lighting at intermodal terminals is considered. This research uses the electricity consumption factor assumed by Kamp et al. (EC, 2005): 5.33 kWh/TEU. Specifically, this factor is calculated by estimating average electricity consumption of cranes and lights in intermodal terminal (100 kWh/h), the number of TEU loaded/unloaded per hour (37.5 TEU/ h), and the number of transshipment points (i.e. 2 intermodal terminals). The production emission factor (kg/GJ) of electricity discussed previously (e.g. EU average: 130.6 kg/GJ) is multiplied to electricity consumption factor in order to estimate emissions from transshipment.

Transmission loss is also considered for electricity for transshipment operation at the intermodal terminal as well as electric powered train. In the UK and US, transmission loss of 7.5% approximately is reported (Woolf, F., 2003, Global Energy Network Institute, 2007, Powerwatch, 2007). Thus, about 8% of extra electricity needs to be generated in order to meet the required power consumption of transshipment and electric powered trains.

3.4 Emission models for freight transport systems

In this section, we attempt to clarify the type of emissions (i.e. direct and production emission) by different mode (i.e. truck and diesel/electric locomotive) and process (drayage, long-haulage, and transshipment). Since this research aims to estimate the CO_2 mass of combined freight systems (i.e. intermodal freight systems), the relationship between entire door-to-door freight activities and emissions emitted by separate modes is mathematically modelled and combined in both the aspects of direct trucking systems and intermodal freight systems as follows:

3.4.1 Notations

Terminals K = [1, 2, … k]
Shippers I = [1, 2, … i]
Consignees J = [1, 2, … j]
Modes m = [Truck, DLoco (diesel locomotive), ELoco (electric locomotive)]
Sources of electricity generation = [coal, oil, nuclear]

E_{truck}	is total emissions from truck trips
$E_{intermodal\ Dloco}$	is total emissions from intermodal freight systems using diesel locomotives
$E_{intermodal\ ELoco}$	is total emissions from intermodal freight systems using electric locomotives
F_{ijm}	is fuel consumption (KJ/tonne-km) of mode m from i to j (or from k to k+1)
D_{ij}	is distance travelled (km) from i to j
W_m	is gross weight of load per trip by m (kg)
TE_m	is exhaust emissions (CO_2) by m (kg/tonne-km)
$PE_{m(s)}$	is production emissions (CO_2) by m (with s sources if the source is electricity) (g/kWh)
EC	is electricity consumption factor (kWh/TEU) at terminals
$Q_{k,k+1}$	is frequency rate of trains (total tonnes arrived at terminal k/capacity of train)
L	is average transmission loss of electricity between power plants and railways (%)
X_{ij}	is 1 if a trip is made, 0 otherwise

3.4.2 Emission models for freight systems

E_{truck} = [Direct emissions] + [Production emissions]
= [Hot emissions and Cold emissions] + [Fuel consumption*Emission rate]

$$= \sum_{i\in I}\sum_{j\in J}\left(\left[D_{ij}W_{Truck}X_{ij}TE_{Truck}\right]+\left[F_{Truck}\ D_{ij}W_{Truck}X_{ij}(PE_{Truck})\right]\right)$$

$E_{intermodal\ Dloco}$ = [Emissions from drayage] + [Emissions from long-hauling] + [Emissions from loading/unloading]
= [Direct emissions from trucks + Production emissions]
+ [Exhaust emissions from long-hauling + Production emissions]
+ [Emissions from loading/unloading]

$$= \sum_{i\in I}\sum_{k\in K}\left(\left[D_{ik}W_{Truck}X_{ik}TE_{Truck}\right]+\left[F_{Truck}\ D_{ik}W_{Truck}X_{ik}PE_{Truck}\right]\right)$$
$$+\sum_{k\in K}\sum_{j\in J}\left(\left[D_{kj}W_{Truck}X_{kj}TE_{Truck}\right]+\left[F_{Truck}D_{kj}W_{Truck}X_{kj}PE_{Truck}\right]\right)$$

Emissions from Drayage

$$+\sum_{k\in K}\left\{\left(\left[D_{k,k+1}W_{DLoco}X_{k,k+1}TE_{DLoco}\right]+\left[F_{DLoco}\ D_{k,k+1}W_{DLoco}X_{k,k+1}PE_{DLoco}\right]\right)\times Q_{k,k+1}\right\}$$

Emissions from long-hauling

$$+\left[\left[2\times(EC)\times\sum_{i\in I}\sum_{j\in J}X_{ij}\right]\times(1+L)\right]\times PE_{transshipment(s)}$$

Emissions from Transshipment

$E_{intermodal\ Eloco}$ = [Emissions from drayage]+ [Emissions from long-hauling] + [Emissions from loading/unloading]

= [Direct emissions from trucks + Production emissions]
+ [Production emissions from long-hauling]
+ [Emissions from loading/unloading]

$$= \sum_{i\in I}\sum_{k\in K}\left(\left[D_{ik} W_{Truck} X_{ik} TE_{Truck}\right] + \left[F_{Truck}\ D_{ik} W_{Truck} X_{ik} PE_{Truck}\right]\right) + \sum_{k\in K}\sum_{j\in J}\left(\left[D_{kj} W_{Truck} X_{kj} TE_{Truck}\right] + \left[F_{Truck} D_{kj} W_{Truck} X_{kj} PE_{Truck}\right]\right)$$ } *Emissions from Drayage*

$$+ \sum_{k\in K}\left\{\left(\left[F_{ELoco}\ D_{k,k+1} W_{ELoco} X_{k,k+1} (PE_{ELoco} + L)\right]\right) \times Q_{k,k+1}\right\}$$ } *Emissions from long-hauling*

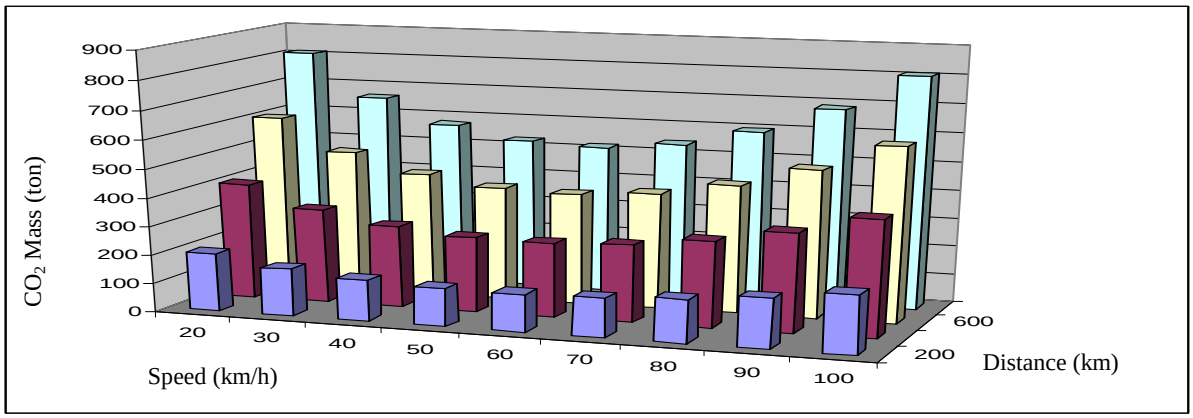
$$+ \left[\left[2\times(\boldsymbol{EC})\times\sum_{\boldsymbol{i\in I}}\sum_{\boldsymbol{j\in J}}\boldsymbol{X_{ij}}\right]\times(1+\boldsymbol{L})\right]\times \boldsymbol{PE}_{\boldsymbol{transshipment(s)}}$$ } *Emissions from Transshipment*

Among several factors, the fuel consumption rate (F_{ijm}), the exhaust emission rate (TE_m), and the production emission rate (PE_m) depend on practical and empirical measurements as reviewed previously. The models are tested in the next section.

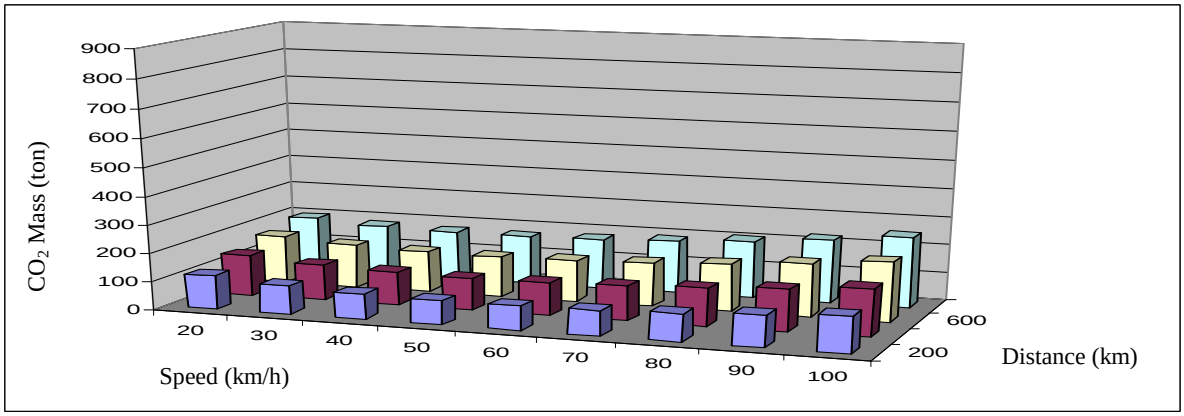
3.5 Application: numerical example

3.5.1 Estimation of CO_2 in respect of three freight systems

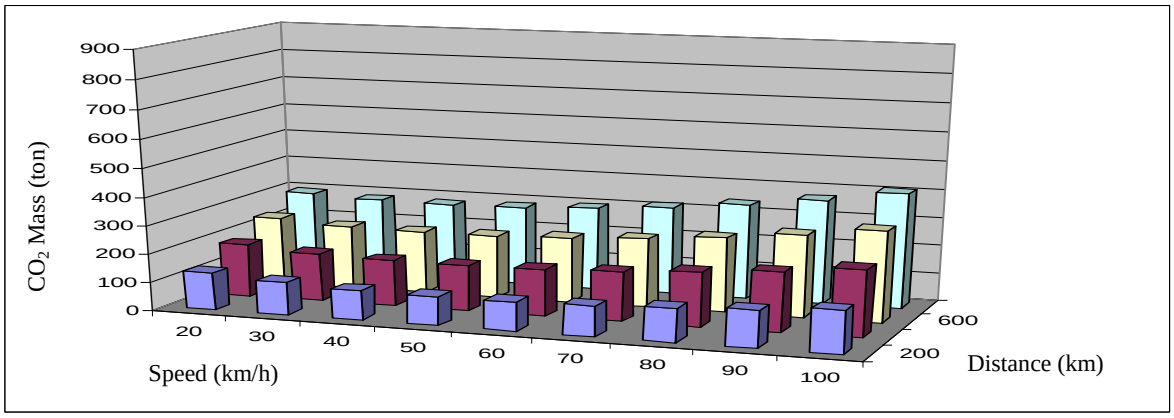
This paper has specified different types of CO_2 mass emitted by truck-only and intermodal systems, and modelled them in the context of door-to-door deliveries. The central question for the numerical example is '*how much CO_2 is emitted if 1,000 TEUs (Twenty Foot Equivalent Units) should move at a given constant speed*'? It is notable that the average speed indicated in this study is the average driving-only speed instead of the average speed. An earlier study assumed 60 km/h for trucks and 40 km/h for trains (Janic, 2007). The average speed in this research is the plausible driving speed (not the total distance divided by total travel time, including delays due to congestion etc.). To compare freight systems with each other, the pre- and end-haulage needs (i.e. drayage) in intermodal systems should be considered. Although the distance of drayage depends on several factors, an average of 50 km might reasonably reflect the market situation in the EU (Janic, 2007). Therefore it is assumed that 100 km of the total transport distance is by truck, leading to the use of truck emission factors for that distance. The total distance travelled by the trucks-only system is assumed to be same as the intermodal freight system. This is an assumption leading to slightly optimistic values for the intermodal systems because drayage might lead to a detour factor >1. The gross weight of a TEU is assumed to be approximately 20 tonnes (i.e. 2.25 tonnes for tare and 17.75 tonnes for load) (Janic, 2007, EC, 2005). Therefore in case of truck-only systems 1,000 trips are needed. Assuming that the trains have three containers per wagon with an average loading factor (i.e. utilisation rate) of 0.7 and 20 wagons per train (Janic, 2007), in case of intermodal systems 25 trips are needed. The average locomotive and wagon weights are approximately 120 tonnes and 24 tonnes respectively, based on the specification of the so called Class 66 locomotives. Thus, the gross weight of a train is 1,340 tonnes, with 600 tonnes empty mass, and 740 tonnes of containers. The EU emission factor for electricity generation (i.e. 127.4 kg/GJ on average in European countries (Lewis et al., 2001)) is used for the crude source of electricity.



(a) CO_2 emissions from truck-only freight systems



(b) CO_2 emissions from intermodal freight systems with diesel powered trains



(c) CO_2 emissions from intermodal freight systems with electric powered trains
(Electricity Source in EU average: nuclear 35%, coal/oil 30%, hydro 14.5%, and gas 9%)

Figure 3.5 Total CO_2 from three systems for 1,000 TEUs

The total mass of CO_2 emitted by trucks under given conditions is estimated for various average speeds (20 km/h to 100 km/h in 10km/h interval). Of course low speeds of 20 – 60 kms are hardly relevant in case of long distance transport. However, they are included to show the impact of speed on emissions. In practice speeds of 60-90 km/h are most relevant. Gradient and temperature are assumed as 0% and 20°C respectively. The mass of CO_2 produced by diesel trucks is definitely proportional to the distance travelled. It is not proportional to the average speed but produces the U-shaped pattern, as shown in Figure 3.5 (a). This means the least amount of CO_2 is emitted at around 60 km/h to 80 km/h. The longer the distance, the more pronounced the U-shape of the function.

For intermodal freight systems with diesel powered- and electric powered locomotives, CO_2 mass is almost proportional to average speed and distance as shown in Figure 3.5(b) and 3.5(c), respectively. Actually, drayage by trucks in intermodal systems is very crucially affecting CO_2 mass in case of relatively short transport distances (i.e. approximately 200km-400km). It is notable that the slopes depicting CO_2 mass in intermodal systems are much gentler than those of truck-only systems. In other words, CO_2 mass from train-based freight systems shows to be less sensitive to speed.

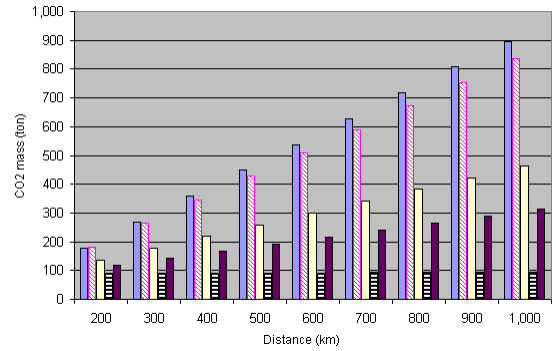
3.5.2 Comparison of CO_2 from freight systems according to the electricity source

The Figure 3.5(c) shows intermodal freight systems with electric powered locomotives, assuming that the percentage of electricity generation is the EU average (i.e. 35 % of nuclear, 30 % coal/oil, 14.5 % of hydro, and 9 % of gas) (Lewis et al., 2001). In addition three scenarios were designed to examine production emissions from different electricity generating sources, and to compare them with emissions from diesel based intermodal system and truck-only systems. The scenarios are based on 100% nuclear power generation dependency, 50% nuclear and 50% coal and oil power generation combined, and 100% coal and oil power generation dependency. As shown in Figures 3.6 (a) to (e), CO_2 emissions for each intermodal system scenario using electric powered trains are estimated assuming the same CO_2 mass per 1,000 TEUs as used in the previous numerical example, and are compared with the truck-only and diesel powered train scenarios. The truck-only system always emits more CO_2 than diesel powered intermodal systems. However, unexpectedly, from 60 km/h on the truck-only system does nor or hardly emit more than electric powered intermodal system assumed 100% usage of coal/oil. Thus, in case of a large share of coal / oil as the input for a power plant the intermodal freight system does not necessarily have lower CO_2 emission than a truck-only system. Note that there are some countries in the EU which depend on coal and oil for generating more than 50% of their electricity needs: Greece 91.7%, Denmark 89.3%, Spain 61.2%, Italy 58%, UK 55.4%, and Ireland 55.4% (Lewis et al., 2001). If the electricity provided to electric locomotives comes purely from nuclear power plants or from 50% nuclear and 50% coal/oil plants, then intermodal freight systems using electric locomotives emit much less CO_2 than truck-only systems. Actually, the average CO_2 emission from electric powered intermodal system in EU countries is nearly the same as in the case of '50% nuclear and 50% coal and oil'.

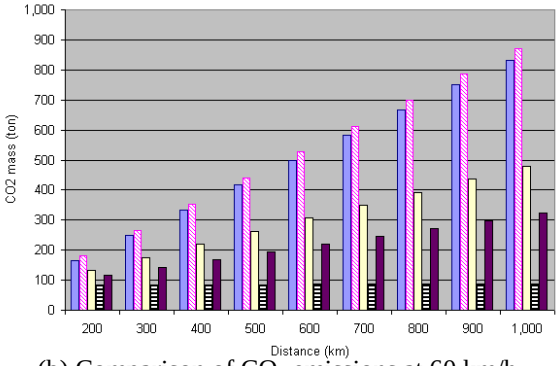
3.6 Conclusion and further research

Since earlier studies have only considered CO_2 mass from individual freight modes, it has not been clarified that intermodal systems emits CO_2 mass less than truck-only systems. The factors influencing emissions for both freight systems are identified. Through the numerical example, the CO_2 mass emitted from three kinds of freight systems are estimated at various average speeds from 100km to 1,000km. In addition, in comparing the CO_2 mass from truck-only systems with one from intermodal systems based on three power sources scenarios, the results partially answer the initial question - *"Are intermodal freight systems really more sustainable than truck-only freight systems in terms of CO_2 emissions?"* - in that the use of electric powered trains does not always result in lower CO_2 emissions, depending on regional/national power generation conditions. That is because some countries in EU are still mostly dependent on coal/oil for electricity generation. This result can offer input for short- or medium-term strategies for controlling CO_2 in EU countries. E.g. the results show in which

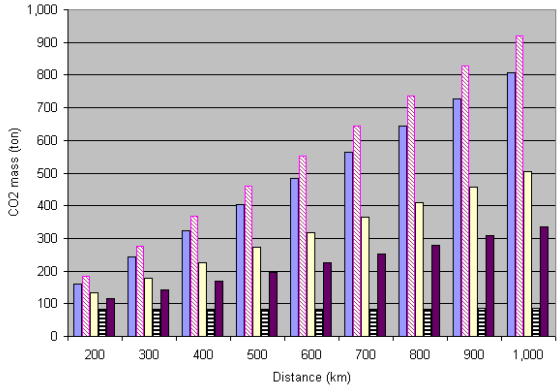
cases pricing policies could be introduced to encourage shift to intermodal transport resulting in lower CO_2 emissions, for example depending on electricity production.



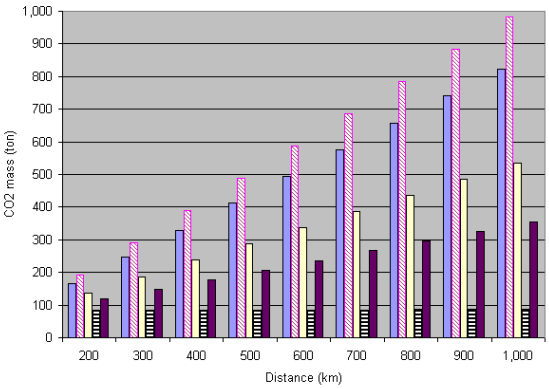
(a) Comparison of CO_2 emissions at 50 km/h



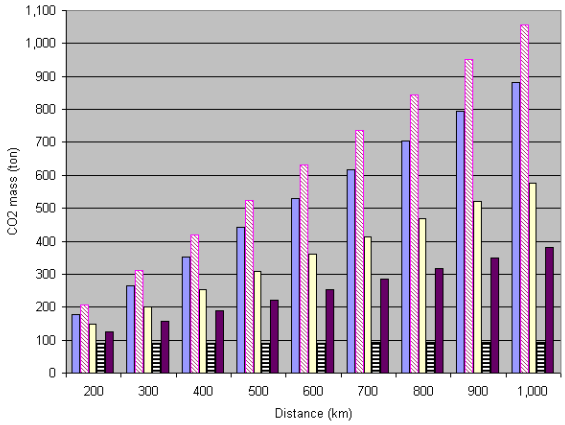
(b) Comparison of CO_2 emissions at 60 km/h



(c) Comparison of CO_2 emissions at 70 km/h



(d) Comparison of CO_2 emissions at 80 km/h



(e) Comparison of CO_2 emissions at 90 km/h

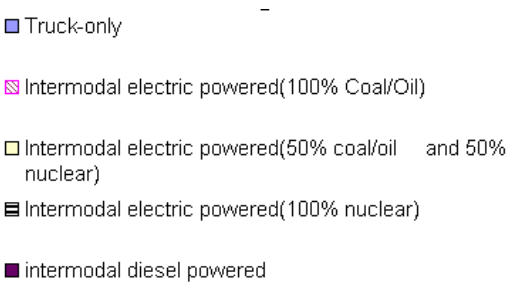


Figure 3.6 CO_2 mass from truck-only, diesel powered locomotive based intermodal system, electric powered locomotive based intermodal system with three electricity power scenarios

This research is a first step to assess CO_2 emissions of intermodal freight transport versus truck only systems. Following Van Wee et al. (2005) we here address three challenges for further improvements. First, the average distance of drayage used in the numerical example (i.e. 50km per one-end) was more or less arbitrary although it reflects logistics market situation in Europe (Janic, 2007). Especially, if drayage distance is greater than the long-

haulage in the case of comparison between the truck-only system and the diesel powered intermodal system, the increased drayage distance can be problematic. In the case of comparison between the truck-only system and the electric powered intermodal system, the increased drayage distance can cause that the emission by the electric-powered intermodal system based on 100% of coal/oil is even worse than one by the truck-only system at 50km/h as shown in Figure 3.6(a). The second challenges relates to the lack of consideration of empty back haul rate (i.e. loading factor for returning). For the truck-only system, it is simple to be considered while another research framework should be needed to analysis the empty back hauls in intermodal system. It is advised to included empty back hauls more sophisticated in the future. Thirdly the total distance travelled by truck-only system and intermodal system might differ. Since the geographical distance through road network is not same as the distance through rail network, different detour factor (larger for rail than for road) could be used. Finally, as already announced in the introduction, it is recommended to develop a comprehensive framework for assessing the emissions of vehicle including the stage of scrapping, and including terminal construction. This would probably be a full research project in itself.

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Chapter 4
Toward a better methodology for assessing CO_2 emissions for intermodal and truck-only freight systems: a European case study

Nam Seok Kim and Bert Van Wee
Delft University of Technology

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Abstract

This study aims to examine whether the intermodal freight system really emits less CO_2 than its road-based counterpart. Three types of freight systems are considered: a truck-only system, a rail-based intermodal freight system, and a vessel (short sea)-based intermodal freight system. Furthermore, nine scenarios are designed in terms of four different power sources for an electrified rail-based intermodal system and three different sized ships for a vessel-based intermodal system. The results show that if the source of electricity and the size of vessel are considered, intermodal systems do not always emit less CO_2 than truck-only systems.

4.1 Introduction

Intermodal freight systems have been recognized as alternative shipping methods that have the potential to be more economical and emit fewer greenhouse gases than unimodal (i.e., truck-only) freight systems. However, "Trends in the Transport Sector" (2006), a report based on statistics published by the European Commission, shows that the share of road usage increased (+33.9 percent) between 1980 and 2004, expressed in tonne kilometres. Concerns about greenhouse gases as well as air pollution have been raised as road usage has increased (EC, 1999, 2000, 2003). Due to the increased awareness and concerns, international organisations and national and local governments have promoted the need to increase the share of non-road freight modes that emit less CO_2 in general (EC, 2002). However, there is scepticism about whether the intermodal freight system really emits less CO_2.

Several emission models for individual transport modes have been developed. Despite some differences in details, the fundamental structures are similar. The amount of emissions is a function of vehicle specification (dominant determinants being manufactured year and engine type or emissions control equipment, yearly mileage, and the size of vehicle), operations related factors (distance travelled, speed cruised, weight loaded or utilisation factors, empty haul rate, the distribution of different-sized loading units, driving cycle characteristics including variables such as the number of stops), and other minor factors (slope/curve of infrastructure, and ambient temperature). The importance of these factors varies between modes. For example, the source of fuel (diesel or electricity) is only very important for rail transportation while for barges the impact of the size of vessel on fuel use is important. The impact of transport distances on emissions is more important for road transport than for rail and waterborne vessels.

This study treats two large issues on CO_2 emissions from transport: (1) the method and assumptions to assess CO_2 emissions from individual modes such as truck, rail, and waterborne vessel; (2) detailed issues related to intermodal systems. In case of the CO_2 emissions assessment method for individual modes, several previous studies resulted in the gram of CO_2 emissions per tonne-km. McKinnon and Piecyk (2010) and Van Essen et al. (2009) recently synthesized them (Appendix 4A). On the one hand, the reported gram of CO_2 emissions per tonne-km was assessed under numerous assumptions. It would be better to realise those assumptions and present either a range of emissions or an emissions function instead of a simple constant per tonne-km based CO_2 factor. Finally, it will be demonstrated that those simple CO_2 factors (i.e., gram of CO_2 emissions per tonne-km) are valid only under a particular assumptions. On the other hand, in the case of intermodal freight systems (including not only the modes involved but also transhipments), additional issues need to be taken into consideration such as the difference of geographical scope between truck trips and rail trips, terminal operation, and the impact of drayage distance. Specifically, this study identified six issues that need to be included but which are quite often underestimated by researchers when CO_2 emissions for intermodal transport are assessed and compared with truck-only systems. Some of these issues also are relevant to calculate emissions of individual transport modes, but become of particular relevance when comparing intermodal transport with single mode transport. First, earlier studies focused on emissions from unimodal freight transport systems based on door-to-door delivery (for truck systems) or terminal-to-terminal delivery (for rail systems). However, for intermodal systems, emissions from terminal-to-terminal by long-haul and emissions from origin/destination to terminals and vice versa

should be taken into account separately. This geographical distinction between truck-only and intermodal systems—one of the main focuses in this study—can cause serious miscalculation when considering emissions from different transport systems. Second, emissions from terminal operations (e.g., from the electricity consumption of electric cranes and lighting, from forklifts and from reach stackers) have not been included. Third, the production emissions of fuel, which can affect the global environment in the medium-term, often have been ignored. The fourth issue is the consideration of sources of electricity related to electric-powered trains and terminal operations. Local electricity supply is rarely considered. The fifth issue is the loss of electricity due to transmission from the power plant to locations of use (i.e., railway and terminal). The sixth issue is ignoring a diversity of loading units with different weights and sizes. This issue in particular should be considered, since intermodal systems only allow standardized loading units. The seventh issue is the capacity of vehicles/vessels and the (often related) utilization factors. Needless to say, two 500-TEU vessels are more efficient than five 200-TEU vessels, for example. These seven issues should be specified and included in the CO_2 emissions assessment process.

The European Commission (EC) (1999) overcame the third issue (the production emissions of fuel) by developing a comprehensive model to assess various emissions from different types of transport modes. This model, Methodology for Calculating Transport Emissions and Energy Consumption (MEET), also provided a background against which to consider the effects of different sources of electricity at the country level, which partially overcomes the fourth issue. However, although the report was very useful for assessing emissions from each individual transport mode, it was not applicable for the combination of freight transport modes, the so-called intermodal (or multimodal) freight system. Therefore, the EC research evolved to assess emissions from whole transport systems instead of individual transport modes, and to compare each at the level of the freight system. The new model based on the MEET was called REal COst Reduction of Door-to-door Intermodal Transport (RECORDIT) (EC, 2000). Environmental impact was estimated more accurately under the new model, because the study limited the geographical boundary at the corridor level (i.e., several factors such as distance travelled and average speed were observed in a more realistic way for certain routes). RECORDIT completely surmounted the first and third issues identified by this study. It also partially improved the second and sixth issues. However, the focus of RECORDIT was to estimate the full cost, internalizing the external costs in monetary terms. Accordingly, the eventual focus was the comparison of the final full cost between different freight transport systems rather than the estimation and comparison of emissions. In addition, the fourth and fifth issues were not addressed in this report. Nevertheless, RECORDIT included vast amounts of information useful for freight emissions assessment.

Based on these two EC projects, Kim and Van Wee (2009) summarized data needs, methodologies, and research frameworks for assessing CO_2 emissions from freight transport systems, including intermodal and truck-only systems in terms of type of fuel sources (i.e., diesel and electricity). However, they did not consider CO_2 emissions from waterborne transports. In addition, since their focus was to develop a framework and to identify data needs, the model was not fully demonstrated but simply presented at the conceptual level using several assumptions. Another EC project, Pilot Actions for Combined Transport (PACT) (EC, 2003), which is mainly based on the work of the Institute for Energy and Environmental Research (IFEU) and the Association for Study of Combined Transport (SGKV) (2001, 2002), demonstrated that the environmental friendliness of intermodal freight systems in terms of CO_2 depends on the study area and boundary. IFEU and SGKV (2001)

paid special attention to the first issue. They compared several case studies that considered the third, fourth, and sixth issues. The most recent European Commission project on the emission assessment from transport, Regional Action for Logistical Integration of Shipping across Europe (REALISE), concentrated on the environmental impact of transports. This project showed a clear comparison between truck-only freight systems and intermodal freight systems, satisfying the second and third issues mentioned above but missing the production emissions issues (Kamp, Lloyd, and Vassallo, 2005).

The current study aims to include all the issues treated in the previous two studies (all the issues mentioned above except the last), develop a model assessing CO_2 emissions for truck-only systems and rail-based and short sea-based intermodal freight systems, and finally, compare CO_2 emissions generated by those systems in a given case area. In addition, scenarios for electricity generation are considered. The remainder of this paper is organized as follows. Section 2 presents intermodal transport geography, introduces the semi-Life Cycle Assessment (LCA) model and briefly describes the methodology and data for both individual transport modes and combined freight systems. Section 3 presents a case study. By combining each process (i.e., drayage by trucks, transhipments at the terminal, and long-haulage) into three freight systems with consideration of four electricity generation options for rail-based intermodal systems, nine scenarios are designed: a truck-only system (TO), a diesel powered train-based intermodal system (DI), four electric powered train-based intermodal systems (EI 1, 2, 3, and 4), and three different size vessel-based intermodal systems (VI 1, 2, and 3). Section 4 presents a sensitivity analyses for four issues: drayage distance, average cruising speed, the ratio of 20ft/40ft containers, and number of flat cars for rail options (i.e., impact of shorter/longer trains). In Section 5, we attempt to answer the question, “Does the rail-based/vessel-based intermodal freight system really emit less CO_2 one than the truck-only freight system?” and summarize findings, limitations and topics for future study.

4.2 Methodology

4.2.1 Intermodal transport geography

The ECMT (European Conference of Ministers of Transport) defines an intermodal freight system as follows: “Intermodal transport is the movement of goods (in one and the same loading unit or vehicle), which uses successfully several modes of transport without handling of the goods themselves in transshipment between the modes” (ECMT, 1998; Janic and Reggiani, 2001; Bontekoning, Macharis, and Trip, 2004). Figure 4.1 represents a geographic distinction of both intermodal freight systems and truck-only systems based on a door-to-door container trip. Intermodal freight systems include three main stages: drayage, terminal operation (transhipment), and long-hauling. Drayage is the stage for collection and distribution. The transhipment process at an intermodal terminal is loading the collected loading units using trucks in non-road modes and vice versa. Long-hauling, which gives the intermodal freight systems a great advantage through economies of scale, is the movement between intermodal terminals. Therefore, the door-to-door distance in an intermodal system for container movement is different from the truck-only system. Van Wee et al. (2005) suggested detour/circuitry factors to overcome this geographic difference in general. However, since detour factors depend on the study area, the distance travelled by different modes should be based on the transport networks in the study area to estimate more accurate distances.

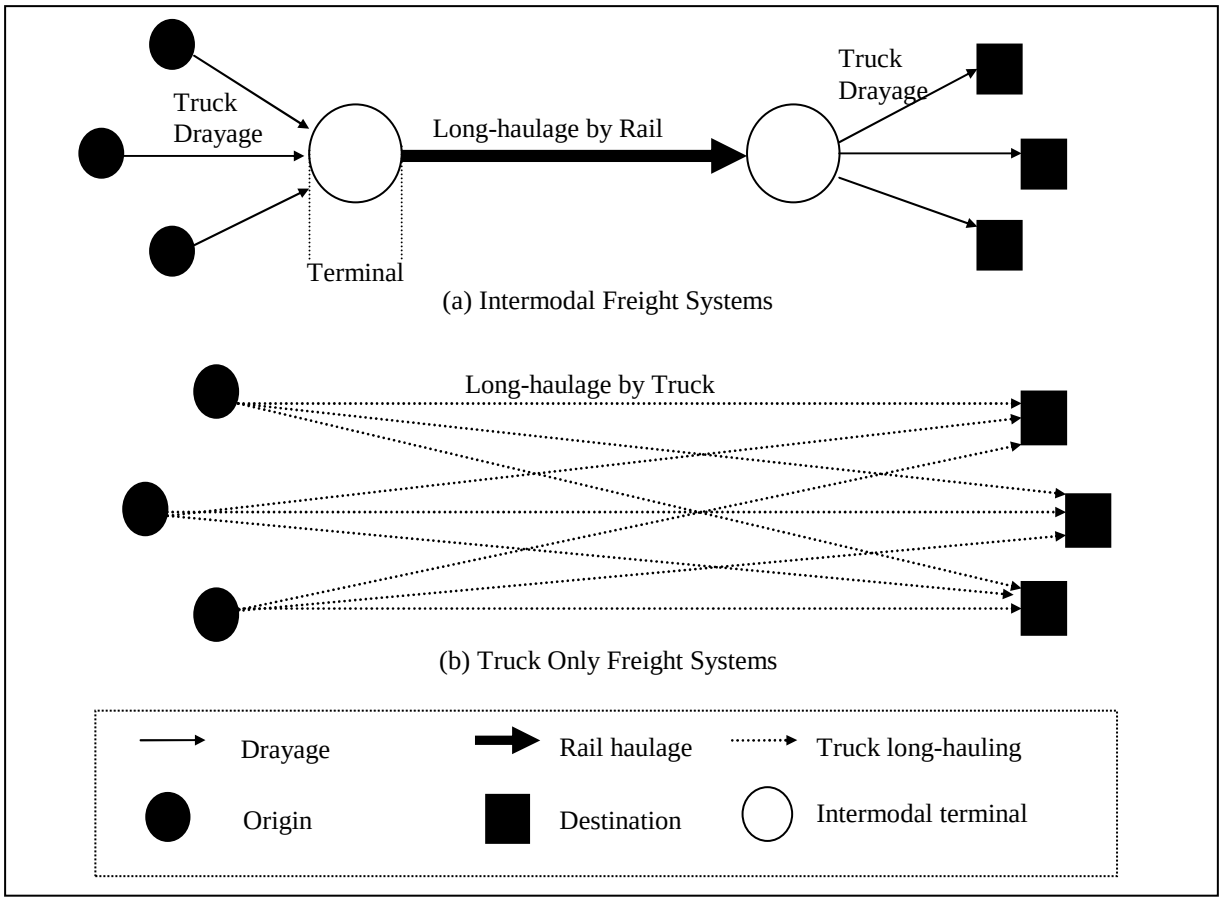

Figure 4.1 Conceptualisation of intermodal freight transport systems and truck-only systems (Source: EC (1998) and Kim and Van Wee (2009))

As discussed previously, the IFEU (Institute for Energy and Environmental Research) and the SGKV (Association for Study of Combined Transport) attempted to clarify this issue by using pilot studies with different transport networks (i.e., road and railway). As shown in Figure 4.2, they concluded that the total intermodal distance will always be longer than for a truck-only system, except when the shippers/receivers and two terminals are on the same line (IFEU and SGKV, 2001, 2002). One method to simplify this issue is to assume the drayage distance as a constant (e.g., 50 km of drayage distance at each end (Rutten, 1995; Janic, 2007)), which is only taken into account in intermodal systems if the specific locations of origin and destination are unknown.

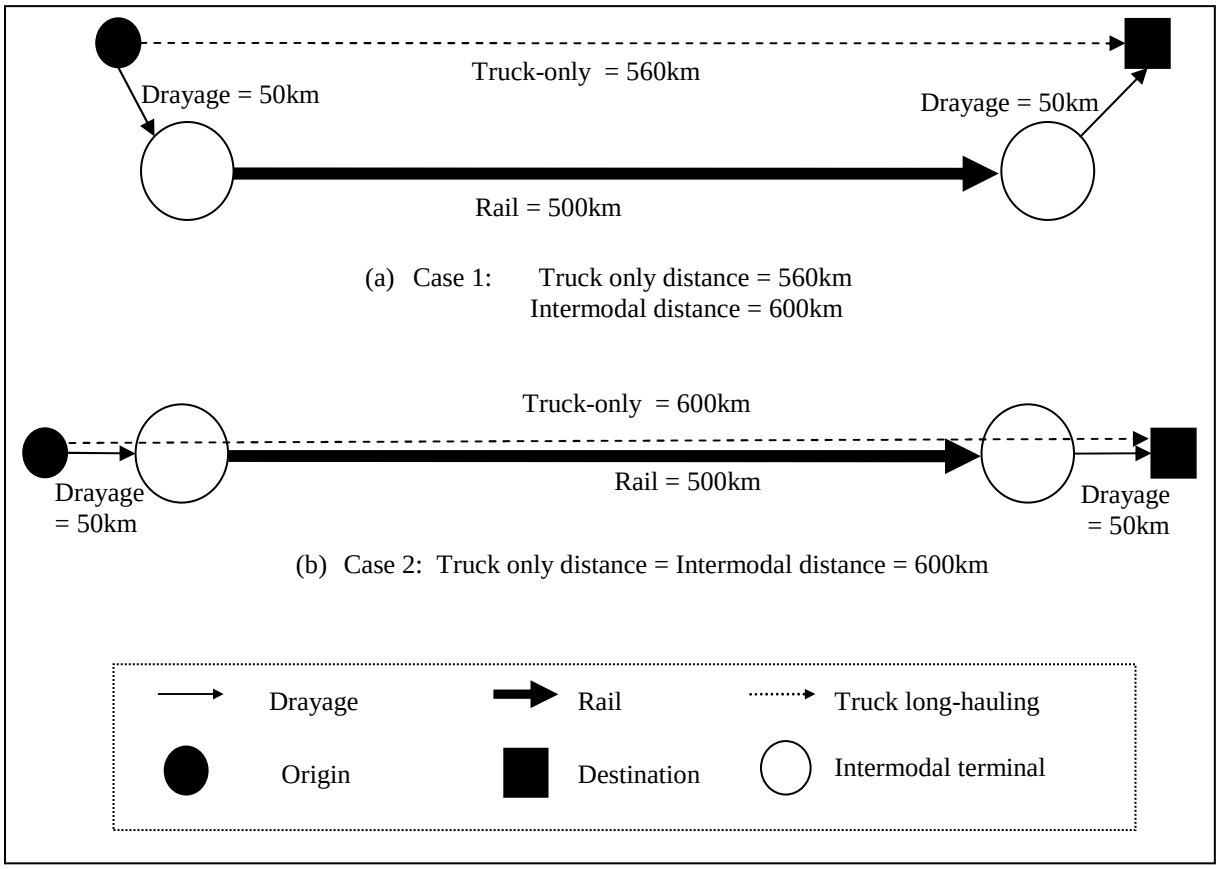

Figure 4.2 Distance of intermodal freight system (reproduction based on IFEU and SGKV, (2001))

4.2.2 Semi-life cycle assessment

In this research, Life Cycle Assessment (LCA) modelling is partially used to estimate specific transportation emissions, making comparisons at the system level possible. In recent years, increasing attention has been paid to this technique in the field of energy consumption and in emissions from freight transportation (Spielmann and Scholz, 2005; Facanha and Horvath, 2006). However, since LCA is an attempt to assess environmentally harmful effects over a long period, it is not always appropriate in short- or medium-term analysis because the life cycles of infrastructures used in freight systems are not comparable. In addition, emissions from the infrastructure do not affect the environment much in the short- and medium-term. However, including emissions related to manufacturing/scrapping vehicles and constructing/deconstructing/ maintaining the infrastructure is definitely meaningful in examining long-term effects.

Since we focus on short- and medium-term analysis, this study includes emissions from exhaust and the production of fuel, but excludes emissions from the construction of infrastructure and vehicle manufacturing, defining the process as Semi-LCA (Kim and Van Wee, 2009) which is used later in the case study. Semi-LCA is applicable in the short- or medium-term when two freight transport systems are compared using the same criteria. For example, since electric trains do not emit CO_2 during operations at the vehicle level, the emissions produced cannot be compared with other modes. Instead, emissions from the generation of electricity, the so-called “production emissions,” need to be considered.

Specifically, emissions from extracting, refining, and transporting crude oil are included in production emissions (EC, 1999; Facanha and Horvath, 2006; Kim and Van Wee, 2009).

4.2.3 Top-down and bottom-up approach

Generally, two methods of estimating emissions from transports are used in current practice: top-down and bottom-up (Van Wee , Janse, and Van den brink, 2005). The former uses aggregate statistics about emissions as well as other factors influenced such as freight demand for and distribution of type of vehicles while the latter focuses on examining emissions by using chemistry or physics principles. The latter is more appropriate for examining the impact of individual determinants on emission levels while the former is more appropriate for practical application. The two methods are complementary. For the purpose of this research, the top-down approach is used mainly, but some details (such as emission factors) are obtained by bottom-up methods. In other words, the basic equation for estimating emissions from transport using the top-down approach in this study is a function of transport activity profiles and fuel consumption that are obtained/assumed by the bottom-up approach (EC, 1999).

Our combined approach is based on the MEET project (EC, 1999), which is used as the main methodology to assess CO_2 emissions in this study. Once the inputs (e.g., demand, fuel, distance travelled, load weight, speed, gradient, ambient temperature, etc.) and outputs (e.g., mass of CO_2) are identified, the relationship between these inputs and outputs is clarified using regression equations estimated by the MEET project (EC, 1999). Then separate estimates are made for the CO_2 mass of four different freight modes (truck, diesel locomotive, electric locomotive, and vessel). Also, as mentioned previously (Subsection 2.2), the scope of the production emissions is limited to those included in the Semi-LCA (i.e., all emissions from fuel extraction, refining, and transportation of fuel). Specifically, in order to assess such production emissions properly, the fuel consumption should be estimated in advance. According to the Carbon Balanced Method, the fuel consumption is estimated based on exhaust CO_2 emissions and other emissions such as CO (carbon monoxide), HC (hydrocarbons; also referred to as volatile organic compounds (VOC)), and PM (particulate matter) (EC, 1999). Specifically, it is presented in Eq. (1) as follows (EC, 1999):

$$[FUEL] = (12 + r_1) \times \left(\frac{[CO_2]}{44} + \frac{[CO]}{28} + \frac{[HC]}{(12 + r_2)} + \frac{a[PM]}{12} \right) \quad (1)$$

Where:
[FUEL] is the mass of fuel
[CO_2], [CO], [HC], and [PM] are the masses of direct (exhaust) pollutants
r_1 and r_2 are the hydrogen to carbon ratios of the fuel and HC emissions respectively (r_1 and r_2 are 2.0 for diesel (EC, 1999))
a is the proportion of carbon in the PM emissions (a=1 is used in EC (1999))

Once the amount of fuel consumed is estimated for diesel-dependent modes (trucks, diesel locomotive powered trains, and waterborne vessels), production emissions are estimated by a pre-defined factor: how much CO_2 emissions are generated when 1 kg. of diesel is extracted, refined, and transported (before it is used for freight transportation): 6.96 kg. of CO_2 /GJ.

For trucks, direct (exhaust) emissions consist of hot and cold emissions. The amount of the direct emission is used as the input for the carbon balance method (i.e., fuel consumed should be balanced with emissions generation) to estimate fuel (EC, 1999). Then, production emissions are considered, including the emissions generated during the processes of extraction, crude oil transportation, and refining. Finally, by adding the two types of emissions, the total emissions from trucks are estimated.

For intermodal freight systems, there are three processes (drayage, long-hauling, and terminal operation), each resulting in a different extent of emissions (direct and production). In the long-haulage process, three types of long-hauling modes are considered: diesel powered train, electric powered train, and vessel (diesel based). A description of the vessel-based intermodal system is omitted since it is similar to the diesel powered rail-based intermodal system.
Electrified vehicles generally emit pollutants in different ways than diesel vehicles. That is, direct emissions (those at the vehicle level) do not exist. Instead, emissions are at the power plant level (production emissions). It is notable that the emission factor of a truck-only system is also used in the drayage stage of intermodal freight systems. Furthermore, for intermodal systems using electrified trains, some power source scenarios are considered to estimate production emission rates (e.g., 100 percent nuclear, 100 percent coal/oil, and 50 percent nuclear and 50 percent coal and oil). For detailed mathematical/technical methodologies to assess CO_2 emissions, we refer to EC (1999) and Kim and Van Wee (2009).

4.3 Case study: a corridor between Western and Eastern Europe

The following case study aims to test the emission models formulated in the previous section. Nine scenarios, including combinations of freight mode, fuel/energy sources, and size of waterborne vessels, were designed to assess the CO_2 emitted from freight systems and to compare each at the freight system level. The assumptions of the case study and characteristics of the study area are described. Then, CO_2 emissions corresponding to the nine scenarios are assessed and compared.

4.3.1 Assumptions and characteristics of three freight systems in the study area

The CO_2 emissions assessments model for different freight systems are applied to three corresponding routes in a Western-Eastern Europe corridor between Rotterdam in the Netherlands and Gdansk in Poland. This corridor was one of the major freight corridors between Western and Eastern Europe (Walker et al., 2004). In the port of Rotterdam, the largest container hub in Western Europe, containers are collected from neighbour countries (Belgium, Northern France, Western Germany, and Luxembourg) and distributed to destination hubs. In this study, the port of Gdansk was selected as one of the most feasible partners of the port of Rotterdam in Eastern Europe to meet the increasing container demand between Western and Eastern Europe. This subsection briefly describes some necessary inputs and the methods used to obtain them.

Distances
Fuel consumption and CO_2 emissions are distance-dependent. In order to accurately estimate the distance travelled, the shortest path finding technique is used in Network Analyst, one of the extension of ArcGIS (Geographic Information System). Figure 4.3 visualizes a primary road network excluding a lower level of roads (e.g., local and inter-city roads). A major rail

network excluding passenger-only rail lines and the new short-sea route from Rotterdam to Gdansk are used to estimate the distances for rail-based and vessel-based intermodal systems (Rotterdam, 2007), respectively.

Speed and travel time

CO_2 emissions from transport are highly correlated to speed (Kim and Van Wee, 2009). In addition, the speed of a transport mode determines travel time. Since travel time is one of the most crucial factors in freight mode choice, it should at least be mentioned to justify this case study. The issue of speed is specified first and then travel time is discussed. Two types of speed are considered: average and average cruising. Average speed is defined as the total distance per total travel time, and is used to estimate the total travel time. Average cruising speed is the average driving-only speed, which is used to assess CO_2 emissions in this study. Considering average speed shows the feasibility of this case study even though it is not relevant for the assessment of CO_2 emissions. Therefore, it is worth taking travel time into account, assuming a reasonable average cruising speed and time losses for three freight systems. With reference to speed limits and technical allowances along the corridor, we assume that cruising speeds for truck-only systems (long-haul), freight trains, and vessels are 90km/h, 90km/h and 20km/h (about 10.5 knots), respectively. The main time loss for both rail and vessel intermodal freight systems is during transhipment (loading/unloading at ports or terminals). In addition, the rail intermodal system requires 30 minutes to 1 hour to change locomotives at some borders (EC, 2006). The truck-only system loses time for truck drivers' resting/sleeping time because drivers must follow European regulations. More specifically, for the truck-only system, assuming 20 hours for driving (10 hours/day as per European regulations) and 24 hours for sleeping and eating, 34 hours are taken. However, cold and idling emissions are not taken into account in this case study because of their very low share in overall emissions during long-distance transport (in this case, more than 1,000 km) (Kim and Van Wee, 2009). The rail-based intermodal system does not need driver sleeping time, but requires drayage time, transshipment time at the terminal and locomotive changing time at the border (EC, 2000). Assuming a drayage distance for each end of 50km (Rutten, 1995; Janic, 2007; Rotterdam, 2007) and an average speed of 60km/h by local trucks, two extra hours are added. In total, 45 hours are taken from Rotterdam to Gdansk. In the same manner, the total travel time for short sea shipping is an estimated 71 hours. However, if it is assumed that all facilities in the logistics chain run for a certain time (e.g., between 8 a.m. to 5 p.m.), in practice the three freight systems have similar travel days although the truck-only system seems to be faster than the other systems. Therefore, intermodal freight systems, at least in this case study, are plausible in terms of economic aspects because they are not expensive and are not crucially slower than truck-only systems.

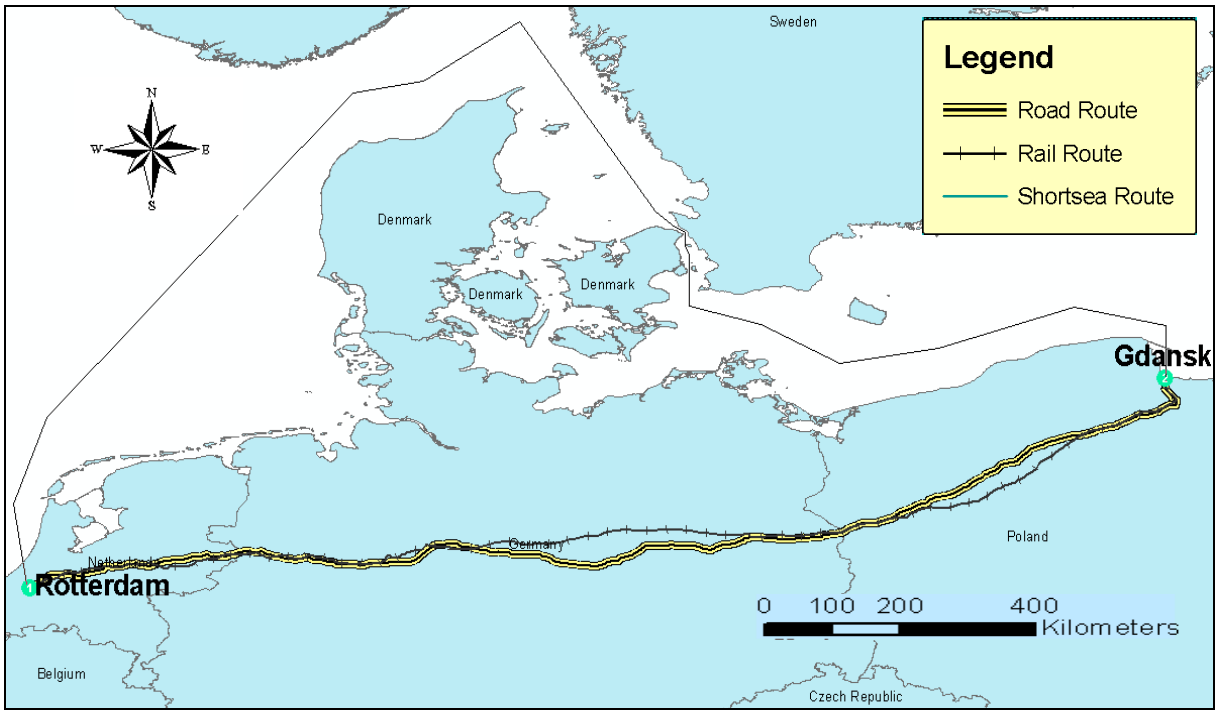

Figure 4.3 Study area and routes for different freight systems

Demand and Loading UnitsThere are several ways to express freight volumes: tonne-km, vehicle-km, or LU (loading units)-km. When the intermodal freight system is compared with the truck-only system, the LU-km seems to be the most appropriate because the units of measurement at the terminal are mostly indicated in terms of LU (e.g., a tonne of CO_2/TEU, €/40 foot container (EC, 2000)). However, the distribution of several types of containers/swap bodies make the loading unit issue more complicated. This issue becomes crucial when intermodal freight systems are compared with truck-only systems. For example, a long-distance truck mostly loads one container regardless of its size. For trains and vessels, one 40-foot container occupies twice the space of the 20-foot containers. This is the main reason to specify the distribution of some types of containers. This case study considers two types of containers: 20-foot and 40-foot.

In 2008 in Rotterdam, 20 ft.-containers had approximately 33 percent of the total container throughput (expressed in TEU), the share of 40 ft.-containers was approximately 67 percent (Port of Rotterdam, 2008). In other words, if we consider of each 1,000 containers, nearly 500 are 20 ft. containers and 500 are 40 ft. containers (resulting in 1,500 TEU in total). The reason to specify the size of container instead of using the unit of TEU is the non-linear relationship between container size and weight. The average gross weight (including tare weight) of a 20-foot container is 14.3 tonne, while the value for a 40-foot container is 22.2 tonne (EC, 2000). In other words, the doubled size of a 40-foot container results in less than double the weight and less than twice the emissions. The impact of the composition of different sized containers on CO_2 emissions will be examined in the sensitivity analyses in the next section. Also, 20 ft. and 40 ft. containers are regarded as Type C and Type A swap bodies, respectively (EC, 2000).

Capacity and loading factors

We assume that the train length is 550 m, allowing 22 wagons per trip. Accordingly, this study assumes that 50 TEUs can be moved at one time at maximum. We assume that three different-sized short sea shipping vessels are used: 200-, 500-, and 800-TEU vessels. Loading

factors for the truck-only system, rail system, and vessel system are assumed as 1.0, 0.75, and 0.75, respectively. The loading factor for the truck-only system can be assumed because a truck can carry at most one container regardless of the type of the loading units, as discussed previously. For the loading units for rail and short-sea shipping, RECORDIT was consulted (EC, 2000). Inputs in terms of freight systems are summarized in Table 4.1.

Table 4.1 Comparison of characteristics of three freight systems in the study area

	Fuel	Distance (km)	Average cruising speed (km/h)	Average speed (km/h)	Travel time (Hours)	Capacity (Maximum)	Loading factor
Truck-only system (TO)	Diesel	1146	90	60	34	One 40 ft. container or two 20 ft. containers	1.0
Diesel powered rail-based intermodal system (DI)	Diesel	1130 (long-haulage) + 100 (drayage by trucks) = 1230	90 for DI and 60 for drayage	50 for DI and 50 for drayage	45	75 TEU per trip	0.75
Electric powered rail- based intermodal system (EI)	Electricity		90 for EI and 60 for drayage	50 for EI and 50 for drayage	45	75 TEU per trip	0.75
Short sea-based intermodal system (SI)	Diesel	2700 (long-haulage) + 100 (drayage by trucks) = 2800	20km/h for SI and 60 km/h for drayage	20km/h for SI and 50 km/h for drayage	71	200-/500-/1,000-TEU per trip	0.75

The central question for the case study is how much CO_2 is emitted if 1,500 TEU (500 20 ft. containers and 500 40 ft. containers) move from places around Rotterdam (from distances of at most 50 km) to places around Gdansk (up to 50 km)? This is more specific than the question asked in the beginning of this study, whether the intermodal freight system really emits less CO_2 than the truck-only freight system. Using several assumptions in terms of demand, vehicle/vessel specification, and travel characteristics, the number of trips for each system can be estimated. Using this assumption, 1,000 truck-only trips are needed for the 1,000 containers. Specifically, 500 20 ft. trucks and 500 40 ft. trucks should be used. For rail-based intermodal freight transport, assuming that the trains have one 20 ft. container and one 40 ft. container per wagon with an average loading factor of 0.75 and 22 wagons per train, 30 trips are needed (i.e., 50 TEU per train). The average locomotive and wagon weights are 120 and 21.5 tonnes respectively, based on the specifications of the so-called “Class 66” locomotives (Kentrail, 2008). Therefore, the gross weight of a train is approximately 1,400 tonnes, with 600 tonnes of empty mass and 600 tonnes of containers (i.e., 14.3 22+22.2 22) assuming it is fully loaded (loading factor=1.0). For the vessel-based short sea intermodal freight transport system, if a 200-TEU vessel with 0.75 of loading factor would be used for the short sea route, 10 trips are needed to ship 1,500 TEU (500 TEU + 500 FEU). If a 500-TEU vessel and a 1,000-TEU vessel with the same loading factor (0.75) were operated, four trips and two trips are required respectively.

4.3.2 Electricity scenarios and results

Nine scenarios were designed to examine direct/production emissions in terms of the main long-hauling/drayage transport modes, sources of electricity, and size of waterborne vessel, as

shown in Table 4.2. The scenarios for electricity generation are based on 100 percent nuclear power generation dependency, 50 percent nuclear, 50 percent coal and oil power generation combined, 100 percent coal and oil power generation dependency, and European average. Note that for the production of electricity used at terminals we assume the European average of the fuel used.

Table 4.2 Nine Scenarios

	Freight Systems	Electricity Scenarios	Vehicle Capacity
Alt 1	Truck-only systems (TO)	N/A	1 - 2 TEU
Alt 2	Diesel powered train intermodal systems (DI)	N/A	75 TEU
Alt 3	Electric powered train intermodal systems (EI 1 to 4)	EI-1: EU average: 35 % nuclear, 30 % coal/oil, 14.5 % hydro, and 9 % gas (Lewis, et al, 2001)	75 TEU
Alt 4		EI-2: 100% coal/oil	
Alt 5		EI-3: 100% nuclear	
Alt 6		EI-4: 50% coal/oil, 50% nuclear	
Alt 7	Short sea-based intermodal systems (SI 1 to 3)	N/A	SI-1: 200 TEU
Alt 8			SI -2: 500 TEU
Alt 9			SI -3: 1,000 TEU

The CO_2 emissions for the nine scenarios are presented in Figure 4.4. Overall, the ranking in terms of the lower mass of CO_2 emissions is Alt5 – Alt 2 – Alt6 – Alt3 – Alt 9 – Alt 4 – Alt 1 – Alt 8 – Alt 7. Before discussing the results we briefly explain a few issues that might lead to a better understanding for Figure 4.4: (1) Alt 1 has neither a drayage nor a terminal operation part; (2) no direct emissions are produced during electrified rail options (Alt 3 – 6); (3) the emissions from both terminal operations and drayage are equal for all intermodal options (Alt 2 – 9); and (4) production emissions in the diesel transport options count for approximately 10 percent of direct emissions (Alt 1, Alt 2, Alt 7–9). The specific findings are summarized as follows. First, the 200-TEU vessel-based intermodal system (Alt 7) emits the highest mass of CO_2, while the short sea-based intermodal system emits the least CO_2 emissions. McKinnon and Piecyk (2010) developed composite emission factors for intermodal combinations. They showed that the small container vessel based intermodal system always emits less CO_2 except in the case of electric rail transport with a high share of nuclear power (as in France): 15.9 grams of CO_2 emissions/tonne-km for short sea-based intermodal systems, 21.2, grams for electrified rail based intermodal systems (EU average), true 10.0 grams for electrified rail-based intermodal systems assuming the power plant average fuel mix of France, and 25.9 gram for the diesel powered rail-based intermodal system, respectively. Our results partly confirm those of McKinnon and Piecyk (2010) . However, they did not consider that short sea-based intermodal transport often has a high detour factor. In our case study, the distance of the main haulage in the case of short sea transport (2,700 km) is more than twice that of

truck-only transport (1,146 km). Our case could be extreme, so we suggest that our results should not be generalized. Nevertheless we think detour factors should be included; because of the sometimes relatively high detour factor for short sea shipping, this mode is not always the least- CO_2 emitting alternative. Second, in general the source of electricity generation is the most important factor— CO_2 emissions of intermodal rail-based transport are lowest with nuclear power generation (Alt 5) and highest with coal and oil (Alt 4). Third, for the CO_2 emissions of short sea intermodal systems, vessel size is the most important factor. Despite the extreme detour of Alt 9, thanks to the larger size of the vessel, it emits less CO_2 than Alt 1. Note that the suitability of vessels depends on network characteristics and the level of demand: the higher the demand, the more likely the use of larger vessels. Fourth, in general, the diesel powered rail-based intermodal system (Alt 2) emits less CO_2 than the electrified rail-based intermodal system, assuming the average combination of electricity power generation (Alt 6).

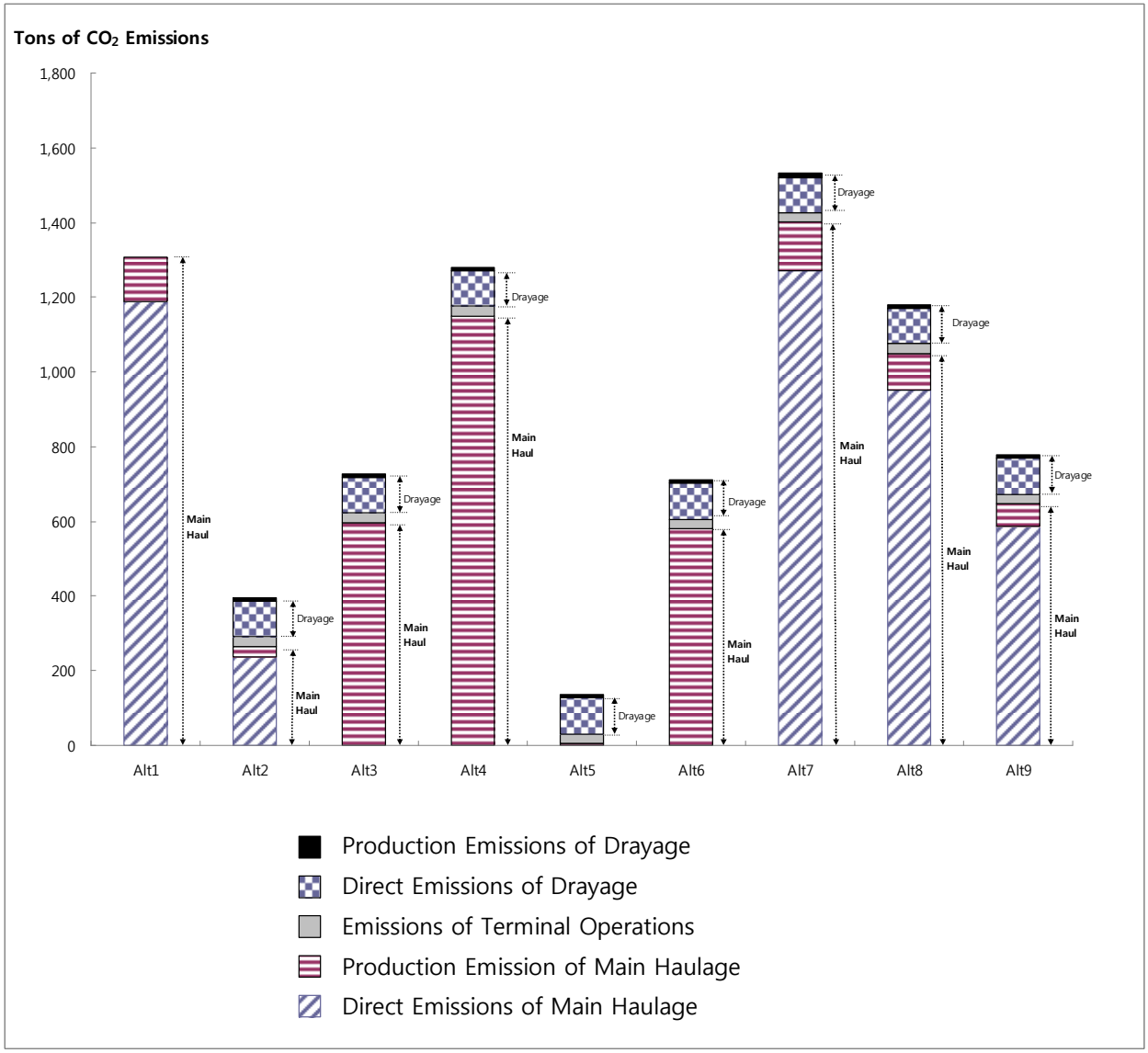

Figure 4.4 Comparison of CO_2 emissions for nine scenarios in tonne

4.4 Sensitivity analyses and discussions

In the previous section, values for some factors were assumed that do not necessarily meet logistics operations in practice. This section presents a sensitivity analysis for those factors shown in Table 4.3.

Table 4.3 Factors in the sensitivity analyses

Factors	The magnitude assumed in this study	The magnitudes examined in sensitivity analysis
Drayage Distance	50km at each end (100km in total)	30km (60km in total), 70km (140km in total)
Average cruising speed (TO)	90km/h	80km/h, 100km/h
# of 20 ft. containers in 1,500 TEU (The remainders is assumed as 40ft. containers)	500 20 ft. containers (accordingly 500 40 ft. containers)	- 210 20 ft. containers (accordingly 645 40ft containers) - 810 20 ft. containers (accordingly 345 40ft. containers)
# of wagons for rail options	22	18, 26

The sensitivity analyses aim to examine the impact of each factor on CO_2 emissions and accordingly to check the change of the ranking presented in the previous section (the ranking of the base case was Alt5 – Alt 2 – Alt6 – Alt3 – Alt 9 – Alt 8 - Alt 4 – Alt 1 – Alt 7).

4.4.1 Drayage distance

As the drayage distances decreases to max 30 km, there is no change in ranking. The truck-only system has the highest CO_2 emissions, except from Alt 7 (short sea and a high detour factor, 200 TUE ships). When drayage distances increases to max 70 km, there is a minor ranking change: Alt 1 and 4 change, resulting in the order Alt 5 – Alt 2 – Alt6 – Alt3 – Alt 9 – Alt 8 - **Alt 4– Alt 1** – Alt 7. The change is the result of a very small change in CO_2 emissions.

4.4.2 Average cruising speed for truck-only system (TO)

When cruising speed is decreased to 80km/h, approximately 114 tonnes of CO_2 emissions are reduced in Alt1. The consequence is the change of rank between Alt 1 and Alt 4: Alt5 – Alt 2 – Alt6 – Alt3 – Alt 9 – Alt 8 - **Alt 1 – Alt 4** – Alt 7. Assuming a cruising speed of 100km/h, CO_2 emissions increase by 200 tonnes. The effect is quite similar to the case of the decreased drayage distance. Although there is no ranking change, the difference in CO_2 emission quantity between Alt 1 and Alt 7 decreases from 223 in the base case to only 23 tonnes.

4.4.3 The number of 20 ft. containers in 1,500 TEU

Generally speaking a reduction in the share (and the number) of 20 ft. containers results in a reduction in CO_2 emissions because of the reduction in weight. Note that in this test the weight of the load to be transported implicitly is changed as well, so the sensitivity tests do

not assume equal cargo to be transported. If the number of 20 ft. container is reduced from 500 to 210, CO_2 emissions from trucks decreased from 1,308 tonnes to 1,212 tonnes (-96 tonnes). However, in the rail-based intermodal options, the impact is much lower (-14 tonnes in case of Alt 2) because the lower load weight is of much less importance. Figure 4.5 shows feasible distributions of containers over flat car types. Specifically, a feasible distribution over both 20 ft. and 40 ft. containers to flat cars in our base case is as shown in Figure 4.5(a) while the distribution for both sensitivity tests are shown in Figure 4.5(b) and d(c). The changes of ranking in case of the first test 4(b) is: Alt 5 – Alt 2 – Alt 6 – Alt 3 – Alt 9 – Alt 8 - **Alt 1 – Alt 4** – Alt 7. If the number of 20 ft. containers in 1,500 TEU would be 810 (Figure 4.5(c)), there is no change of the ranking.

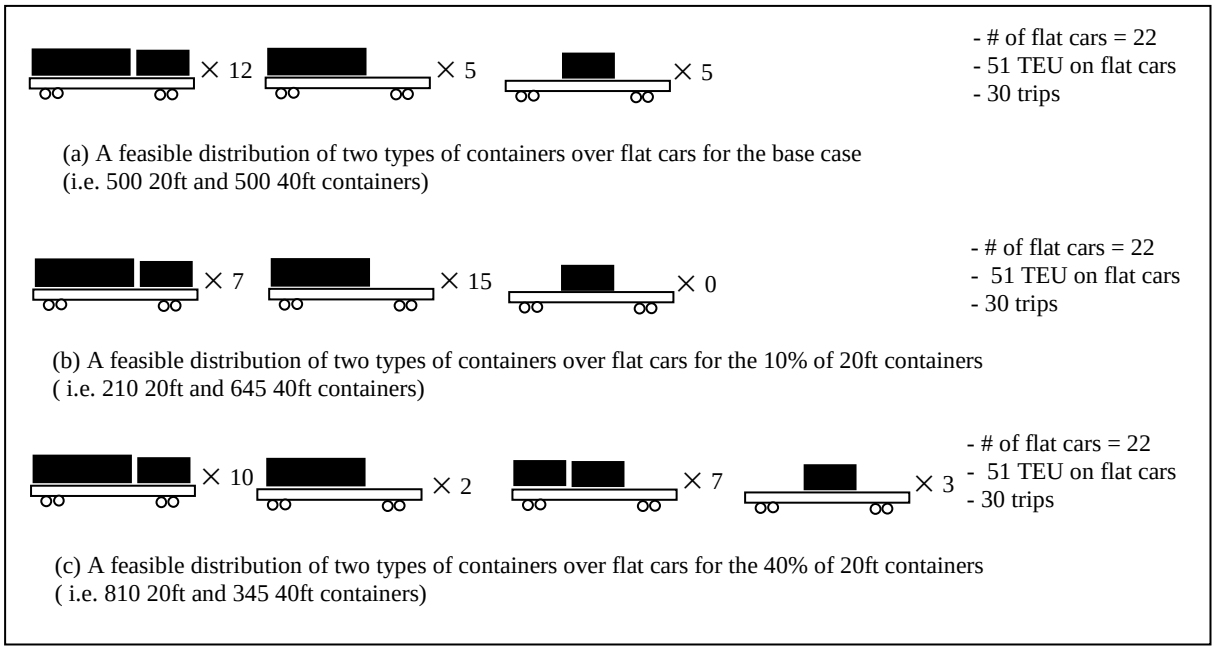

Figure 4.5 Feasible distributions of two types of containers over flat cars for the base case and two alternative cases (10% and 40% of 20ft containers respectively)

4.4.4 The number of flat cars for rail options

When the number of flat cars decreases, rail options emit more CO_2 because then more trips are needed. Longer trains emit less CO_2 per unit. In the case of 18 flat cars (four removed flat cars resulting in six more rail intermodal trips of shorter trains), the ranking is changed to: Alt 5 – Alt 2 – Alt6 – **Alt 9 – Alt 3** –Alt 8 - **Alt 1 – Alt 4** –Alt 7. In the opposite case (i.e., the number of wagons is 26–longer trains) the ranking is changed to: Alt 5 – Alt 2 – Alt 6 – Alt 3 – Alt 9 – **Alt 4 – Alt 8** - Alt 1 – Alt 7.

Our overall conclusion is that changes in the assumptions could lead to changes in the ranking of transport alternatives. As a result, it is risky to draw generally applicable conclusions with respect to CO_2 emissions of options to transport goods.

4.5 Conclusion and future research

Chapter 3 in this dissertation overcame most shortcomings of previous studies (i.e., the five issues out of six discussed previously: the geographical distinction between truck-only and intermodal systems, emissions from terminal operations, production emissions of fuel, the source of electricity, the loss of electricity) (Kim and Van Wee, 2009). This extended version adds four issues to the last version and examines a case study. First, the total distances travelled by truck-only systems and intermodal systems are considered based on the corresponding network system. The distances estimated by GIS for the case study were more accurate than those derived using detour/circuitry factors. In addition, the average speeds cruised by trucks, trains, and vessels are considered, too. Second, the issue of loading units is specified as 20 ft. and 40 ft. containers. Third, an additional intermodal freight system (short sea shipping intermodal) is included in the analysis. Finally, the extended model is applied to a case study. Furthermore we included a sensitivity analysis for the values of factors that affect CO_2 emissions.

In considering the initial question of whether the rail-based/vessel-based intermodal freight system really emits less CO_2 than the truck-only freight system, we found that this is not always true. Results depend on assumptions with respect to factors such as the source of electricity, size of vessel, drayage distance, the ratio of 20 ft. to 40 ft. containers, the average cruising speed for truck-only systems, and the number of flat cars for rail options is taken into consideration. The first two factors are examined in a scenario analysis (Section 3) while the other factors are examined in sensitivity analyses (Section 4). In both the scenario analysis and sensitivity analyses, the ranking regarding CO_2 emissions clearly was changed. According to those results, at least in Europe, the intermodal freight system does not always emit less CO_2 than truck-only systems. The results in this study could show the contradiction to tonne-km based CO_2 emissions factors to some extent (See Table 4A (d) in Appendix 4A).

This study might require further improvement. The first challenge for future research is the consideration of the empty back-haul rate. This will lead to the different loading factors for the return trip. It would be simple to consider the back-haul rate for the truck-only system, while another research framework would be needed to analyze empty back-hauls in intermodal systems. The second challenge relates to the consideration of different truck types to be used for drayage versus the truck-only system. In practice, in most cases, the trucks used for drayage have different characteristics than those used for long-distance haulage. In particular, drayage trucks tend to be older and less fuel efficient. As a result, different emissions factors would need to be used for more accurate results. Third, we recommend developing a comprehensive framework (i.e., a Full-LCA), including the emissions for scrapping and infrastructure construction/deconstruction for long-term analysis.

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Appendix 4A

Table 4A (a) Published emission factors for heavy articulated truck

Organization	Gram of CO_2/tone-km	Assumptions about vehicle loading
NTM	59	60% utilization
IFEU	66	Average
TREMOVE	77.2	>32t GVW
DEFRA	82	>32t GVW/27% empty running/59% load factor
INFRAS	91	
ADEME	109	max load 25t/21% empty running/57% load factor
STREAM	120-160	> 20t GVW
Max Planck Institute	182	> 40t GVW
	80	< 40t GVW

Source: McKinnon and Piecyk (2010) and Van Essen et al.(2009)

Table 4A (b) Published emission factors for rail freight movement (Gram of CO_2/tone-km)

Organization	All rail freight	Diesel-hauled	Electric-hauled
ADEME	7.3	55	1.8
NTM	15	21	14
AEA Technology	20		
DEFRA	21		
INFRAS	22.7	38	19
TRENDS	23		
TREMOVE	26.3		
IFEU		35	18
McKinnon/EWS		18.8	
STREAM		20 – 60	15– 60

Source: McKinnon and Piecyk (2010) and Van Essen et al.(2009)

Table 4A (c) Published emission factors for inland waterway/barge movement

Organization	Gram of CO_2/tone-km	Assumptions
INFRAS	31	
TRENDS	31	
TREMOVE	32.5	
IFEU	28-35	
STREAM	35-95	32 TEU
STREAM	40-105	96 TEU
STREAM	30-90	200 TEU
STREAM	25-80	470 TEU
STREAM	10-40	1,900 TEU (Deep sea)

Source: McKinnon and Piecyk (2010) and Van Essen et al.(2009)

Table 4A (d) composite emission factors for intermodal combinations

Intermodal combination		Road distance as % of total			
		5%	10%	15%	20%
road-rail	average rail freight	24.0	26.0	28.0	30.0
	electrified rail (EU average)	21.2	23.3	25.5	27.6
	electrified rail (France)	10.0	12.8	15.5	18.2
	diesel rail	25.9	27.8	29.7	31.6
road-inland waterway		32.6	34.1	35.7	37.2
road short-sea	large tanker (18371 tonnes)	7.9	10.7	13.6	16.4
	small container vessel (2500 tonnes)	15.9	18.4	20.8	23.2
	larger container vessel (20000 tonnes)	14.0	16.6	19.1	21.6
	all short sea	18.3	20.6	22.9	25.2

Source: McKinnon and Piecyk (2010) and Van Essen et al.(2009)

Table 4A (e) Recommended average emission factors

Transport mode	Gram of CO_2/tone-km
Road transport	62
Rail transport	22
Barge transport	31
Short sea	16
Intermodal road/rail	26
Intermodal road/barge	34
Intermodal road/short sea	21
Deep-sea container	8

Source: McKinnon and Piecyk (2010)

Chapter 5
The relative importance of factors that influence the break-even distance of intermodal freight transport system based on the Monte Carlo method

Nam Seok Kim and Bert Van Wee
Delft University of Technology

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Abstract
The break-even distance of an intermodal freight system is a crucial piece of information for shippers as they decide whether to choose a specific freight transport system. It is also important for policy makers who want to demonstrate to shippers that the intermodal system is substantially more beneficial over a certain distance and encourage shippers to use it. However, the break-even distance is highly dependent on market situations. In other words, it is not possible to estimate the definitive break-even distance that is generally applicable. To date, the literature has addressed factors, including costs and distances, that impact the break-even distance without considering the relative importance of each of these factors. This study attempts to address this gap in knowledge by evaluating the relative importance of geometric and cost factors. The former includes drayage distances (i.e., pre- and post-haulage by trucks), truck-only distance, rail distance, the shape of the market area, and the terminal location, while the latter includes the drayage truck rate, the long-distance truck rate, the rail rate, and the terminal handling rate. Finally, by developing a Monte Carlo-based simulation model, the relative importance can be evaluated. The key finding is that the geometric factors and terminal handling costs are not more significant than the transport costs (i.e., rail costs and long-distance trucking costs) in general. Specifically, to shorten the break-even distance,

either reducing the rail rate or increasing the truck rate is the most effective strategy. A one percent change in these factors is almost seven times, three times, and twice as effective as a one percent change in the handling costs at terminals, rail distance, and drayage cost, respectively. Furthermore, neither the oval-shaped market area nor a terminal relocation attracts customers to intermodal systems in general. When two options are combined, the synergic effect is significant.

5.1 Introduction

Intermodal freight transport systems have the potential to perform better than unimodal systems in economic and environmental terms; as a result, transport policies that encourage intermodal transport have been implemented. Landmark publications include the EU White paper 'European transport policy for 2010 - time to decide' (EC, 2001b) and The Intermodal Surface Transportation Efficiency Act in the United States (USDOT, 1991). However, in terms of its current share, intermodal transport seems to be performing below its potential. The modal split of the transport of goods in billion ton-kilometers for EU-27 is 45.6% by road, 37.3% by sea (domestic and intra-EU-27 transport only), 10.5% by rail and 6.5% by inland waterways and pipelines (EC/Eurostat, 2007). Because non-road transport modes should be a main part of the intermodal freight system, the relatively lower mode share of rail and inland waterway is a strong indicator of the low market share of intermodal transport.

Among several conditions influencing the freight mode choice, the economic feasibility of a freight mode in given circumstances is obviously one of the most significant factors. According to LOGIQ, an EU research project into the decision making-process in intermodal transport, "the cost is the most important criterion in the decision making process" (EC, 2000a, 2006). The break-even distance is often used to evaluate the economic feasibility of an intermodal freight system. It is defined as *the distance at which the costs of intermodal transport equal the costs of truck-only transport* (Rutten, 1995).

Once the break-even distance (or its range) has been estimated, the choice of freight mode by the private sector, especially by the cost saving-oriented shipper, becomes much easier. However, unfortunately, it seems to be difficult to generalize the break-even distance because it is influenced by several factors, such as drayage truck distances, long-haulage rail distance, truck-only distance, drayage rate, long-haulage rate, truck-only rate, trans-shipment rate, detour factors and terminal locations (Nierat, 1997, Zumerchik et al., 2009). Break-even distances found in the literature are often based on a specific study area or were estimated by simply assuming values for those factors or ignoring some of those factors.

Although the definitive break-even distance cannot be estimated, it might be possible to evaluate the relative importance of the factors that influence the break-even distance. In this study, we address four related modeling issues that may be helpful to consider when examining the relative importance of these factors. First, the definition and boundaries of break-even distance are unclear. Specifically, the break-even distances found in previous studies are one of the following distances: (a) the door-to-door distance by truck, (b) the hub-to-hub long-haulage distance by non-road (rail), (c) the total distance including drayage by trucks and long-haulage by non-road, or (d) the market distance between two economic activity centers. Secondly, some studies consider the distance as the crow flies while others consider the actual (network-based) traveled distance. Thirdly, there is a lack of insight into

the transferability of the geometric factors once these are obtained for a specific case (i.e., spatial heterogeneity). To improve transferability, the geometric factors must be generated based on geometry theories. Finally, cost functions could be enhanced. The cost functions found in previous studies are mostly simple constant rates rather than distance-dependent or quantity-dependent rates. In the price competition between two different modes (or even systems), these functions should be taken into account to demonstrate the impact of economies of scale, more specifically, either economies of distance or economies of quantity (McCann, 2001).
The factors considered in this study largely fall into two categories: *geometric* factors and *cost* factors. The former consist of drayage distance, long-haulage distance, truck-only distance, the shape of the market area, and terminal locations. A Monte Carlo simulation method, which can generate numerous shipper-receiver (origin-destination) pairs in confined areas, is used to approximate the average estimates of such geometric factors on the break-even distance. In other words, the random effect of the distances decided by those random points is examined. *Cost factors* include truck drayage costs, long-distance truck costs, rail costs, and terminal transshipment costs. Because some cost factors also have inherent uncertainty due to spatial heterogeneity, random effects are also included in the Monte Carlo simulation model.

In Section 2, break-even distances reported in previous research are presented. Using a cost-distance graph, the break-even distance is represented in a two dimensional graph. We then address the four issues described above in Section 3. The details for geometric factors and cost factors that influence the break-even distance are systematically presented. In Section 4, under the assumption that the intermodal terminals are located in the center of a circular market area, the relative importance of the geometric and cost factors is evaluated through two sets of distance assumptions: 500 km for the long-haulage distance and 50 km for the radius of the circle-shaped market area, and 1,000 km and 100 km for these variables, respectively. In Section 5, we examine the impact of changing the shape of the market areas and moving the terminal locations on the break-even distance when these assumptions are not made. It is important to note that these two factors (i.e., the shape of the market area and the location of the terminal) are handled separately because they are not fundamental factors, such as distance and cost, but indirect geometric factors that affect fundamental factors. Finally, we summarize our findings, the limitations of the study, and future work in the conclusions section.

5.2 Break-even distance of intermodal freight system

5.2.1 Conventional approach

There are two types of break-even distances reported in previous studies. First, the break-even distance obtained by a survey, interviews with shippers, or market observation in a given freight corridor/market: *the survey/interview approach*. In this case, no causal relationship with external factors is found. Giannopoulos and Aifantopoulou-Klimis (1996), for example, remark that “intermodal transport has generally been more competitive over longer distance: 500 km is usually used as a criterion for the viability of intermodal service”. This criterion has been applied in Europe. To some extent, the Ministry of Transport of The Netherlands (1994), Van Duin and Van Ham (2001), Konings and Ludema (2000), Bontekoning and Priemus (2004), Van Klink and Van Den Berg (1998), and Bärthel and Woxenius (2004) have utilized this simple market perception without any specific analysis. UIRR (1999) distinguishes

domestic and international intermodal transport: 550 km for domestic intermodal systems and 760 km for international intermodal systems (Bärthel and Woxenius, 2004). In North America, researchers estimate the break-even distance to be about 500 miles (800 km) (Transport Canada, 1996, Resor and Blaze, 2004, Lim and Thill, 2008) by using market observation. This survey/interview approach is simple, but the applicability of its results to other corridors/markets is limited.

Second, some researchers estimate the break-even distance through cost modeling in a given study area: *the mathematical modeling approach*. The basic equation used in this approach states that the total truck-only costs equal the total intermodal costs, as in Eq. (1).

$$TC_{TO} = TC_{IM} \quad (1)$$

Where, TC_{TO} is the total costs for the truck-only system and where TC_{IM} is the total costs for the intermodal system.

Many previous studies have used Eq. (1) to estimate and compare the break-even distance for the current situation with an improved break-even distance (i.e. mostly the shorter break-even distance), based on proposed strategies. Below we present the dominant strategies as found in the literature, and give quantitative effects for specific cases. Appendix 5B gives a summary of previous studies on break-even distances.

- Better drayage operation
  - Morlok and Spasovic (1994), Spasovic and Morlok (1993), and Nozick and Morlok (1997) show the impact of better operation of drayage on the break-even distance. The improved drayage operation shortens the break-even distance *from 1,300 km to about 770 km*.
- Rail operation and technology
  - EC (2004b) shows the impact of the increased efficiency of railroad. The break-even distance is shortened *from 738 km down to 609 km*.
  - Fowkes et al. (1989a) examined the impact of the higher utilization rate of train space and the higher size of containers. In extreme cases the break-even distance can be reduced *from 1,030 km* for 40 foot containers with 50% utilization rate to *520 km* for 20 foot containers with 90% utilization.
  - Janic (2008) shows the impact of the increased length of a train (i.e. higher capacity). The break-even distance is improved *from 1,100 km* (for the conventional intermodal freight train with a length of 500-600m) *to 600-700 km* (for the long intermodal freight train, 800m – 1,000m long).
  - Resor and Blaze (2004) examine the introduction of double-stack technology in the United States. The break-even is reduced *from 1,500 km to* either *645 km* (the effect of introducing double deck rail operation) or even to *200 km* (for the effect of double deck operation as well as central drayage operation)
- Transshipment technology
  - EC (2004a) shows the break-even distance could be substantially decreased *from 500 - 600 km to 300 km* by introducing CargoSpeed.
- New terminal/relocation of terminal
  - Arnold et al. (2004) show that there may be *no impact* from adding a new terminal or relocating a terminal in the intermodal market area.
- Pricing

- Wichser et al. (2007) shows that the expected rise in fuel pricing and wage cost in Eastern Europe might cause the lower break-even distance *from 1400 km to 500 - 700 km.*
- Janic (2007) examines the case that external costs are incorporated into freight cost function and rail frequency is unknown. In his study the break-even distance decreases *from 1,000 km* to either *800 km* (for 10 trains/week) or *650 km* (for 20 trains/week).

However, the possibility of generalizing those results based on the mathematical modeling approach is limited. Specifically, the break-even distance is estimated based on TC_{TO} and TC_{IM} which should be different in different regions and time periods. In other words, the spatial and temporal heterogeneity of cost functions and varying market circumstances make generalizations of break-even distances (i.e. the definitive break-even distance) impossible.

5.2.2 Graphic representation and intermodal/truck-only cost review

Focusing on the mathematical modelling approach, the break-even distance is often described as a simple cost-distance graph as shown in Figure 5.1. It is useful to understand how various costs at the different stages of an intermodal chain are interrelated, to clearly present the break-even distance when both uni- and intermodal systems have the same total cost for a certain distance, and to examine the impact of changing a cost factor on the break-even distance. Note that similar figures are also shown in, for example, McGinnis (1989), Rutten (1995), Konings (1996), and United Nation (2006).

In Figure 5.1, there are four points (*A*, *B*, *C*, and *D*), with four corresponding projected points (*A´*, *B´*, *C´*, and *D´*) on the X-axis, and four different slopes/lengths (***a***, ***b***, ***c***, and ***d***). Point A indicates the origin location at which the initial cost occurs. For convenience we assume that the initial costs for both the intermodal and the truck-only system at Point *A* are equal, although in practice the initial costs for two transport systems generally differ. Point *B* and *C* are the locations of the two intermodal terminals (i.e. hubs). *D* is the location of the final destination (i.e. receivers). When the four points are projected on the X-axis, the segments between two points indicate physical distances. Specifically, $\overline{A'B'}$ and $\overline{C'D'}$ are the drayage distances, $\overline{B'C'}$ is the long-haulage distance, and $\overline{A'D'}$ is the break-even distance.

$\boldsymbol{a_{Hi}}$ is the rate for drayage (€ per km) in origin hub region H_i as a part of the intermodal chain and ***b*** is the rate for long-distance truck costs (€ per km), which is generally lower than $\boldsymbol{a_{Hi}}$ where $H_i \in [H_O,H_D]$. Differences can relate to different road infrastructure and traffic characteristics: drayage mainly occurs at urban or regional roads while truck-only transport has a high share of relatively fast and therefore relatively cheap motorways. Since drayage at each end in the intermodal chain takes place in different areas, the rates (i.e. $\boldsymbol{a_{HO}}$ and $\boldsymbol{a_{HD}}$) could be different. For example, Min (1991) reported the various drayage trucking costs across a region in Japan ranging from 1.80 $ / km-cubic foot for Kyoto to Nagoya to 5 $/km-cubic foot for Kobe to Tokyo. The European Project RECORDIT (2000b) also shows huge differences in drayage costs across European countries: 0.62 € / km for 20 foot containers and 1.23 € / km for 40 foot containers in Patras, Greece and 1.89 € / km for 20 foot containers and 3.78 € / km for 40 foot containers in Basel, Switzerland. It is notable that the share of drayage costs in the total costs is 30-40% (Spasovic and Morlok, 1993, FHWA, 1994, EC, 2000b,

2001a). Resor and Blaze (2004) reported that drayage costs around a port region in the U.S. account for more than 70% of the total costs when the transport distance is about 300km.

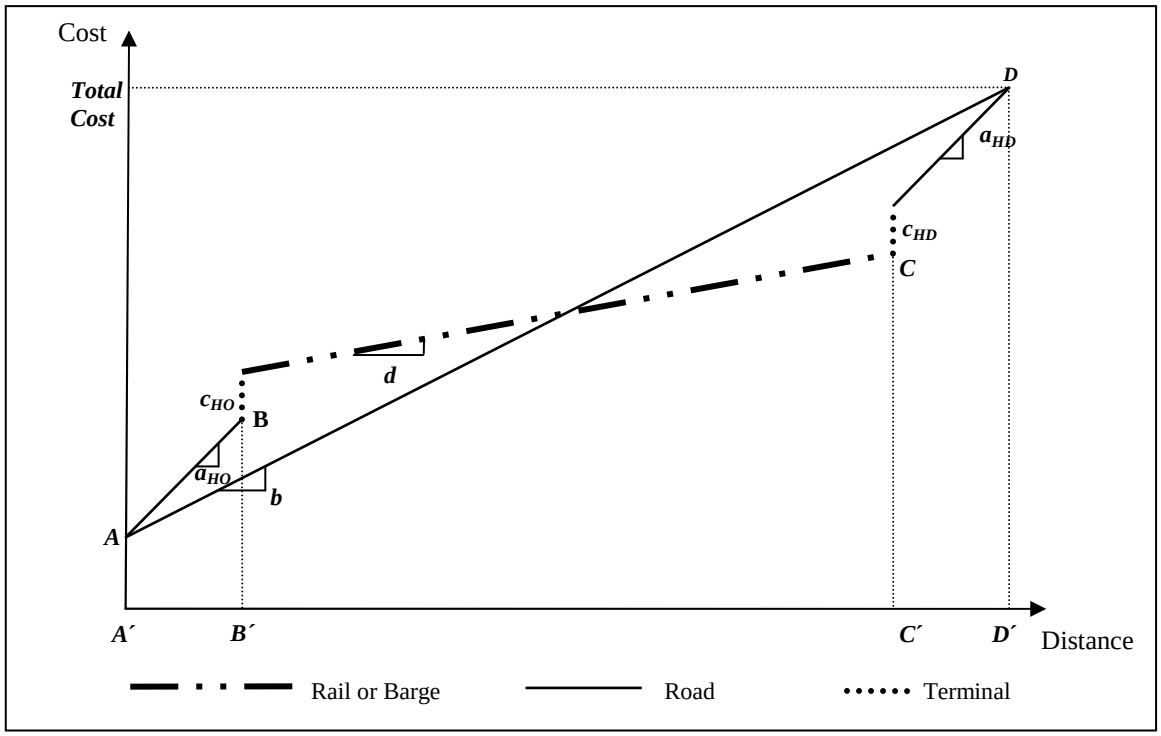


Figure 5.1 Cost structure for intermodal system and truck-only system (Based on Rutten (1995) and United Nations (2006))

Barton et al. (1999) surveyed experts and practitioners about the long distance truck rate (***b***) in Minnesota, in the United States. The industry consensus was 0.78 $/ km. Resor and Blaze (2004) reported $ 189 for the value of ***A*** (truck-only system) and 0.876 $/km for ***b*** in Figure 5.1.

c_i is the terminal cost. RECORDIT demonstrates that terminal costs vary between location of the terminal and the transport modes handled (EC, 2000b). Six types of intermodal terminal can be distinguished: truck-rail, rail-rail, truck-inland waterway, truck-deep sea, rail-deep sea, inland waterway-deep sea. In this study, we mainly consider the first three terminal types in which the range of costs is € 27 – 49 per lift. Barton et al. (1999) reported the transhipment costs as $ 140 per lift and Resor and Blaze reported $ 30 per lift (2004).

d is the non-road transport rate as a function of distance, weight, capacity of transport mode and service quality. The value of ***d*** may decrease if the volume increases. Resor and Blaze (2004) and Janic (2008) collected all costs such as locomotive/railcars ownership and maintenance, crew, fuel, and so on for the United States and Europe respectively. 0.122 $/km are found in a US case (Resor and Blaze, 2004). Janic (2008) developed a model with more than 10 explanatory variables, but did not present ranges for unit costs. RECORDIT reported 0.23 – 0.68 €/km (EC, 2000b). Table 5.1 shows a summary of the rate costs obtained from previous studies after the year 2000.

Appendix 5A presents the cost structure for transport to/from a sea port, in which no drayage is needed at one end of the trip.

Table 5.1 Minimum and maximum cost factors as found in literature

20 Foot container			*40 Foot container*		
	Min	Max		Min	Max
a (€/km)	0.29	1.89	***a*** (€/km)	0.58	3.78
b (€/km)	0.62	0.67	***b*** (€/km)	1.37	1.52
c (€/ container)	27	49	***c*** (€/ container)	27	49
d (€/km)	0.23	0.68	***d*** (€/km)	0.46	1.35

(Main Sources: Resor and Blaze (2004), EC (2000b), and Janic (2008))

5.3 Methodology

5.3.1 Redefinition of break-even distances of intermodal freight system

Subsection 3.1 presents three types of intermodal break-even distances based on the three average distance factors ($\overline{D_{HoHd}}$, $\overline{D_{drayage}}$, and $\overline{D_{TO}}$) presented in Figure 5.2. These three distances are assumed to be the average linear distance "as the crow flies". $\overline{D_{TO}}$ and $\overline{D_{drayage}}$ are the average over-all OD pairs, while $\overline{D_{HoHd}}$ is for a given H_oH_d pair. Specifically, $\overline{D_{HoHd}}$ is the non-road distance (e.g., the rail distance in this study) between H_o and H_d. We note that it can also be regarded as the market distance between two markets. D_{HoHd} , the actual rail distance between H_o and H_d, is also expressed as $\alpha_{Rail} \times \overline{D_{HoHd}}$, where α_{Rail} is the rail detour factor, which can be defined as the ratio of actual distance to Euclidean distance (Levinson and El-Geneidy, 2009) and is referred to as either the *route factor* or *circuity factor* for long distance rail haulage ($\alpha_{Rail} \geq 1$; α_{Rail} =1 when D_{HoHd} is the Euclidean distance). $\overline{D_{drayage\_o}}$ is the average drayage distance between all points (i.e., shippers) and a terminal in market *o*. A market area *o* is assumed to be a circle with radius $\boldsymbol{R_o}$, where an intermodal terminal is located in the center. $\overline{D_{drayage\_o}}$ is defined as $\sum_{n=1}^{N} D^n_{drayage} / N$, where $D^n_{drayage}$ is the drayage distance in market *o* for the nth shipper and *N* is the number of shipper-receiver pairs (O-D pair) within market *o*. $\overline{D_{drayage\_d}}$ is defined in the same way for market *d*, the destination market area. In addition, $D_{drayage} = \alpha_{Uroad} \times \overline{D_{drayage}}$, where $D_{drayage}$ is the actual drayage distance and α_{URoad} is the road detour factor in urban areas for drayage by trucks. $\overline{D_{TO}}$ is the average distance over all OD pairs. In addition, $D_{TO} = \alpha_{NUroad} \times \overline{D_{TO}}$ where α_{NURoad} is a road detour factor in non-urban areas (e.g., regional/international) for truck-only systems. It is notable that Southworth and Peterson (2000) and Lim and Thill (2008) developed impedance functions rather than detour factors (α_{Uroad}, α_{NURoad} , and α_{Rail}) as in this study.

One may argue that the circular shape of the market area does not necessarily occur in practice. We assume that the market area is large enough to cover all OD-pairs for which intermodal transport is an option. If so, the shape of the area does not matter. A graphical check of intermodal OD-pairs confirms our assumption: very few intermodal OD-pairs are located near the edge of the market areas. Strictly speaking, our conclusions only hold for the given circular shaped market areas. We did not further increase the size of the market areas for computational reasons.

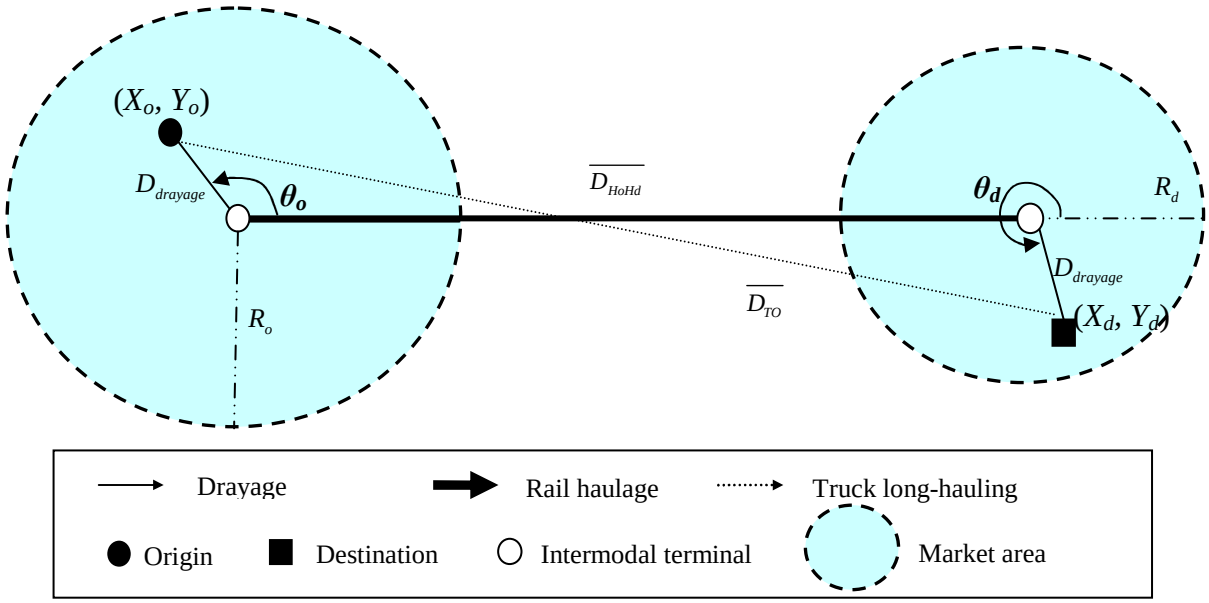


Figure 5.2 Three average distances and a general shipper-receiver pair

It is notable that previous studies modelling the break-even distance for intermodal freight transport systems have not fully taken into account the above-mentioned clarification. Rutten (1995), for example, specified Eq. (2) as follows:

$$FC_{to} + VC_{to} \times BE = FC_{im} + VC_{im} \times BE \qquad (2)$$

Where, FC_{to} and FC_{im} are the fixed costs of a truck-only and intermodal freight system respectively (€/ Loading Unit), VC_{to} and VC_{im} is the variable cost of truck-only and intermodal freight system respectively (€/ km), and *BE* is the break-even distance that is applied for both systems (km).

What distance components from Figure 5.2 should be used in Eq. (2) to estimate the break-even distance? The *BE* on the left side (i.e. the truck-only system) should be $\alpha_{NUroad} \times \overline{D_{TO}}$ while the *BE* on the right side is *either* the summation of the legs of the intermodal chain with the long-haulage distance (i.e. $\overline{D_{HoHd}} + \overline{D_{drayage\_o}} + \overline{D_{drayage\_d}}$) *or* the long-haulage distance only ($\overline{D_{HoHd}}$). Then, the relationship is:

$$\overline{D_{IM}} \neq \overline{D_{TO}} \neq \overline{D_{HoHd}}^{\,6} \qquad (3)$$

Where, $\overline{D_{IM}} = \overline{D_{HoHd}} + \overline{D_{drayage\_o}} + \overline{D_{drayage\_d}}$

If $\overline{D_{drayage}}$ is negligible in relation to the total distance, any distance factors in Eq. (3) (i.e. either $\overline{D_{HoHd}}$, $\overline{D_{IM}}$,or $\overline{D_{TO}}$) might be acceptable as a candidate for the break-even distance. However, if this is not so, those three distances should be considered separately. Two

[6] $\overline{D_{IM}} \neq \overline{D_{HoHd}}$ is obvious since $\overline{D_{IM}}$ is always greater than $\overline{D_{HoHd}}$ while $\overline{D_{TO}} \neq \overline{D_{HoHd}}$ does not seem to be straightforward. It is also notable that Eq. (3) is inconsistent with $\overline{A'D'}$ as presented in Figure 5.2. $\overline{A'D'}$ was represented as both $\overline{D_{IM}}$ and $\overline{D_{TO}}$. The details will be fully considered in 3.2.2.

previous approaches are worth presenting to clarify this issue. On the one hand, Rutten (1995) regarded drayage costs as part of FC_{im}. Obviously, $\overline{D_{drayage}}$ is not taken into account in $\overline{D_{IM}}$. Therefore, the *BE* considered by Rutten (1995) is $\overline{D_{HoHd}}$ when two systems have the same total cost. On the other hand, Janic (2007, 2008) regarded $\overline{D_{TO}}$ as the *BE* when the total costs for the two systems are equal. Both approaches seem to treat the modeling barrier adequately. However, it would be more appropriate to consider the drayage costs as a part of VC_{im} for the former rather than FC_{im} and to distinguish $\overline{D_{TO}}$ with $\overline{D_{HoHd}}$ for the latter. Hereafter, when the total costs are equal for two systems, three *BE* distances are defined as follows:

- BE_{Market} is the break-even market distance, which should be equal to $\overline{D_{HoHd}}$ and the average distance between market centers (i.e. hubs);
- BE_{IM} is the break-even distance of the intermodal system based on the distance actually traveled, which is approximated to $\overline{D_{IM}}$;
- $BE_{Door\text{-}to\text{-}door}$ is the break-even distance of an intermodal system based on door-to-door distance, which is equal to $\overline{D_{TO}}$.

Then, Eq. (2) is properly revised as

$$FC_{to} + VC_{to} \times BE_{Door\text{-}to\text{-}door} = FC_{im} + VC_{im} \times BE_{IM} \quad (4)$$

More precisely,

$$\mathrm{FC_{to}} + VC_{to} \times \overline{D_{TO}} = FC_{im} + VC_{drayage\_o} \times \overline{D_{drayage\_o}} + VC_{drayage\_d} \times \overline{D_{drayage\_d}} + VC_{long\text{-}haul} \times \overline{D_{HoHd}} \quad (5)$$

In addition, it could be of interest to clarify the three break-even distances with respect to actors. $BE_{Door\text{-}to\text{-}door}$ is appropriate for individual shippers since the focus is the feasibility of the intermodal systems compared to the truck-only system for their businesses, while BE_{IM} is useful for intermodal operators or a group of shippers concerned with the collected freight flows in order to decide the feasibility of the entire intermodal chain. BE_{market} should be concerned by the rail operator, terminal operators or policy makers that mainly decide the locations of hubs and demarcate the market boundary.

5.3.2 Geometric factors

This subsection is designed to confirm Eq. (3) and to determine additional geometric characteristics.

Random points and average drayage distance ($\overline{D_{drayage}}$)

Different drayage distances may also be the result of different shipping contexts, which influence the cost structure. Morlok and Spasovic (1994), Janic (2007, 2008), Nierat (1997), Rutten (1995), and Kreutzberger (2008) reported or assumed 160-km, 50-70-km, 57-km, 50-km and 25-km average drayage distances, respectively. The large range of drayage distances might be caused by spatial heterogeneity of the case study areas. Thus, it is necessary to systematically estimate $\overline{D_{drayage}}$ for the general case. We suppose that all shippers, which are represented as (X_o, Y_o) in Figure 5.2, are uniformly distributed within the origin market area.

Additionally, we suppose that a market area is a circle with radius ***R***. Then the average distance between any points (shippers) in a circle to the center (a terminal) is calculated using a Monte Carlo method. To generate a random point, X and Y are two random numbers that are determined as follows:

$$X = ß\ Cos\ \theta,\ Y = ß\ Sin\ \theta \tag{6}$$

where *ß* is a random number between 0 and the radius of market area (***R***) that defines the length from the center (i.e., hub) and θ is also a random number between 0° and 360° that defines the angle.

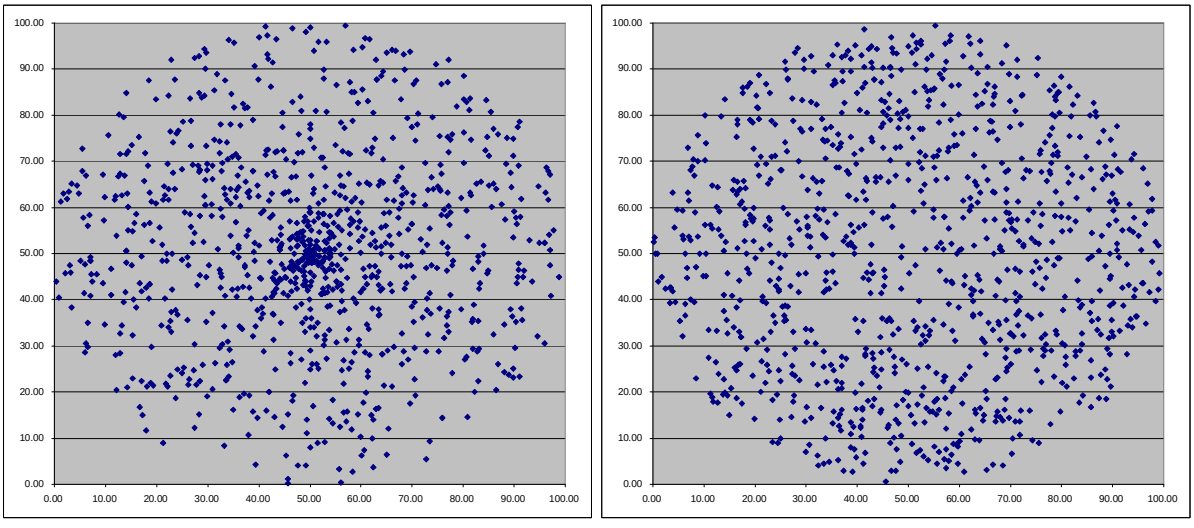
The average (i.e., $\sum_{n=1}^{N} \beta_n / N$, where N is the number of points) seems to be $\overline{D_{drayage}}$ for all of the generated points. However, because many points are generated randomly with this method, the more random points are likely to be plotted near the center (i.e., the density of points is higher toward the center). In other words, the distribution is not uniform but center-biased (See, Figure 5.3(a)). To avoid this biased plotting, ***R*** ($\sqrt{\mu}$) can be estimated by calculating the inverse of the cumulative distribution, where μ is a random number, $0 \le \mu \le 1$ and ***R*** is the given radius of a market area (presented as $\boldsymbol{R_o}$ or $\boldsymbol{R_d}$ in Figure 5.2). Thus, instead of Eq. (6), the random point used in this study is:

$$X = R \times \sqrt{\mu} \times Cos(\theta) \text{ and } Y = R \times \sqrt{\mu} \times Sin(\theta) \tag{7}$$

where $0 \le \boldsymbol{R}\ (\sqrt{\mu}\ ) \le \boldsymbol{R}$

Obviously,

$$\overline{D_{drayage}} = \sum_{n=1}^{N} R(\sqrt{\mu_n}) / N \tag{8}$$



(a) Biased random distribution toward the center (b) Non-biased random distribution

Figure 5.3 shippers distribution in an origin market area with 50km of radius

Figure 5.3 (b) shows 100 pairs of (*X*, *Y*) with the two random numbers that are uniformly distributed in the origin market area with a 50-km radius based on Eq. (7), while Figure 5.3(a)

shows the distribution based on Eq. (6). Examining 15 cases from $\boldsymbol{R}$= 50 km to 200 km with steps of 10 km, Eq. (9) can be estimated.

$$\overline{D_{drayage}} \approx (2/3) \times \boldsymbol{R} \approx 0.667 \times \boldsymbol{R} \quad (9)$$

Also note, because μ could be zero, a terminal can be regarded as either an origin or a destination. Equation (9) (as well as Eq. (10) below) is useful to understand the relationship between the radius of market area and average drayage distance in the analysis of this paper.

Average truck-only distance ($\overline{D_{TO}}$)

Suppose two points ((X_o, Y_o), (X_d, Y_d)) are randomly generated in two different circle-shaped market areas with two different radii ($\boldsymbol{R_o}$ and $\boldsymbol{R_d}$) and matched as in Figure 5.2. The average distance between the two points expressed as $\overline{D_{TO}}$ can be formulated as:

$$\overline{D_{TO}} = \sum_{n=1}^{N} \frac{\sqrt{\left[\left(CX_o + R_{on}\sqrt{\mu_{on}}Cos\theta_{on}\right) - \left(CX_d + \overline{D_{HoHd}} + R_{dn}Cos\sqrt{\mu_{dn}}\theta_{dn}\right)\right]^2 + \left[\left(CY_o + R_{on}\sqrt{\mu_{on}}Sin\theta_{on}\right) - \left(CY_d + R_{dn}\sqrt{\mu_{dn}}Sin\theta_{dn}\right)\right]^2}}{N} \quad (10)$$

Where θ_{on} and θ_{dn} are the nth random interior angle of origin and destination market area respectively, where, $\sqrt{\mu_{on}}$ and $\sqrt{\mu_{on}}$ are the nth random number between 0 and 1 for origin and destination market area respectively, where (CX_o,CY_o) and (CX_d,CY_d) is the center point of origin and destination market area respectively, and where R_{on} and R_{dn} is the nth radius in origin and destination market area respectively.

A similar approach is found in a previous study (Fowkes et al., 1989b). However, they did not consider the market boundary. In other words, the radius of the market circle ($\boldsymbol{R_o}$ or $\boldsymbol{R_d}$) was not specified.

In the proposed simulation model, when the number of shipper-receiver pairs is large enough, $\overline{D_{TO}}$ seems to be equal to $\overline{D_{HoHd}}$. However, it has been shown that these two distance components are generally not the same. Furthermore, it is found that there is a relationship among three average distances as followed:

$$\overline{D_{TO}} - \overline{D_{HoHd}} \approx \psi(\overline{D_{drayage}} / \overline{D_{HoHd}})^{w} \neq 0$$
$$\overline{D_{TO}} \approx \psi(\overline{D_{drayage}} / \overline{D_{HoHd}})^{w} + \overline{D_{HoHd}} \quad (11)$$

Note, Eq. (9) is used for changing $\boldsymbol{R_o}$+$\boldsymbol{R_d}$ to $2 \times (2/3) \times \overline{D_{Drayage}}$ in Eq. (11). ψ and ω are estimated as 81.97 and 1.86 (R^2 = 0.95, the number of $\overline{D_{HoHd}}$ and $\boldsymbol{R_o}$ combination = 42, the number of trail = 20, the number of OD pairs = 5,000) (See, Appendix 5C for the details). Finally, Eq. (3) is more clarified as in Eq. (12) below.

$$\overline{D_{IM}} > \overline{D_{TO}} > \overline{D_{HoHd}} \quad (12)$$

To summarize, it was also found that the difference between $\overline{D_{TO}}$ and $\overline{D_{IM}}$ increases as $\overline{D_{Drayage}}$ increases. Thus, in general, the competitiveness of the intermodal model decreases significantly as $\overline{D_{Drayage}}$ increases.

5.3.3 Cost factors

The cost components (***a***, ***b***, and ***d*** (€/km/TEU) presented in Table 5.1 are obviously useful. However, they are *linear constant rates that do not include the discount effect as distance increases.* They can be replaced with a *distance-dependent cost function that properly reflects the distance effect.* Technically, the proposed cost function is not linearly proportional to distance, as emphasized by Taaffe et al.(1996) and suggested as an interesting subject for future research by Lim and Thill (2008). If these cost functions are considered, the total cost for the intermodal freight system and truck-only system is formulated as follows:

$$TC_{IM} = \Psi_{IM\_drayage}(D_{drayage}) \times X \times 2D_{drayage} + \Psi_{IM\_longhaul}(D_{HoHd}) \times X \times D_{HoHd} + 2 \times TS \times X \quad (13)$$

$$TC_{TO} = \Psi_{TO}(D_{TO}) \times X \times D_{TO} \quad (14)$$

where TC_{IM} is the total cost of the intermodal freight transport system (€), TC_{TO} is the total cost of the truck-only freight transport system (€), $\Psi_{IM\_drayage}(D_{drayage})$ is the distance dependent cost function for truck drayage in an intermodal system (€ / LU-km), $\Psi_{IM\_longhaul}(D_{HoHd})$ is the distance dependent cost function for long-distance rail in an intermodal system (€ / LU-km), $\Psi_{TO}(D_{TO})$ is the distance dependent cost function for a long-distance truck (€ / LU-km), and TS is the trans-shipment cost (€ / LU). We note that all of the distance dependent cost functions can be regarded as marginal cost functions in terms of distance.

As a result, Figure 5.1 could be replaced by Figure 5.4, where ***a***, ***b***, and ***d*** have continuously changing slopes as distance increases. This graph is an application of intermodal systems that fully reflects the economies of distance of individual freight transport modes (McCann, 2001).

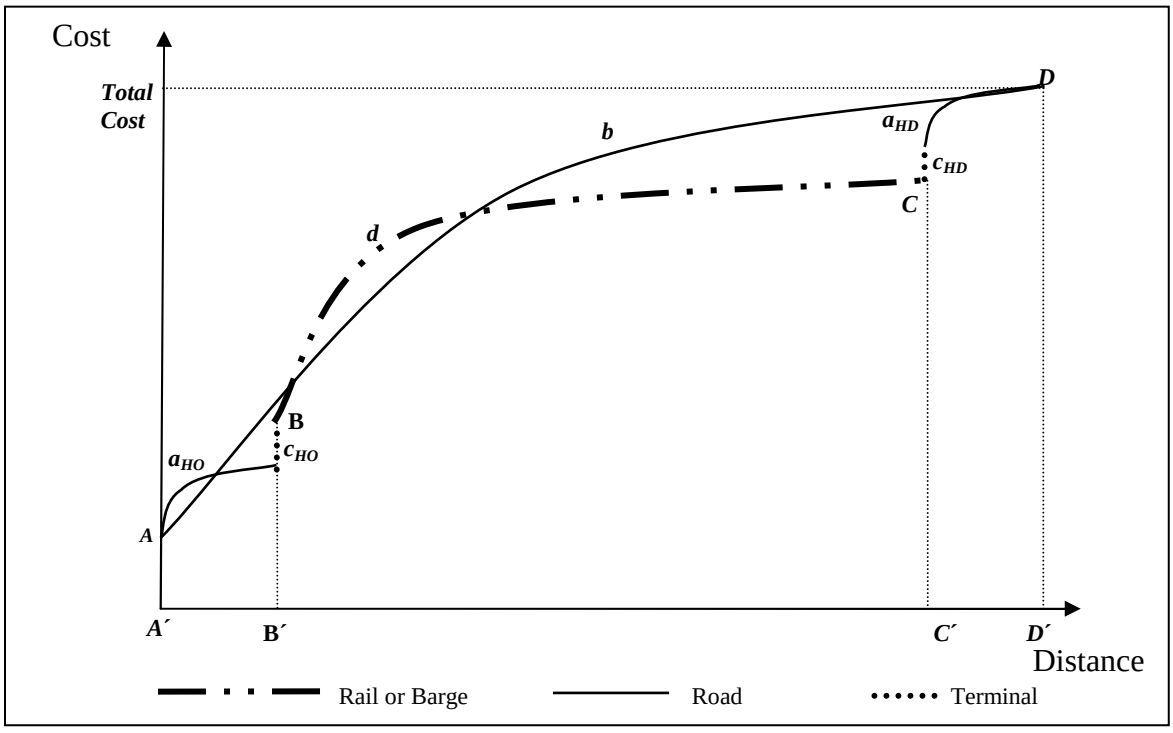


Figure 5.4 Distance-dependent cost structure for intermodal system and truck-only system

5.4 Analyses and results

All of the analyses in this section were performed based on the Monte Carlo simulation model developed in MATLAB 7.4 (R2007a). In Subsection 4.1, assuming that a terminal is located at the center of a circled market area with 50-km $\boldsymbol{R_o}$ and $\boldsymbol{R_d}$ and 500-km $\overline{D_{HoHd}}$, a reference situation is presented with the resulting mode share and some characteristics of the shippers choosing intermodal systems rather than the truck-only system. Some sensitivity analyses are done with ±10 – 20% changes in geometric and cost factors relative to the reference situation in Subsection 4.2. Another situation ($\overline{D_{HoHd}}$ is 1,000 km and $\boldsymbol{R_o}$ and $\boldsymbol{R_d}$ are both 100 km) and its sensitivity analysis are additionally examined in Subsection 4.3. In Subsection 4.4, the relative importance of factors influencing the break-even distance is summarized. Finally, two important geometric factors are tested in the same way: the shape of the market area and the location of terminals.

5.4.1 Reference situation: $\overline{D_{HoHd}}$ =500km and R_o=R_d= 50km

10,000 O-D pairs ((X_o,Y_o) and (X_d, Y_d)) are randomly generated between two market areas. The distance between two hubs and the radius of two market areas is assumed to be 500 km and 50 km, respectively. Based on the distance-dependent cost function and the estimated average distances (e.g., average drayage distances and average truck-only distances) presented in Section 3, total costs for both the truck-only systems and intermodal systems are estimated, and finally, the shipper-receiver pairs for whom the intermodal option is cheaper are selected. The percentage of chosen pairs is considered to be the intermodal system share. In the case study, the distance dependent cost function for both drayage and the truck-only system is assumed to be $5.46\times(Distance)^{-0.278}$ (Janic, 2007, 2008) (See Appendix 5D for the details of this function). It is confirmed that the distance-dependent cost functions are within the range of $\boldsymbol{a}$ and $\boldsymbol{b}$ presented in Table 5.1. Based on Arnold et al. (2004), we assume rail costs to be 65% of total truck-only costs. This distance-dependent cost function is also within the range of d presented in Table 5.1. Therefore, for all remaining case studies, the constant unit costs ($\boldsymbol{a}$, $\boldsymbol{b}$, and $\boldsymbol{d}$ in Table 5.1) are replaced by the distance dependent unit costs: $\boldsymbol{a} = \boldsymbol{b} = 5.46\times(Distance)^{-0.278}$; $\boldsymbol{d} = 0.65\times5.46\times(Distance)^{-0.278}$. For $\boldsymbol{c}$, a rate within 27-49 (€/LU) is chosen randomly; the average $\boldsymbol{c}$ is about 38 (€/LU).

The road detour factor in urban areas for drayage (α_{Uroad}) and in regional/international areas for long-distance trucking (α_{NUroad}) is assumed to be 1.30 and 1.20, respectively. The railway detour factor (α_{Rail}) is assumed to be 1.25, which indicates a smaller detour than the urban road area and a larger detour than the non-urban area. Because higher detour factors depend on lower road/rail network density, the number of terminals stopped at (in network), and natural obstacles such as lakes and mountains, it is difficult to generalize them without a case study (Ballou et al., 2002). Obviously, there is spatial heterogeneity in that, for example, the average detour factor for an inter-city road was estimated to be 1.46 in Europe and 1.2 in the U.S. (Ballou et al., 2002). Nevertheless, as both the total distance travelled and Euclidean distances increase, the detour factors are reported to decrease for randomly generated OD pairs (Levinson and El-Geneidy, 2009).

The preliminary test results for the reference situation are shown in the second column of Table 5.2. The average total cost of the intermodal system (€ 646/LU) is higher than the truck-

only system (€ 583/LU). The mode (system) share of the intermodal system in this case is about 8.37 %; the intermodal system is more competitive for about 837 pairs out of 10,000 pairs than the truck-only system in terms of costs. It is clear that, as shown in the third column in Table 5.2, the average truck-only total cost is higher than the average intermodal total cost for the intermodal pairs. The average drayage distance is significantly reduced from 33.3 km to 19.4 km. In other words, reduced drayage distance has a great impact on the competitiveness of intermodal systems. The maximum D_{TO} is another important geometric indicator. If D_{TO} exceeds 566 km, an intermodal system is never chosen in this test. If the drayage costs are relatively low, intermodal transport is generally more competitive. The spatial distribution of the pairs of intermodal options (i.e., shippers/receivers who select the intermodal option, which are referred to as *intermodal pairs*) represented as ■ in Figure 5.5 is also interesting. The intermodal points form an oval that leans slightly in the opposite direction of the long-haulage. It is notable that Hanjoul et al. (1989) and Nierat (1997) found the shape of the market area: the family of Descartes' ovals. Nierat (1997) suggested that for *all of the shippers within the oval market area*, the intermodal system is competitive (cheaper). However, not *all of the points in the boundary* necessarily choose the intermodal option, as shown in Figure 5.5. Specifically, the green diamond shaped points shown as ♦ in Figure 5.5(b) are the randomly generated shipper and receiver locations in the original and destination areas, respectively. The origins and destinations are randomly matched. If all of the points in the boundary are chosen, the black square points shown as ■ are superposed on the diamonds (♦). However, only the visualized 837 black squares are superposed. Thus, 837 shipper-receiver pairs select the intermodal options (See the number of pairs in Table 5.2). The reason that intermodal transport is not chosen for all origins and destinations in the oval area is that given the origin, the destination is randomly chosen in the study area and vice versa. Thus, an origin in the market area could be linked to a destination near the border of the destination market area, and therefore, intermodal transport is not competitive.

An important question is: *What is the break-even distance in this case?* Is the break-even distance 500 km under a set of given conditions (e.g., a market area with a 50-km radius, costs for trucks, rail, and terminal operations, and detour factors)? The general answer is that there is no *one* break-even distance because the split between intermodal and truck-only pairs is not linked only to the door-to-door distance. Furthermore, BE_{Market} and BE_{IM} are clearly not 500 km. We tested longer market distances from 600 km to 1,700 km. The system (mode) share increases as the long-haulage distance increases: about *50%* for 750 km, *80%* for 900 km, and *100%* for 1,335 km and longer distances. Strictly, the BE_{IM} in this situation is 1,335 km, in which *all shipper-receiver pairs select the intermodal option*.

However, increasing the long-haulage distance is not the only way to increase the higher intermodal mode share. Other factors obviously affect the intermodal share as well. This raises another question: *Which factor is the most effective factor in increasing intermodal mode share and decreasing* BE_{IM}? We attempt to answer this question using sensitivity analysis in the next subsection.

Table 5.2 Comparison between 10,000 random pairs and the selected pairs

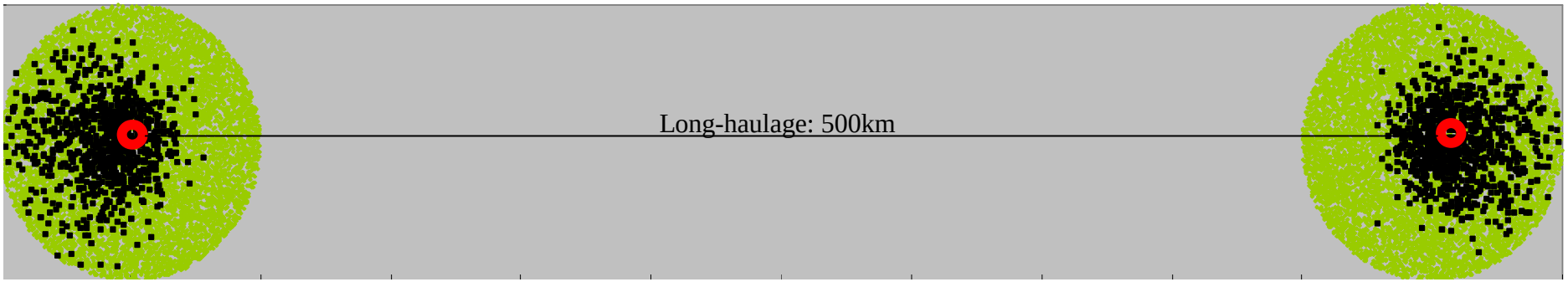
	All pairs	Intermodal-selected pairs ($TC_{IM} < TC_{TO}$)
The number of pairs	10,000	837 (i.e. intermodal share: 8.37%)
Average truck-only total cost (TC_{IM})	583	599
Average intermodal total cost (TC_{TO})	646	581
Average drayage distance	33.3 km in each area, 66.6 km in total	19.4 km in each area 38.4 km in total
Average D_{TO}	501 km	520km
Max D_{TO}	596 km	566km
% of drayage cost	20%	15%

5.4.2 Sensitivity Analysis on the basis of the reference situation

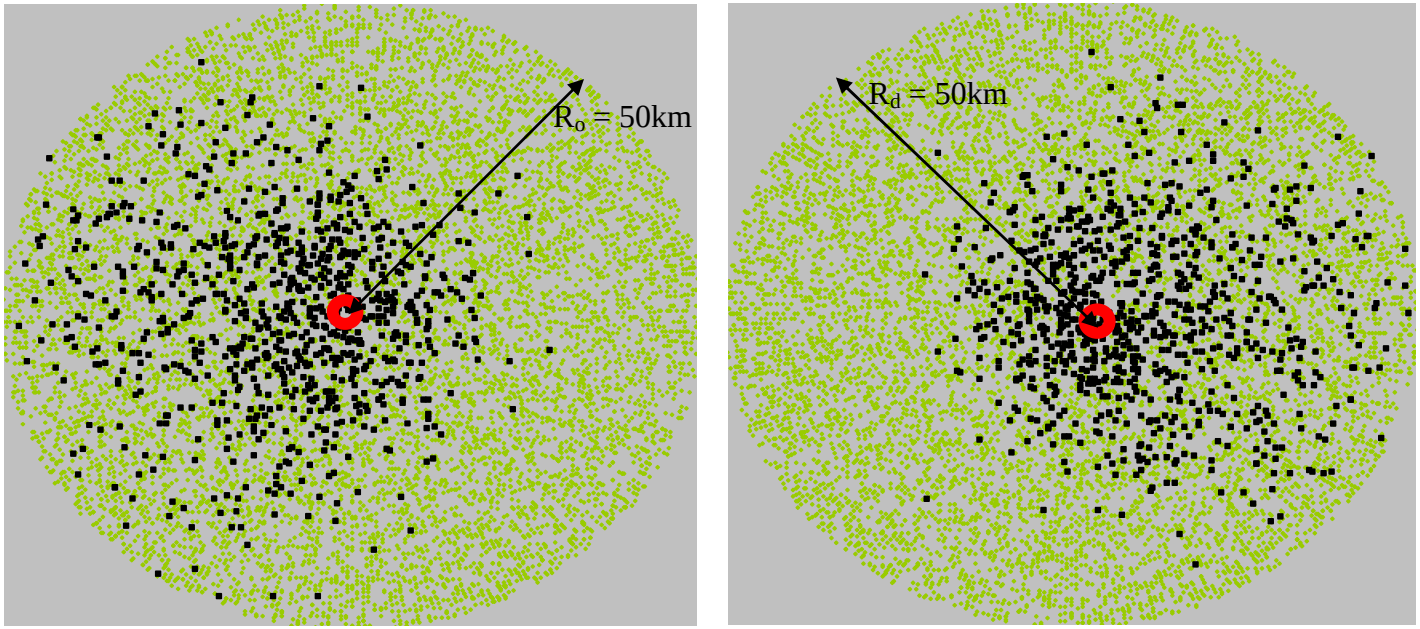
Examining six factors by changing ± 10% ~ ± 20% based on the reference situation, the average intermodal shares with standard deviations are reported. Inversely, we found the distance at which the intermodal share is about[7] 90% and 100%, indicating $BE_{90\%}$ and $BE_{100\%}$, respectively. Finally, using simple linear regression models we find the slope (i.e., 8th column in Table 5.3) that indicates the impact of a change in the factors on the intermodal shares, where the dependent variable is the intermodal share (i.e., 5th column in Table 5.3) and the independent variable is the magnitude of changes (i.e., 3rd column in Table 5.3) with 10% steps, including the reference situation (i.e., 0%; no change) and the conditions for 90% and 100% intermodal share. The slope is calculated over the full range of changes in the independent variable. The ranking in the 9th column in Table 5.3 is estimated based on the magnitude of the slope. In other words, a higher absolute value of slope in linear regression model means a higher ranked factor. The standard deviations of the intermodal share (i.e., 6th column in Table 5.3) are reported to show the random effects caused by shipper-receiver locations and terminal costs. They are not greater than 1% of the average intermodal share. Overall, the random effects are not significant.

Using the example presented above (we call this the reference situation, which is also visualized in Figure 5.5 and presented in Table 5.2), the impacts of the changed conditions for those factors on the intermodal share as well as the break-even distance are examined through sensitivity analysis for six factors ($\boldsymbol{R_o}$, $\overline{D_{HoHd}}$, $\boldsymbol{a}$, $\boldsymbol{b}$, $\boldsymbol{c}$, and $\boldsymbol{d}$) in this section. Due to changing factors in trials of the simulation model, the same experiment is repeated 20 times (i.e., 10,000 O-D pairs are randomly generated 20 times). We report the average intermodal mode share and the standard deviation of the intermodal mode share.

[7] The reason to express 'about' 90% and 100% is because the exact 90% and 100% of the intermodal share was rarely found in the simulation due to the random effect. Every single trial randomly generates different 10,000 OD pairs.



(a) The distribution of all and selected points for two market area.



Shippers' area (origins) Receivers' area (destinations)

(b) The distribution of all and selected points for shipper/receiver market area.

Figure 5.5 Simulation result for 10,000 randomly generated shipper-receiver pairs

Table 5.3 Simulation Tests with $\overline{D_{HoHd}}$ =500km and R_o=R_d= 50km (20 trials for 10,000 random OD pairs)

Test#	Factor	Change rate	Changed value	Ave. intermodal share (%)	S.D. (%)	Changes of Ave intermodal share	Slope in linear regression(R^2)	Ranking (Relative importance)
Base	Reference situation: $\boldsymbol{a} = \boldsymbol{b} = 5.46 \times (Distance)^{-0.278}$; $\boldsymbol{d} = 0.65 \times 5.46 \times (Distance)^{-0.278}$; $27 \leq \boldsymbol{c} \leq 49$(€/LU); α_1 =1.3, α_2 =1.2, α_3 =1.25			8.37	0.28	0		
1	$\boldsymbol{R_o}$ and $\boldsymbol{R_d}$ (Radius of market area)	-20%	40 km	17.26	0.38	+8.89	-1.09 (R^2 = 0.93)	3
		-10%	45km	11.65	0.31	+3.28		
		+10%	55km	5.74	0.24	-2.63		
		+20%	60km	4.17	0.19	-4.20		
	Condition for 90% IMS(Intermodal Share)	-64%	18km	90				
	Condition for 100% IMS	-79%	10.5km	100				
2	$\overline{D_{HoHd}}$ (Long-haulage distance)	-20%	400km	1.84	0.12	-6.54	0.60 (R^2 = 0.95)	5
		-10%	450km	4.07	0.16	-4.30		
		+10%	550km	13.96	0.27	+5.59		
		+20%	600km	21.38	0.41	+13.01		
	Condition for 90% IMS	+98%	990km	90				
	Condition for 100%IMS	+167%	1,335km	100				
3	$\boldsymbol{a}$ (Drayage rate)	-20%	$0.8 \times \boldsymbol{a}$	27.06	0.47	+18.69	-1.02 (R^2=0.96)	4
		-10%	$0.9 \times \boldsymbol{a}$	15.06	0.33	+6.69		
		+10%	$1.1 \times \boldsymbol{a}$	4.42	0.22	-3.96		
		+20%	$1.2 \times \boldsymbol{a}$	2.53	0.12	-5.84		
	Condition for 90% IMS	-62%	$0.38 \times \boldsymbol{a}$	90				
	Condition for 100%IMS	-90%	$0.1 \times \boldsymbol{a}$	100				
4	$\boldsymbol{b}$ (Truck-only rate)	-10%	$0.9 \times \boldsymbol{b}$	0.14	0.04	-8.24	2.09 (R^2 = 0.86)	1
		+10%	$1.1 \times \boldsymbol{b}$	48.00	0.53	+39.63		
		+20%	$1.2 \times \boldsymbol{b}$	85.00	0.49	+76.63		
	Condition for 90% IMS	+23%	$1.23 \times \boldsymbol{b}$	90				
	Condition for 100%IMS	+45%	$1.45 \times \boldsymbol{b}$	100				
5	$\boldsymbol{c}$ (Terminal cost)	-20%	$0.8 \times \boldsymbol{c}$	15.08	0.3	+6.71	-0.28 (R^2 =0.98)	6
		-10%	$0.9 \times \boldsymbol{c}$	11.23	0.31	+2.87		
		+10%	$1.1 \times \boldsymbol{c}$	5.74	0.24	-2.63		
		+20%	$1.2 \times \boldsymbol{c}$	4.00	0.13	-4.37		
	Max Condition	-100%	$\boldsymbol{c} = 0$	61.92	0.47	+53.55		
6	$\boldsymbol{d}$ (Rail rate)	-20%	$0.8 \times \boldsymbol{d}$	63.87	0.39	+55.50	-1.72 (R2 = 0.92)	2
		-10%	$0.9 \times \boldsymbol{d}$	31.96	0.52	+23.59		
		+10%	$1.1 \times \boldsymbol{d}$	0.77	0.11	-7.60		
	Condition for 90% IMS	-32%	$0.68 \times \boldsymbol{d}$	90				
	Condition for 100%IMS	-55%	$0.45 \times \boldsymbol{d}$	100				

Test #1: Impact changes in the drayage distance

The radius of a market area affects the average drayage distance. The changed drayage distance is obviously associated with the intermodal share. To attract 90% of shipper-receiver pairs in the market area to the intermodal system, the radius of the market area should be less than 18 km (i.e., a 64% reduction of the radius). When the intermodal share is 100%, which is the condition of BE_{IM}, the radius is 6 km (i.e., 88% reduction of the radius). Six kilometers of average drayage seems to be unrealistic. In other words, 500 km of BE_{Market}, and 508 km[8] of BE_{IM} are also unlikely to be found in practice. Nevertheless, a smaller market area and accordingly shorter drayage distance are clearly shown to increase the intermodal mode share. A policy option to decrease the average drayage distance could be to build a new intermodal terminal in the market area. An additional terminal in the market area clearly almost halves

[8] 508 km = 500 km (long-haulage distance) + 6 (radius of a market area) × 2/3 (converting from radius to drayage distance based on Eq. (9)) × 2 (two market area)

the average drayage distance. However, it seems to be still open to debate as to whether a new terminal or relocation of terminals significantly decreases the break-even distance and eventually increases the intermodal share in practice. Trip and Bontekoning (2002) reported that the effect of a new terminal leads to a shorter break-even distance, while Arnold et al. (2004) argued that a new terminal is not really effective (Woxenius et al., 2007). We this issue further, at least theoretically, in Section 5.

Test #2: impact of market distance change

The intermodal share increases as $\overline{D_{HoHd}}$ increases because of the lower per-km costs of non-road modes compared to road modes. It is interesting that the overall impact of market distance change on the intermodal mode share (0.60, R^2 = 0.95), which is indicated as the slope of the regression model in Table 5.3, is ranked as the 5th out of six factors. However, looking at ± 10% changes in test #2 (-4.30% and +5.59% for -10% and +10% change, respectively), the impact of such changes is greater than some other higher ranked factors: for example, $\boldsymbol{R_o}$ in test #1 (+3.28% and -2.63% for -10% and +10% change, respectively), which is ranked 3rd. In other words, for small changes (±10%), the changes in $\overline{D_{HoHd}}$ have a greater impact on the intermodal share than an equally large change in $\boldsymbol{R_o}$, which shows that the relationship between independent and dependent variables over the whole range of changes in the independent variable is not fully linear. More specifically, the impact on the intermodal share of a change in $\overline{D_{HoHd}}$ decreases as the change increases. It is notable that although the better regression form could be modeled as, for example, $y = -0.002x^2 + 0.90x + 11.68$ (R^2 = 0.97), the linear form should be used for comparison with other tests. Note that the condition for 100% intermodal share (i.e., 1,335 km) shown in Table 5.3 is the same as the BE_{IM} discussed in Subsection 4.1.

Test #3: impact of drayage cost change

It is confirmed that lower drayage costs lead to a higher intermodal share. A 20% reduction in drayage costs increases the intermodal share from 8.37% to 27.06% (i.e. the mode share of the reference situation). According to previous studies (Morlok et al., 1990, Spasovic and Morlok, 1993, Nozick and Morlok, 1997, EC, 2001a), decreasing drayage cost has been recognized as one of the most effective options for shortening the break-even distance. However, it is relatively less effective than other options in terms of relative importance. To sum up, the key finding here in *Test #3* is that reducing drayage costs alone does not always guarantee a higher intermodal share. To reach 90% of intermodal share, the drayage cost needs to be decreased to 77%, which hardly happens in practice. As policy options to reduce drayage costs, the optimization of a drayage operation through a central control in the hub area is the recognized example (Morlok and Spasovic, 1994, Nozick and Morlok, 1997, Resor and Blaze, 2004).

Test #4: impact of Long-distance truck cost change

Increasing the long distance truck costs is the most effective way to increase the intermodal share in this case study. A 10% increase of truck cost results in only a 39.63% increase in the intermodal share. Policy measures to increase these costs could include a distance-based road tax. The implementation of a distance-based road tax, such as that discussed recently in the Netherlands (Lowy, 2009) might be a strategy to increase the intermodal share since it has a relatively small impact on the drayage price. An increase in truck costs of only 23% results in an intermodal share of 90%. The R^2 of the linear regression (R^2 = 0.86) is lower than for the other factors. The plotted points indicate non-linearity. Points around 90%-100% show a much lower slope (i.e. less sensitive mode share to truck-costs) than points around 10%-20%.

Actually, a better fitted regression model is a polynomial form: $y = -0.033x^2 + 3.24x + 25.12$ ($R^2 = 0.94$). Nevertheless, as mentioned previously, the linear form should be used for the purpose of comparison (i.e. relative importance).

Test #5: impact of terminal cost change
Some previous studies expected that new technologies or optimized operations for transshipments would contribute considerably to a higher intermodal share (EC, 2004a). However, they may not only consider the reduced cost but also take into account some other effects (e.g. new technology might attract shippers to use the intermodal system due to the reduced costs as well as other reasons such as faster transshipment and secured process). In this study, we simply tested the ±10% to ±20% changes of the terminal costs without considering the changes related to other effects. The result shows that even when the terminal cost is free of charge, the intermodal share would only be about 62%. In other words, it is not possible to reach even 90% of intermodal share through decreasing terminal costs.

Test #6: impact of rail cost change
As rail costs decrease, the intermodal share significantly increases. Compared to *Test #4* (long-distance truck cost change), it is slightly less effective. Conversely, increasing rail costs leads to a very serious situation: if the rail cost increases by 10%, the intermodal system is barely used (0.44% intermodal share). A feasible strategy to reduce rail cost is to increase the rail capacity. Janic (2008) examined the impact of using long intermodal freight trains in Europe (a train length between 800 m and 1,000 m with 38-40 rail flat wagons) and showed that there is a significant cost reduction and accordingly a shorter break-even distance when compared to the conventional intermodal freight trains (a length of 500-600 m with 25-30 rail flat wagons). The operating frequency (e.g., 5 trains /week or 20 trains / week) can also contribute to reduced rail costs (Janic, 2007). Subsidies or tax benefits for the rail industry are a conventional way to reduce rail costs. For example, the diesel oil for locomotives, so-called 'red' diesel, is basically the same quality as 'white' diesel for trucks. The only difference is that the red diesel is provided at a tax-discounted price.
Detour factors (α_1, α_2, and, α_3) could be included in the sensitivity analysis. However, because the effects equal those of the reduced unit costs for drayage, truck-only and rail rates, we do not present them. Infrastructure network policies could also be developed to reduce detours to achieve shorter drayage distances and long-haul rail distances.

5.4.3 Sensitivity Analysis on the basis of $\overline{D_{HoHd}}$ =1,000km and R_o=R_d= 100km

Another market situation was designed at the same rate as the reference case (i.e. the market radius at each end is 10% of the long-haulage distance) and examined. The purpose is to examine the impact of different market sizes and the long-haul distances on our findings by comparing them with the reference situation. In this Subsection some significant differences between the previous case (hereafter, Case 1) and the case based on the new condition (hereafter, Case 2) are discussed rather than the details. The intermodal mode share in Case 2 is 24.47% (0.49 standard deviation for 20 trails), which is almost three times higher than in Case 1. The higher intermodal share in Case 2 could be evidence that the intermodal system is much more competitive in the long-distance market (1,000km) than the medium distance market (500km). In order to understand this significantly increased intermodal share, the cost function used in the analysis needs to be discussed (See, Appendix 5D). For the long distance truck and rail competition, the unit cost around 500km (Case 1) is not significantly higher

than one around 1,000km (Case 2). The unit costs are equally improved. However, the unit cost rate steeply decreased over short distances where drayage is considerably affected. Therefore, the increased drayage distance significantly contributes to the higher intermodal mode share. In addition, the impact of terminal costs, which is only taken into account in the intermodal system, is diminished as the absolute amount of the total cost for both systems increases.

Table 5.4 shows the results for Case 2. Overall, the general trends of the impacts of the changes in factors are equal to those of Case 1. However, there are a couple of minor changes in Case 2 compared to Case 1: as the market size increases, the impact of ***b*** is slightly stronger while the impact of ***d*** and ***c*** is weaker. The differences in the other variables are almost negligible and do not need to be reported.

Table 5.4 simulation tests with $\overline{D_{HoHd}}$ =1,000km and R_o=R_d= 100km (20 trials for 10,000 random OD pairs)

Test #	Factor	Change rate	Changed value	Ave. intermodal share (%)	S.D (%)	Change	Slope in linear regression (R^2)	Ranking
Base	Same as in Table 5.3			24.27	0.49	0		
1	***R_o*** and ***R_d*** (Radius of market area)	-20%	80km	43.53	0.46	+19.26	-1.11 (R^2 = 0.97)	3
		-10%	90km	32.72	0.49	+8.45		
		+10%	110km	18.34	0.37	-5.93		
		+20%	240km	13.89	0.35	-10.38		
	Condition for 90% IMS	-49.5%	50.5km	90				
	Condition for 100%IMS	-64%	34km	100				
2	$\overline{D_{HoHd}}$ (Long-haulage distance)	-20%	800km	9.04	0.16	-15.23	0.61 (R^2 = 0.92)	5
		-10%	900km	15.86	0.29	-8.41		
		+10%	1,100km	34.64	0.47	+10.37		
		+20%	1,2000km	45.25	0.45	+20.98		
	Condition for 90% IMS	+72%	1,720km	90				
	Condition for 100%IMS	+140%	2,400km	100				
3	***a*** (Drayage rate)	-20%	0.8 × ***a***	54.00	0.55	+29.73	-1.05 (R^2 = 0.97)	4
		-10%	0.9 × ***a***	38.35	0.45	+14.08		
		+10%	1.1 × ***a***	14.85	0.34	-9.42		
		+20%	1.2 × ***a***	8.82	0.29	-15.45		
	Condition for 90% IMS	-47%	0.53 × ***a***	90				
	Condition for 100%IMS	-76%	0.24 × ***a***	100				
4	***b*** (Truck-only rate)	-20%	0.8 × ***b***	0.003	0.01	-24.27	2.25 (R^2 = 0.91)	1
		-10%	0.9 × ***b***	1.38	0.13	-22.89		
		+10%	1.1 × ***b***	70.22	0.47	+45.95		
		+20%	1.2 × ***b***	94.39	0.21	+70.12		
	Condition for 90% IMS	+17%	1.17 × ***b***	90				
	Condition for 100%IMS	+35%	1.35 × ***b***	100				
5	***c*** (Terminal cost)	-20%	0.8 × ***c***	31.63	0.47	+7.36	-0.14 (R^2 = 0.99)	6
		-10%	0.9 × ***c***	27.93	0.53	+3.66		
		+10%	1.1 × ***c***	21.38	0.43	-2.89		
		+20%	1.2 × ***c***	18.29	0.31	-5.98		
	Max Condition		***c***= 0	62.04	0.55	+37.77		
6	***d*** (Rail rate)	-20%	0.8 × ***d***	83.63	0.23	+59.33	-1.18 (R^2 = 0.92)	2
		-10%	0.9 × ***d***	56.47	0.69	+32.32		
		+10%	1.1 × ***d***	4.82	0.20	-19.45		
		+20%	1.2 × ***d***	0.30	0.05	-23.97		
	Condition for 90% IMS	-24%	0.76 × ***d***	90				
	Condition for 100%IMS	-45%	0.55 × ***d***	100				

5.4.4 Relative Importance for break-even distance

Table 5.5 presents the relative importance (i.e., ranking) of the factors in terms of the intermodal share for ±10% change in factors and the slope of the linear regression equation (8th column in Table 5.3 and 5.4), which indicates the overall impact of one unit change of a factor. The relative importance, represented as a ranking for the ±10% change, is not necessarily the same as the linear model in both Case 1 and Case 2. However, the orders of rankings in Case 1 for both ±10% change and the linear model are the same in Case 2.

Table 5.5 Rankings and relative importance of factors

	Case 1: 500km of long-haul age distance with 50km of drayage distance					Case 2: 1,000km of long-haul age distance with 100km of drayage distance				
	Sign	±10%		Linear model		Sign	±10%		Linear model	
		Ranking	Mode share Change (%)	Ranking	Relative Impact		Ranking	Mode share Change (%)	Ranking	Relative Impact
R	-	**5**	3.28	**3**	1.09	-	**5**	8.45	**3**	1.11
$\overline{D_{HoHd}}$	+	**4**	5.59	**5**	0.60	+	**4**	10.37	**5**	0.61
a	-	**3**	6.69	**4**	1.02	-	**3**	14.08	**4**	1.05
b	+	**1**	39.63	**1**	2.09	+	**1**	45.95	**1**	2.25
c	-	**6**	2.87	**6**	0.28	-	**6**	3.66	**6**	0.14
d	-	**2**	23.59	**2**	1.72	-	**2**	32.32	**2**	1.18

In both cases, ***b*** is the most influential factor in both the ± 10% change as well as in the linear model. ***d*** is ranked 2nd, and ***c*** is the least effective one among the factors. For ***R***, $\overline{D_{HoHd}}$, and *a*, it is interesting to check the difference in ranking between the ± 10% change and the linear model. For example, the decreased market radius represented as $\boldsymbol{R_o}$ in Table 5.5 is not effective initially (ranked 5th,) but it moves to 3rd most effective in the linear model in the two cases. The phenomenon indicates that decreasing the radius of the market area is not more effective than reducing the drayage cost (***a***) and increasing the long-haulage distance ($\overline{D_{HoHd}}$) in the early stage. The impact of the decreased radius becomes increasingly more effective and is finally more effective than the other two factors. Thus, if there are only three options available to shorten the break-even distance (the decreased market area radius, the increased long-haulage distance, and drayage cost reduction) and if one wants to highlight the dramatic effect of these factors, the decreased market area radius is the better option *in the long term* (in general) than the others, while *in the short term*, the reduction in drayage costs is the most effective factor among these three factors.

Nevertheless, the generalized relative impact is based on the linear model. The effects based on the relative importance can be summarized as follows: *to shorten break-even distance, increases in the long-distance trucking rate is more effective than*

- decreasing terminal handling costs 7.5 times;
- halving the drayage rate or radius length
- increasing the rail distance 3.5 times.
- decreasing rail costs 1.7 times

The relative importance for Case 2 is summarized similarly: *the effect of increases in the long-distance trucking rate* is equal to the effect of

- decreasing terminal handling costs 16 times
- halving the drayage rate or radius length
- increasing rail distance 3.7 times
- decreasing rail costs 1.2 times

5.5 Further discussions on market shape and terminal location

All of the analyses in Section 4 are performed under the assumption that the share of a market is *a circle* and the terminal is located *at the center*. These assumptions are released in this section. According to Nierat (1997), the intermodal market area might belong to the family of Descartes' ovals. We simplify the market shape as an ellipse defined as $x^2/(\boldsymbol{R_o}+L)^2 + y^2/((\boldsymbol{R_o}-M)/2)^2 = 1$, where L and M are constants. Specifically, L and M are set to make the area of the ellipse (i.e., $\pi\times(\boldsymbol{R_o}+L)\times(\boldsymbol{R_o}-M)$) equal to the area of the circle (i.e., $\pi\times R_o^2$). For example, if L=10 km and $\boldsymbol{R_o}$=50 km, M=50 – 50^2/(50+10) = 8.33. L and M, which eventually determine the share of ellipse, are graphically defined in Figure 5.6(a). Figure 5.6(b) is the reference situation assuming 500 km of $\overline{D_{HoHd}}$ and 50 km of $\boldsymbol{R}$. Three additional tests are designed. First, the terminal in the proposed ellipse-shaped market area is located at the center: Test #7 in Figure 5.6(c). Second, the origin and destination terminal locations are on the right and left sides of the circle at 10 – 40% of $\boldsymbol{R}$, respectively: Test #8 in Figure 5.6(d). N is defined as the corresponding distance to be moved by 10 – 40% of $\boldsymbol{R}$. Third, the assumptions of Tests #7 and #8 are combined (i.e., the non-centered terminal in an ellipse-shaped market): Test #9 in Figure 5.6(d).

Table 5.6 Simulation tests for market shape and terminal location (20 trials for 10,000 random OD pairs)

Test #	Factor	Change rate	Ave. intermodal share (%)	S.D	Changes from reference case	Slope in linear regression(R^2)
7	L and M (Ellipse-Shaped market area)	+10%; L= 5km; M= 4.55 km	8.31	0.29	-0.06	0.031 (R^2 = 0.031)
		+20%; L=10km; M=8.33km	8.44	0.23	+0.07	
		+30%; L= 15km;M=11.54km	8.43	0.21	+0.06	
		+40%; L=20km; M=14.29km	8.31	0.22	-0.06	
8	N; Relocation terminals	+10%; N = 5km	8.61	0.32	0.24	0.014 (R^2 = 0.95)
		+20%; N= 10km	8.63	0.21	0.26	
		+30%; N=15km	8.77	0.29	0.40	
		+40%; N=20km	8.98	0.26	0.61	
9	L, M, and N Relocation terminals with ellipse-shared market area	+10%; L= 5km; M= 4.55 km; N=5km	14.02	0.26	5.65	0.90 (R^2 = 0.98)
		+20%; L=10km; M=8.33km; N=10km	22.66	0.51	14.29	
		+30%; L=15km; M=11.54km; N=15km	35.59	0.37	24.22	
		+40%; L=20km; M=14.29km; N=20km	42.54	0.36	34.17	

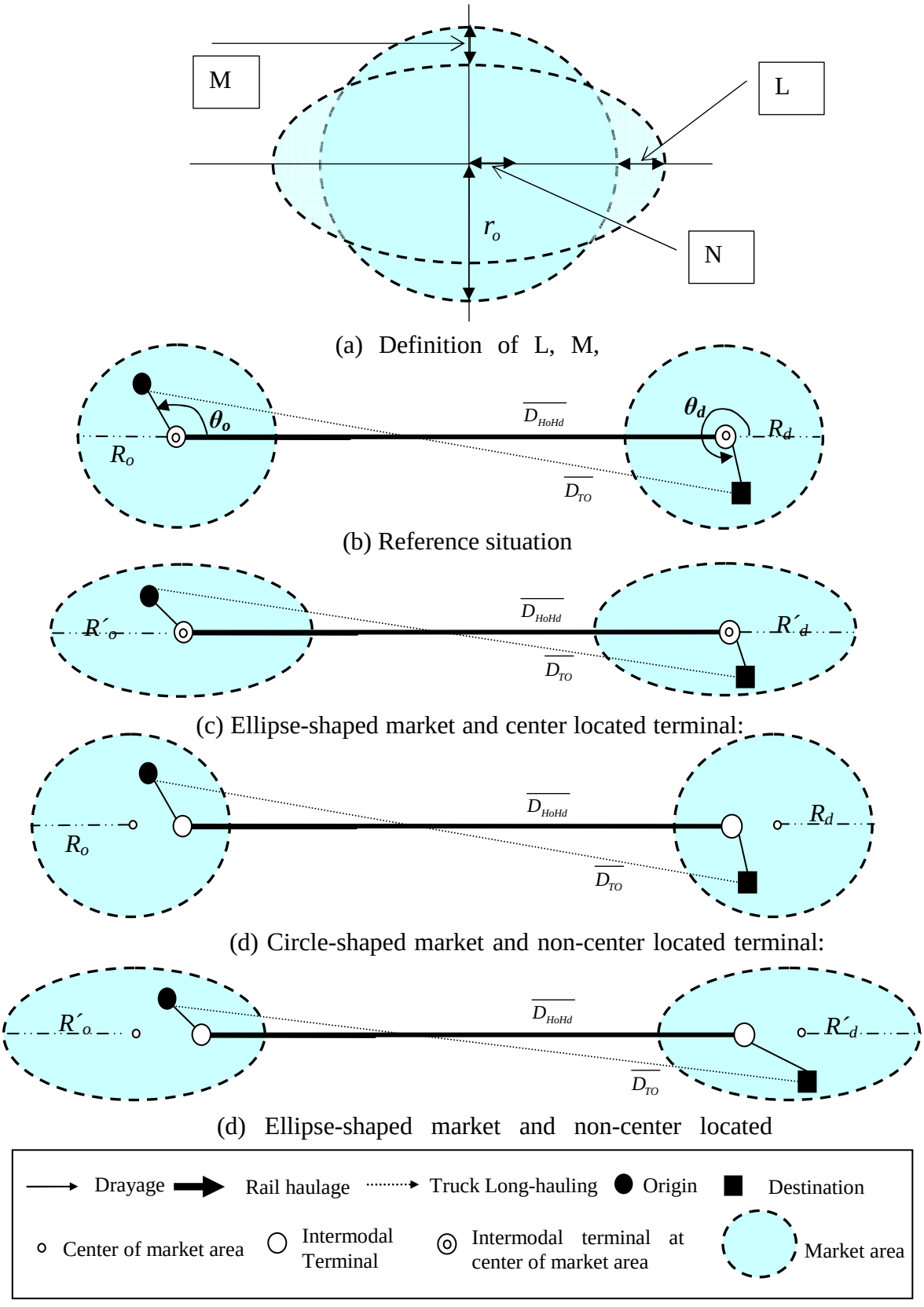
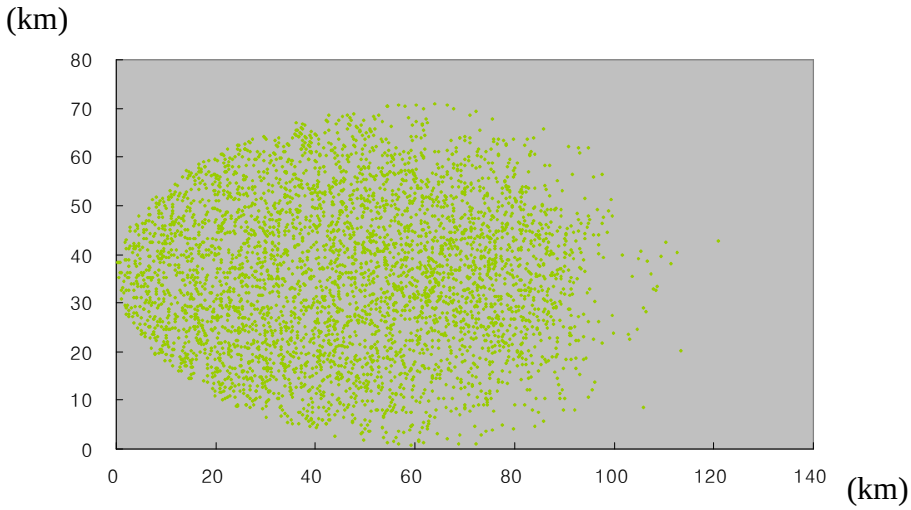
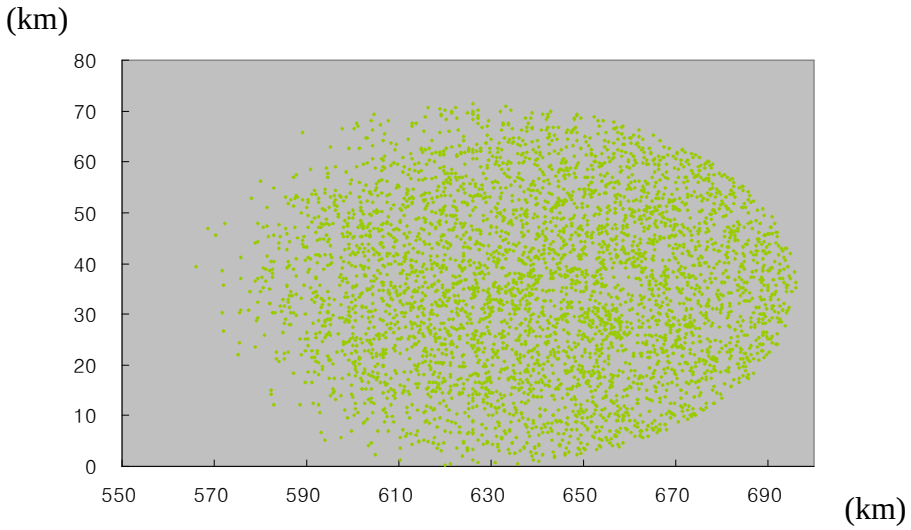


Figure 5.6 Graphical illustrations of tests in terms of ellipse-shaped market areas and terminal relocations

The result of sensitivity analysis for those factors is presented in Table 5.6. In test #7, as the circled market area changes to the proposed ellipse, the intermodal share does not change significantly. The low R^2 value indicates that the oval-shape change itself is not associated to the intermodal share. The minor changes presented result from the randomness. Test #8 examines the impact of the terminal relocation. Compared to the other tests in the previous section, the number of changes is very minor but clearly shows an increasing intermodal share. It is surprising to see the results of test #9 when test #7 and #8 are combined. Test #9 clearly shows the synergic effect: the effect on the intermodal share of combining the factors of test #7 and #8 is larger than the sum of the effects of tests #7 and 8.



(a) Intermodal Selected shippers



(b) Intermodal selected receivers

Figure 5.7 Spatial distributions for selected 4,259 shipper-receiver pairs (Test #9: +40% case)

This dramatic phenomenon reflects that more customers in the area 'behind' the terminal (i.e., the opposite direction of the main haulage) may select the intermodal option due to the increased truck-only distance and therefore accept the costs shown in Figure 5.7. Note that the three tests in this section are not comparable to the tests in the previous section. Specifically,

these two factors (i.e., shape of market area and the location of terminal) are handled separately because they are not fundamental factors such as drayage distance or truck-only distance but indirect geometric factors that influence fundamental factors.

5.6 Conclusions

Because the break-even distance of the intermodal freight system is highly dependent on the market situation, generalization is not possible, even though it is crucial information for both the private and public sectors involved in logistics. However, the relative importance (i.e., relative level of effectiveness) of several factors that influence the break-even distance can be evaluated in general terms. The factors considered in this study consist of geometric and cost factors. The former includes drayage distances (i.e., pre- and post-haulage by trucks), truck-only distance, rail distance, the shape of the market area, and the terminal location, while the latter includes the drayage truck rate, the long-distance truck rate, the rail rate, and the terminal handling rate. Because each factor is not deterministic, this study uses a Monte-Carlo simulation method, which can generate random values within certain ranges, to estimate the relative importance of the related factors.

Reviewing previous studies shows that the break-even distance is not well-defined in terms of average distance and perspective. Therefore, we categorized three break-even distances: $\boldsymbol{BE_{market}}$, $\boldsymbol{BE_{IM}}$, and $\boldsymbol{BE_{door\text{-}to\text{-}door}}$ that correspond to $\overline{D_{HoHd}}$, $\overline{D_{IM}}$, and $\overline{D_{TO}}$, respectively. These three geometric factors are systematically estimated using the Monte-Carlo method. This study also paid special attention to the cost function. Previously, cost functions have been calculated as a per-km constant function, while this study introduces distance-dependent costs for drayage rate, long-haulage rail rate, and long-distance trucking rate.

In the simulation model, we estimated the relative importance of changes of ± 10 and ± 20% in six geometrically-relevant models. A key finding is that the impact of changes in the geometric factor is not more significant than cost changes when distance-dependent cost functions are used. The specific result is that geometric factors (distances) and terminal handling costs are not more significant than transport costs (i.e., rail costs and long-distance trucking costs). In addition, the result also shows that reducing the drayage costs is not more effective than either an increase in long-distance truck costs or a decrease in rail costs. Thus, reducing drayage costs will not necessarily guarantee a sufficient increase in the intermodal share. More specifically, a one percent change in these factors is almost seven times, three times, and two times more effective than a one percent change in the handling costs at terminals, rail distance, and drayage costs, respectively. These results give intermodal operators insight that is useful for prioritizing investments that could reduce the logistical cost by shifting toward intermodal transport. The results could also be useful for policy makers to decide the priority of policy options, such as providing subsidies to stimulate intermodal transport. For example, increasing truck rates, e.g., by adding taxes, has been found to be the most effective policy to increase the intermodal mode share (see Table 5.5). If a fund to either increase the intermodal mode share or decrease the intermodal break-even distance is limited, it should have priority over reducing drayage costs ($\boldsymbol{R_o}$ and $\boldsymbol{R_d}$) and terminal cost ($\boldsymbol{c}$ ranked at 6). Furthermore, it was found that neither the oval-shaped market area nor terminal relocation significantly increased the intermodal share. However, when these two options were combined, a synergic effect occurred that led to a significant increase in intermodal transport. Our results

are useful for guiding decisions on new terminal locations while accounting for the shape of the potential market area.

Though we aimed to show the importance of several factors that influence break-even distances that are generally ignored in literature, we do not present a full overview of all factors that could be considered, nor did we include those factors in all possibly relevant ways. As a result, there are some limitations to our analyses. First, the radius defining the origin market area (R_o) and the destination area (R_d) are assumed to be equal. It may be interesting to study the impact of unequal market area sizes. Second, this study only takes into account the economies of distance, which is one economy of scale in freight transport. The economies of scale based on quantity (i.e., cheaper rate as quantity increase) could also be another important factor, although it is expected that there may be a correlation with economies of distance. Third, in our study we only focus on the *strategic* level. At the *operational* level, factors such as speed (including congestion levels), and 'just-in-time aspects' may be important. Fourth, the sampling method used in this study could be improved. As often is the practice in (GIS-based) spatial analysis, it is an option to lay a fine mesh on the study area and uniformly draw in each cell. However, even in this case, matching such two points randomly and making OD pairs might be required. The result will not be significantly changed, but the sampling method will be more straightforward. Fifth, the cost functions could be enhanced by accounting for labor laws that limit the number of consecutive hours of driving. Finally, future analyses could include simulations with multiple terminals serving the territory, and then even the market area could be changed relative to the locations of the multiple terminals. The number of terminals and their spatial arrangement could then be varied and the response in terms of intermodal market share analyzed. Despite these limitations, this study is still meaningful in terms of finding the priority based on the relative importance of factors relevant for the break-even distance when multiple options are available to increase the intermodal share (i.e., shortening the break-even distance).

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Appendix 5A

Figure 5A illustrates the cost curve for transport from a port to a destination. In this case, intermodal transport is more competitive because a drayage process is unnecessary at the origin area.

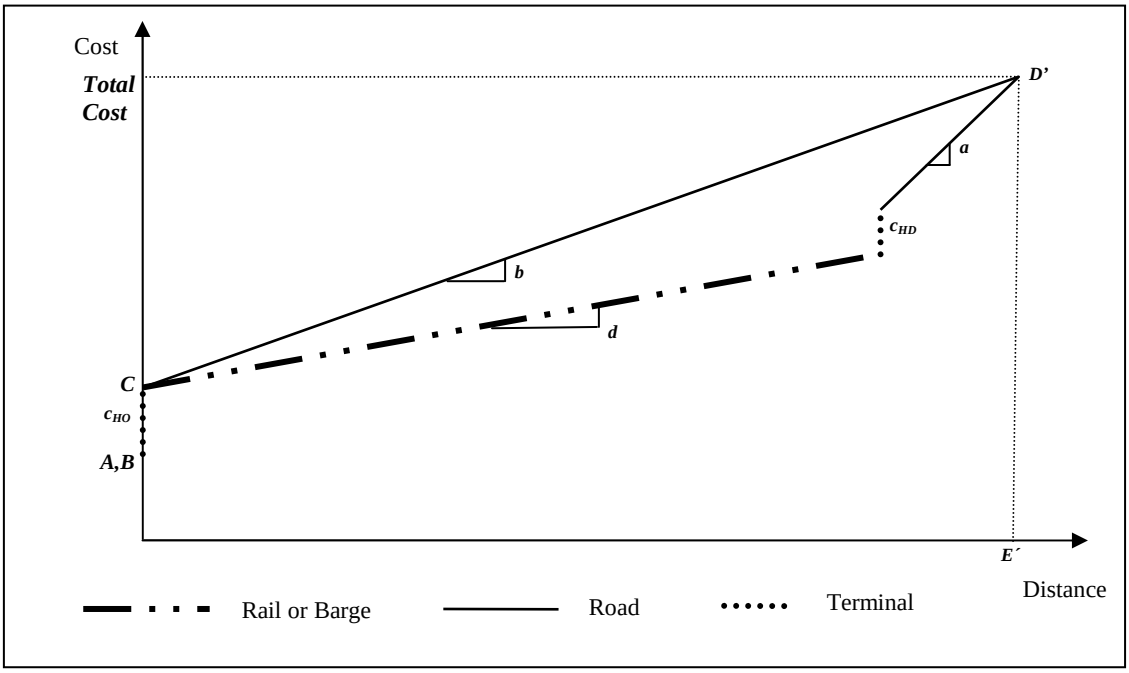


Figure 5A Comparison between intermodal system and truck-only system in the case of transport from sea ports to destinations

(Note, a similar graph is also shown in Rutten (1995) and Macharis and Pekin (2009))

Appendix 5B

Table 5B (a) Break-even distance from port[9]

Authors (year)	Condition	Drayage (km)		Long haulage (km)		Total (km)		Main long-haul mode	Commodity	Place (Origin and Destination)	Year
		Min	Max	Min	Max	Min	Max				
Resor, R. R. and Blaze, J. R (2004)	Before Double Deck introduction with on-dock rail	30	100	150	700	965	1,449	Rail	Container	Port of New York and New Jersey, U.S.	Before 2000
	After Double Deck introduction with on-dock rail	30	100	150	700	645	965	Rail	Container		2000
	After Double Deck introduction with on dock rail + drayage and terminal improvement (central control)	30	100	150	700	192	289	Rail	Container		
Ministry of Transport (MOT, 1994), Van Duin and Van Ham (2001), Konings and Ludema (2000), Bontekoning and Priemus (2004)	Barge					100		Barge	Container	Europe	1994
	Rail					200		Rail	Container	Europe	

Table 5B (b) Break-even distance in the case of door-to-door trip

Authors(year)	Condition	Drayage (km)		Long-haulage (km)		Total (km)		Main long-haul mode	Commodity	Place (Origin and Destination)	Year
		Min	Max	Min	Max	Min	Max				
Van Klink and Van Den Berg (1998)						500		Rail	Container	Europe	
ICF	Min= 1991, Max=2002					784	952	Rail	Container	Europe	1991 - 2002
Kombiverkehr	Domestic					350		Rail	Container	Europe	1998
UIRR in Bärthel and Woxeniu(2004)	Min=Domestic, Max=International					550	760	Rail	Container	Europe	
Rutten (1995)	Possibly	50	50			100		Rail	Container	Europe	
Bärthel and Woxenius (2004)	Short terminal stops and night haul	50	50			650		Rail	Container	Europe	
Ministry of Transport (MOT, 1994), Van Duin and Van Ham (2001), Konings and Ludema (2000), Bontekoning and Priemus (2004)	Survey/Typical					250		Barge	Container	Europe	1994
						400		Rail	Container	Europe	

[9] Concerning the values of "min."and "max." in Tables B (a) and B (b), it should be noted that these are not absolute values. They are conditional to the assumptions as made in the respective studies, e.g. with respect to the geographical area or market segment.

Table 5B(b) (Continued)

Authors(year)	Condition	Drayage (km)		Long haulage (km)		Total (km)		Main long-haul mode	Commodity	Place (Origin and Destination)	Year
		Min	Max	Min	Max	Min	Max				
Fowkes et al.(1989a)	Min=20 foot container and 90% utilization, Max=40 foot container and 50% utilization			322	644			Rail	Container	U.K.	1987
Stock J.R. and Lambert D.M. (1987)	Neither (i.e. min and max) are the break-even distance but average distance. We assumed the average distance was found by the authors since the economical feasibility on the distance is reflected by the market.			617				Rail	Container	U.S.	1987
				376	1367			Barge			
Oum (1979)	Min (320km) = Nonmetallic basic product Max (640km) = Fruit, Vegetable c.f. : 480km - Other refined petroleum products					320	640	Rail	Different types of commodities	Canada	1979
Morlok and Spasovic (1994)	Typical	160								U.S.	1994
Janic et al. (1998)	Innovative bundling network Min = Competitiveness to road haulage Max= Complete domination					150	500	Rail	Container	Europe	2002
Janic (2007, 2008)	The full cost including internal and external costs Min: high frequency of train operation (20 trains/ week) Max: current frequency of train operation (5 trains/week)	50	75			650	1050	Rail	Container	Europe	2002
Nierat (1997)		57		630					Container	Europe	1997
Kim et al. (2009)	Market Observation	50	200	1200		1300			Container	Europe	2008
Giannopoulos and Aifantopoulou-Klimis (1996)	Typical					500		Rail	Container	Europe	1997
Kreutzberger (2008)	Market Observation, economic analysis, network analysis	25				600			Container	Europe	

Appendix 5C: A simulation model

This appendix is designed to demonstrate Eq. (3) ($\overline{D_{IM}} \neq \overline{D_{TO}} \neq \overline{D_{HoHd}}$, where $\overline{D_{IM}} = \overline{D_{HoHd}} + \overline{D_{drayage\_o}} + \overline{D_{drayage\_d}}$) and to find a relationship among these factors. In both the origin and destination areas, uniformly distributed 5,000 random points are generated and matched for the 42 combinations consisting of $\overline{D_{HoHd}}$ and R (see the table below). Based on Eq. (10), the average distance between two points is estimated for all combinations. $\overline{D_{TO}}$ can be estimated by repeating this procedure 20 times. Table 5C and the regression model below contain the details.

Table 5C Simulation results for estimating $\overline{D_{TO}}$ with 100km step of $\overline{D_{IM}}$ and 25 km step of *R*

	$\overline{D_{HoHd}}$ (km)	R (km)	$\overline{D}_{TO}$ (km)	S.D.		$\overline{D_{HoHd}}$ (km)	R (km)	$\overline{D}_{TO}$ (km)	S.D
1	500	50	501.19	0.50	22	800	50	800.80	0.46
2	500	75	502.95	0.68	23	800	75	801.97	0.80
3	500	100	505.20	0.94	24	800	100	803.15	1.07
4	500	125	507.72	1.56	25	800	125	804.74	1.31
5	500	150	510.68	1.73	26	800	150	806.72	1.63
6	500	175	515.26	1.71	27	800	175	810.58	2.22
7	500	200	521.13	1.84	28	800	200	812.64	2.09
8	600	50	601.01	0.52	29	900	50	900.57	0.46
9	600	75	602.60	0.64	30	900	75	901.37	0.89
10	600	100	604.28	1.09	31	900	100	902.81	0.98
11	600	125	606.64	1.27	32	900	125	904.50	1.18
12	600	150	609.07	1.42	33	900	150	906.05	1.41
13	600	175	612.94	1.55	34	900	175	908.55	2.34
14	600	200	616.86	1.49	35	900	200	910.88	2.59
15	700	50	700.98	0.38	36	1000	50	1000.36	0.58
16	700	75	702.22	0.70	37	1000	75	1001.35	0.63
17	700	100	703.78	1.17	38	1000	100	1002.34	0.97
18	700	125	705.41	0.75	39	1000	125	1004.01	1.38
19	700	150	708.08	1.22	40	1000	150	1005.93	1.59
20	700	175	711.14	1.41	41	1000	175	1007.22	2.21
21	700	200	713.95	2.16	42	1000	200	1010.42	1.47

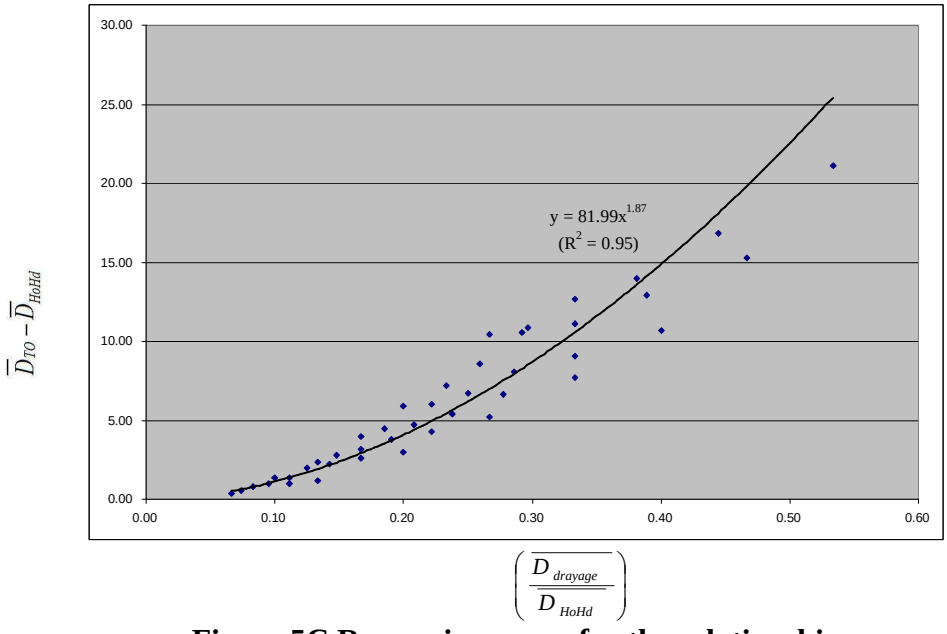


Figure 5C Regression curve for the relationship

Appendix 5D: Distance-dependent cost function

Table 5D Distance-dependent unit cost and total costs (Janic, 2009)

Unit cost = $5.46 \times Dist^{-0.278}$ (Euro/km)

Distance	Unit cost	total cost = Distance × Unit cost	
50	1.84	92.01	Used for drayage
100	1.52	151.77	
150	1.36	203.39	
200	1.25	250.34	
250	1.18	294.11	Used for Long distance truck-only system
300	1.12	335.49	
350	1.07	374.98	
400	1.03	412.93	
450	1.00	449.59	
500	0.97	485.12	
550	0.94	519.68	
600	0.92	553.37	
650	0.90	586.29	
700	0.88	618.52	
750	0.87	650.11	
800	0.85	681.12	
850	0.84	711.60	
900	0.82	741.58	
950	0.81	771.10	
1000	0.80	800.19	

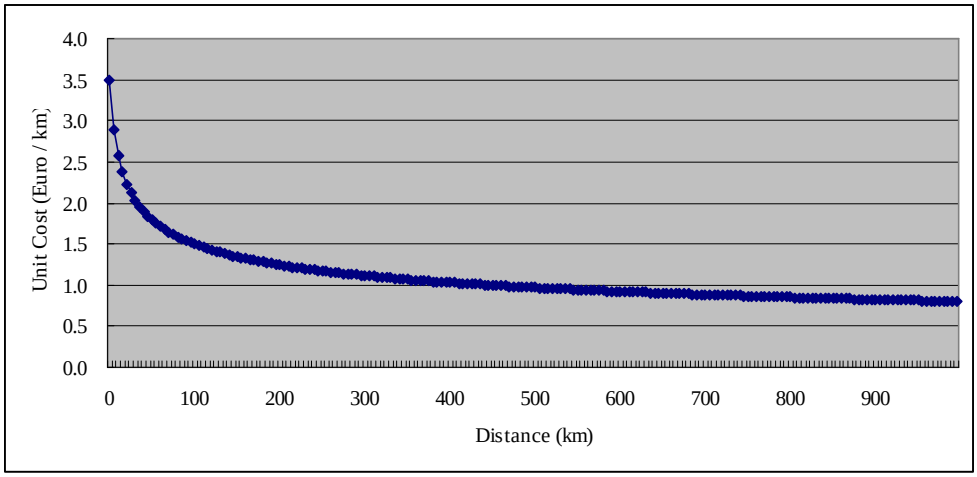


Figure 5D.1 Distance dependent Unit cost function

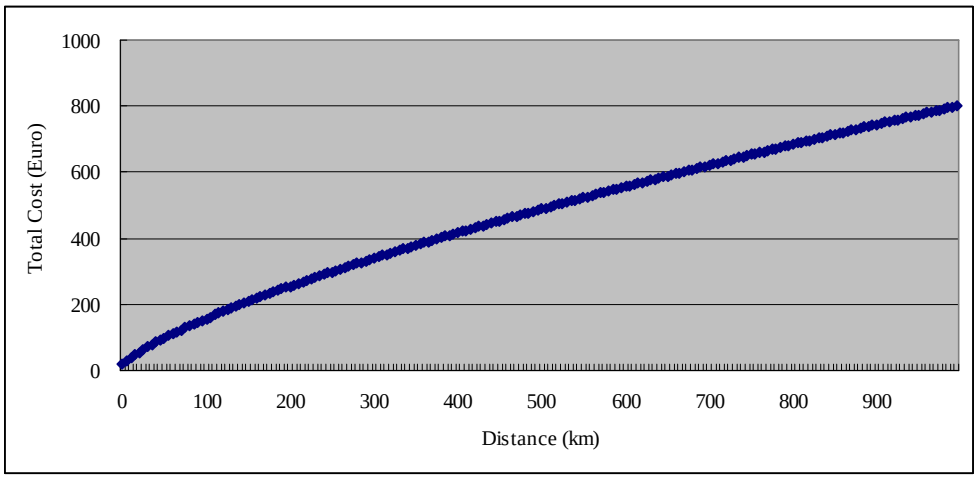


Figure 5D.2 Distance dependent total cost function

Chapter 6
Formulation and application of the multimodal minimum cost flow problem incorporating economies of scale

Nam Seok Kim[a], Byungkyu (Brian) Park[b], and Bert Van Wee[a]

[a] Delft University of Technology, The Netherlands
[b] University of Virginia, The United States

This Chapter is based on a paper that was accepted for the presentation at the Transportation Research Board (TRB) 90th annual meeting and that was submitted to the Journal of Advanced Transportation in 2010.

Abstract

This study developed a framework incorporating economies of scale into the multimodal minimum cost flow problem. To properly account for the economies of scale observed in practice, we explicitly modeled economies of scale on quantity, distance and vehicle size in a given multimodal freight network. The proposed multimodal minimum cost flow problem contains concave equations due to economies of scale for quantity, non-linear equations due to economies of scale for both quantity and distance, and non-continuous equations due to the economies of scale for vehicle size. A genetic algorithm was applied to find acceptable route, mode, and vehicle size choices for the multimodal minimum cost flow problem. Four scenarios considering various demand and capacity including the current logistics operating scenario in a Western-Eastern European corridor were examined. The GA optimization results demonstrated how the economies of scale influenced system (mode), route choices, and total cost under various demand/service capacity scenarios. In addition, the vehicle batch strategy for each near-optimal solution is found for the four scenarios.

6.1 Introduction

The intermodal freight system has been recognized as an alternative to the truck-only system (EC, 1997, 1998, 2001, USDOT, 1991). Despite its disadvantages—such as high extra costs for relatively short-distance collection/distribution by trucks (referred to as either drayage or pre- and post- haulage) and their transshipments, congestions at ports and intermodal terminals and a less-flexible schedule—the intermodal freight system still has great potential to significantly reduce total logistics costs, mainly through economies of scale gained in long-haulage by non-road transport modes such as waterborne vessel or rail. However, it is generally understood that specifying economies of scale in a cost function is quite difficult (McCann, 2001). Especially when the cost function is formulated for an Operational Research (OR) problem, to solve it practically the problem the formulated cost function has been often over-simplified such as linear function. Thus, the economies of scale was not fully incorporated in OR problems. To properly take into account the economies of scale in OR problems, non-linear function and even non-continuous function if necessary should be considered. In addition, as the number of transport modes increases in a given network, the formulation and solution of OR problems generally become more complicated. Thus, if a multi-modal related network problem such as Multimodal Minimum Cost Flow Problem (MMCFP) with non-linear and even non-continuous objective functions would be considered, it is extremely difficult to solve it by traditional linear- and non-linear programming methods. This study aims to formulate the MMCFP incorporating economies of scale and to solve it by using a proposed genetic algorithm based heuristic algorithm. The expected outcome of this study is mode (system[1]) /route choice with batch strategy for the given ODs either directly or via hubs (for example, "Ten A type (e.g. 1 TEU truck or 2 TEU truck) of trucks and B type of train are selected between node 1 and hub 1 → the combination of a C type of vessel and D type of train are selected between hub 1 and hub 2 → E type of train and five A type of trucks share are selected hub 2 and node 2"). The core of this outcome, which has not been shown in previous studies, is the feasibility to select multiple modes with different sized vehicles between two nodes.

There are three newly added components influencing the modeling and solution as follows:

- Enhanced Multi-modal network representation (Section 2)
- Cost functions incorporating economies of scale in the form of OR problem (Section 3)
- Solution technique to solve the proposed OR problem (Section 4)

As noted, the multimodal transport operations in practice are often oversimplified in OR problem formulation. In this study, based on the definition of intermodal freight transport system, some overlooked multimodal network issues are incorporated. This enhanced multi-modal network captures more realistic intermodal options. We defined three types of economies of scale existing in a freight transport market: Economies of Scale for Quantity (ESQ), Economies of Scale for Distance (ESD), and Economies of Scale for Vehicle Size (ESVS). In general, ESQ, ESD, and ESVS can be defined as the cost discount effect as quantity shipped, distance travelled, and the vehicle size increase, respectively. The cost function incorporating those three different types of economies of scale is the main

[1] The sequence of transport modes

component of the objective function of the proposed MMCFP. The cost function is examined in Section 3 while the MMCFP based on the cost function is formulated in Section 4. It is notable that the formulated objective function in MMCFP is non-linear, non-continuous, and non-convex. Thus, meta-heuristic approach instead conventional linear programming and non-linear programming methods is appropriate to solve it. We developed a GA-based heuristic algorithm to solve the proposed MMCFP in Section 5. The added value is that since handling constraints is most challenging part when a GA is used, the developed algorithm paid special attention to effectively treat the constraints in the MMCFP. Finally, the developed GA-based algorithm for the MMCFP is tested in a small multimodal network in Europe. Then, the final outcome for the given network is presented: route/mode choice and the batch strategy for the chosen route/modes in terms of combination of different sized vehicles.

6.2 Proposed network representation and route/system choice sets

We begin our discussion by defining an intermodal freight system. The European Conference of Ministers of Transport (ECMT) defined the intermodal (combined) transport system as follows:

> Combined transport is a transport in which the major part of the European journey is carried out ***by rail, inland waterways or sea*** and in which any initial and/or final legs carried out ***by roads*** are as short as possible (ECMT, 1998).

It is explicitly pointed out that trucks take the initial and final legs (i.e., short distances) and non-road modes serve for the main haulage (i.e., longer distances). Thus, when a multimodal network is drawn in this study, we assume all initial and final trips are done by trucks even though there are some exceptions in practice. In order to properly reflect in the form of drawn multimodal network, we speculate the aggregation of nodes. When a node is represented in a multi-modal network, it is generally assumed that all individual shippers/receivers are located at the center (so-called centroid). In the case of truck-only system, it makes sense since some shippers are advantageous in terms of the distance travelled to the receivers and the others are not. However, in the intermodal cases, we need to consider some extra transport costs within a node if the node is not a real shipper/receiver. More specifically, if two nodes are connected with three modes as shown in Figure 6.1(a), the intermodal terminals for rails or vessels should be hidden nodes. Otherwise, those trips are special cases rather than general intermodal trips. If nodes could be represented as shippers' and receivers' real locations, Figure 6.1(b) is more appropriate. In addition, since hubs are explicitly represented, it would be realistic to add some constraints at hubs. However, collecting and presenting all the locations of shippers/receivers is time consuming. Alternatively, we propose an enhanced multimodal network with penalty concept assuming that all shippers must pay for extra operational costs within any nodes unless they would select truck-only systems. Figure 6.1(c) and 6.1(d) describe the proposed multimodal network representation with non-road drayage penalty ($\delta_{initial}$) and extra transshipments ($TSc_{(truck,\ rail)}$). This study only considers rail-drayage as a non-road drayage since rail network at the regional level is mostly as dense as road network.

The penalty concept shown in Figure 6.1(d) leads to the more realistic and flexible option such as truck → rail → vessel → rail → truck rather than the conventional intermodal option such as truck → rail → truck. Based on the proposed network representation, Figure 6.2 shows an example of arc (1,3) with nine feasible combinations of transport modes. Obviously,

these nine feasible combinations are applicable to any other OD. *r* indicates the feasible combinations; *r* = 1 is the truck-only system; *r* = 2 and 6 are the conventional rail based- and vessel based intermodal system respectively. The others (*r* = 3, 4, 5, 7, 8, and 9), so-called "2nd level intermodal systems", have at least one rail-drayage at either initial or final leg. Note, a penalty is applied for all the 2nd level intermodal systems due to the extra drayage described in Figure 6.1(d).

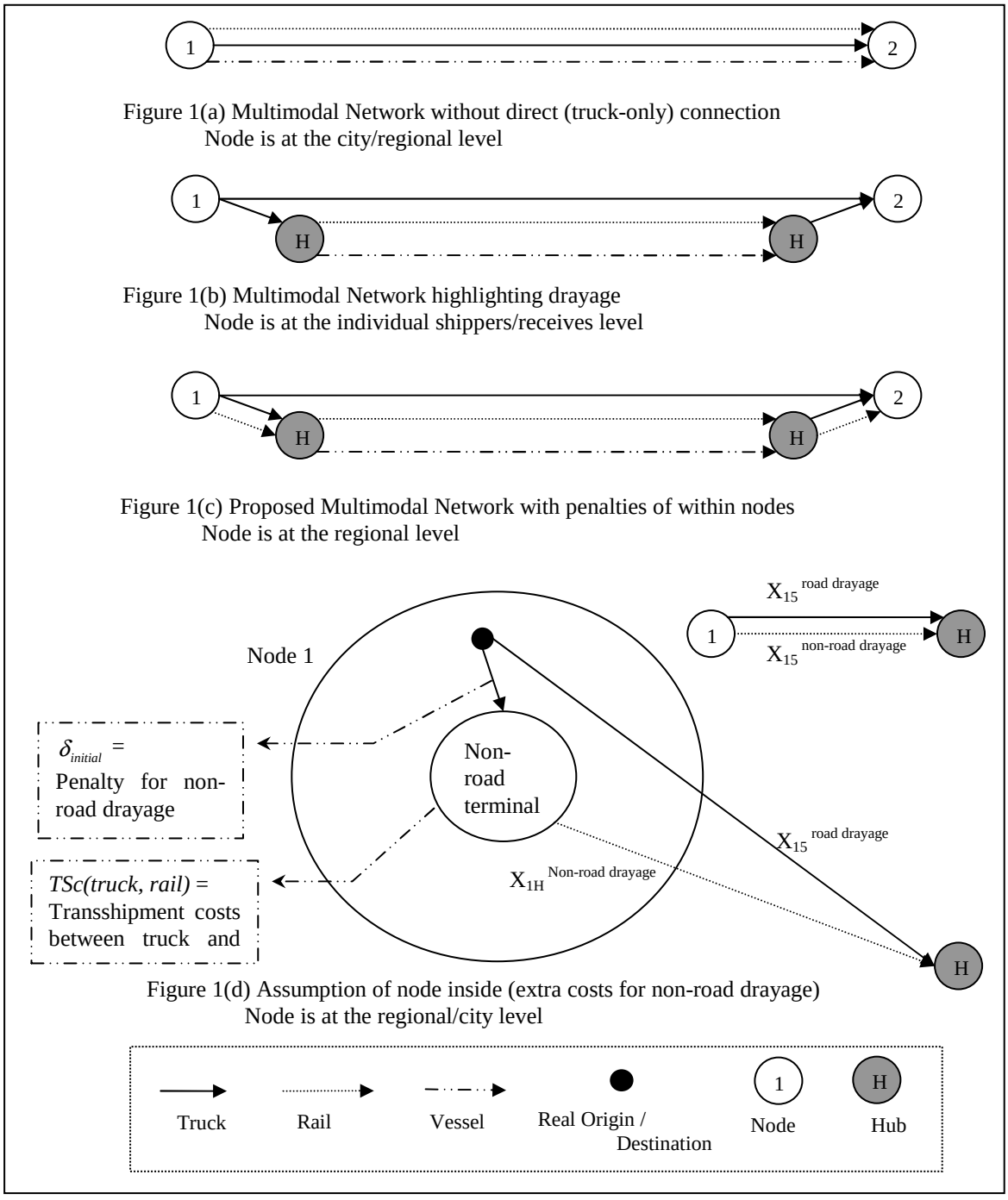


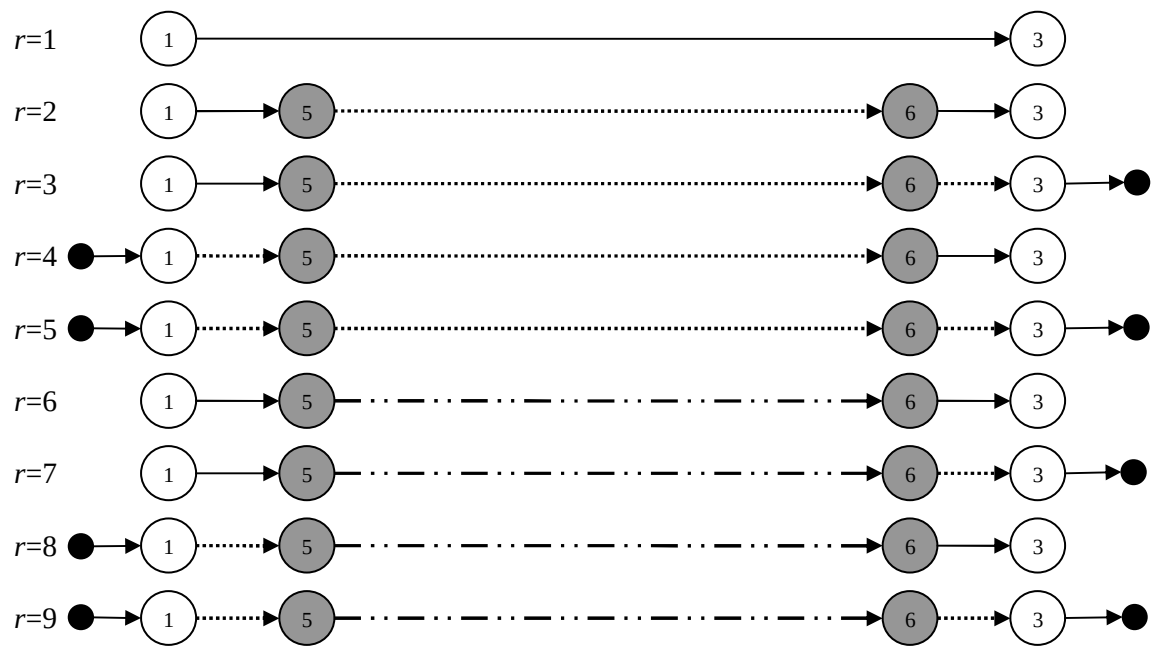
Figure 1(a) Multimodal Network without direct (truck-only) connection
Node is at the city/regional level

Figure 1(b) Multimodal Network highlighting drayage
Node is at the individual shippers/receives level

Figure 1(c) Proposed Multimodal Network with penalties of within nodes
Node is at the regional level

Figure 1(d) Assumption of node inside (extra costs for non-road drayage)
Node is at the regional/city level

Figure 6.1 Multimodal network representation



Options (r)	Mode(s) : $k_n \in K$					Description
	Penalty ($\delta_{initial}$)	Pre-haulage (k_1)	Main haulage (k_2)	Post-haulage (k_3)	Penalty (δ_{final})	
1	***0***	***0***	***1***	***0***	***0***	Truck-only system
2	***0***	***1***	***2***	***1***	***0***	Conventional Rail-based intermodal system
3	***0***	***1***	***2***	***2***	***P***	Rail-based intermodal system with rail-post haulage
4	***P***	***2***	***2***	***1***	***0***	Rail -based intermodal system with rail-pre haulage
5	***P***	***2***	***2***	***2***	***P***	Rail-based intermodal system with rail-pre/post haulage
6	***0***	***1***	***3***	***1***	***0***	Conventional Short sea-based intermodal system
7	***0***	***1***	***3***	***2***	***P***	Short sea-based intermodal system with rail-post haulage
8	***P***	***2***	***3***	***1***	***0***	Short sea-based intermodal system with rail-pre haulage
9	***P***	***2***	***3***	***2***	***P***	Short sea intermodal system with rail-pre/post haulage

1, ***2*** and ***3*** indicate truck, rail, and vessel, respectively.
P in the penalty columns indicates that extra trucking costs are required for handling initial collections or final distributions.

Figure 6.2 Description of feasible intermodal choice sets

6.3 Previous and proposed unit cost functions incorporating economies of scale

In many MMCFPs, *the unit cost* is assumed as a linear function that is proportional to either quantity (e.g. TEU[2]), distance (e.g. km), or the composite form (e.g. TEU-km) for analytical simplicity. An ideal way to specify these three types of economies of scale in a MMCFP would be to develop a comprehensive *unit cost function* that is likely to be a non-linear

[2] TEU is Twenty-foot Equivalent Unit

function of quantity, distance, and vehicle size, and to incorporate such a comprehensive function into the objective function. It is straightforward that the unit cost function plays a vital role in many OR models including MMCFPs. This is because the total cost in objective function is determined by multiplying the unit cost function with the assigned quantities (a decision variable in many cases).

6.3.1 Previous unit cost function incorporating economies of scale in OR problem

When considering ESQ (Economies of Scale in terms of Quantity) only in most of the previous OR problems, the unit cost in the objective function has been over-simplified to be as

- constant unit costs that are homogeneously applied to every link (arc) and are consequently linearly associated with the quantity assigned to it (Skorin-Kapov et al., 1996)
- piecewise linear cost functions in which the unit cost is stepped down when the quantity shipped is over a certain assumed quantity criteria (Chang, 2008), or
- non-linear discount functions that are dependent only on quantity (O'Kelly and Bryan, 1998, Horner and O'Kelly, 2001, Racunica and Wynter, 2005)

The prototype of the objective function for a MMCFP is to minimize the total cost, TC_{ij}, as follows:

$$\text{Minimize } TC_{ij} = \sum_{(i,j)\in A} C_{ij} X_{ij} \quad (1)$$

Where $\boldsymbol{A}$ is a set of arcs between nodes i and j
C_{ij} is a unit cost for arc (i,j) (€ / TEU[1])
X_{ij} is a decision variable for arc (i,j) (TEU)

Unit cost (C_{ij}) generally plays a key role in these kinds of problems. Skorin-Kapov et al. (1996), for example, developed a model with a fixed constant discount factor between hubs to attempt to describe ESQ in the hub location problem as follows:

$$\text{Minimize } TC^k_{lm} = \sum_{(i,j)\in A} \sum_{(l,m)\in H} \sum_{k\in K} \alpha_{lm} \times C^k \times X^k_{ij} \times d^k_{lm} \quad (2)$$

Where
TC^k_{lm} is the total cost between hubs $(l,m) \in$ H, for mode k (€)
α_{lm} is a discount factor between hubs $(l,m) \in$ H
C^k is the *constant* unit cost of flows between hubs $(l,m) \in$ H (€/TEU-km)
X^k_{ij} is the quantity shipped between $(i, j) \in$ A (TEU)
d^k_{lm} is the distance between hubs $(l,m) \in$ H (km)

C^k is not expressed as a function of quantity or distance but constants depending on mode (k). Therefore, any economies of scale can not be expressed with C^k. If this constant were estimated with consideration of economies of scale, this model would have taken into account only ESQ at most that indirectly affect inter-hub flows. O'Kelly and Bryan (1998) developed a

[1] TEU is Twenty-foot Equivalent Unit

hub location problem considering ESQ only for passenger transports. They also assumed that economies of scale were gained in inter-hub links only. Racunica and Wynter (2005) overcame this assumption by allowing the amount of economies of scale on inter-hub links to be relatively larger than other local links (i.e., drayage or pre-/post- haulage). The simplified cost formulation adopted by the above studies is:

$$TC_{lm}^{k} = \sum_{(i,j)\in A} \sum_{(l,m)\in H} \left(C_{lm}^{k}(X_{ij}^{k}, \alpha_{lm}) \times X_{ij}^{k} \times d_{lm}^{k} \right) \quad (3)$$

Where $C_{lm}^{k}(X_{ij}^{k}, \alpha_{lm}^{k})$ is the unit cost function (€/TEU-km or €/ton-km) via hubs *l* and *m* where cost is **dependent** on flows X_{ij}^{k}.

The core of this approach was to develop the discount function $C_{lm}^{k}(X_{ij}^{k}, \alpha_{lm}^{k})$, which depends on quantity and the characteristics of the route between hubs. Such a discount function describing economies of scale has been commonly used in previous studies due to analytical simplicity (O'Kelly and Bryan, 1998, Horner and O'Kelly, 2001, Racunica and Wynter, 2005).

6.3.2 Proposed unit cost function incorporating economies of scale in OR problem

Although it is easy to estimate the demand-dependent cost function (i.e. $C_{lm}^{k}(X_{ij}^{k}, \alpha_{lm}^{k})$), it is still independent of both distance and vehicle size. As discussed in Jara-Díaz et al. (1992), both distance and quantity non-linearly affect the marginal cost. However, obviously, each mode has different dependencies with ESQ, ESD, and ESVS. That is, if the unit cost functions for each mode are properly developed, the issues of double-counting and correlations could be avoided. Moreover, some freight modes might have quantity-sensitive cost functions while others might have distance-sensitive (e.g., trucks) or vehicle-size sensitive (e.g., waterborne transport) cost functions. Since an intermodal freight system consists of more than two modes, it might be unfair for the cost to be solely a function of quantity (i.e., ESQ), ignoring ESD and ESVS.

Reflecting the above-mentioned issues, the objective function with the proposed unit cost function is:

$$TC_{ij}^{k} = \sum_{(i,j)\in A} \sum_{k\in K} \sum_{v\in V} \left(C_{ij}^{k}(X_{ij}^{k}, d_{ij}^{k}, S^{kv}) \times X_{ij}^{k} \times d_{lj}^{k} \right) \quad (4)$$

Where $C_{ij}^{k}(X_{ij}^{k}, d_{ij}^{k}, S^{kv})$ is the proposed *minimum* unit cost which is a function of quantity (X_{ij}^{k}), distance (d_{ij}^{k}), and vehicle size (S^{kv}) for *v* type of vehicle of *k* mode (|*v*| = the number of vehicle type) for each mode (*k*).

The minimum unit cost of *k* mode is defined as the minimum value among different unit costs depending on what types of vehicles are used. The minimum unit cost, $C_{ij}^{k}(X_{ij}^{k}, d_{ij}^{k}, S^{kv})$, will be shown in the case study (Table 6.1) based on previous studies assuming there are 3 types of vehicles for each mode (Janic, 2007, 2008, Cullinance and Khanna, 1999). In addition, if the shipped demand is greater than the capacity of the largest vehicle, multiple vehicles should be used. In other words, different unit costs can be found depending on batch strategy, which is related to ESVS. The algorithm for finding the minimum unit cost through the batch strategy is as follows:

Step 1: For each mode, set up initial given distances (d_{ij}^{k}) and v types of vehicle.
Step 2: Generate choice sets based on S^{kv} for each k. The number of choice sets is $2^{|v|}$-1. For example, if there are 3 types of vehicle (i.e., $|v| = 3$) indicating ***a***, ***b***, and ***c*** (***a*** is the largest and accordingly the most efficient if it is fully loaded), the number of choice sets (i.e., batch strategy) is 2^3-1=7; (***a***→***b***→***c***), (***a***→***b***), (***a***→***c***), (***b***→***c***), (***a*** only), (***b*** only), and (***c*** only).
Step 3: For each vehicle size and mode, estimate $C_{ij}^{k}(X_{ij}^{k}, d_{ij}^{k}, S^{kv})$ as X_{ij}^{k} increases.
Step 4: For each mode and each generated choice set, calculate the number of vehicles used and the number of remaining TEUs for one smaller level vehicle.
Step 5: For each mode, estimate $\Phi^{k}(X, d, C_n)$, where $\Phi^{k}(X, d, C_n)$ is the unit cost function of nth combination.
Step 6: Find the minimum unit cost and the optimal batch for given quantity (X) and distance (d).
Step 7: Increase the fixed distance up to a certain level and return to Step 3.

Figure 6.3 shows an example of the unit cost competition of three different freight systems based on Table 6.1. When Figure 6.3 is drawn, some details are assumed as follows:

- There are three different sized vehicles for each mode (i.e. seven choice sets (i.e., batch strategy))
- The vehicle types used in the test were 1 TEU, 2 TEU, and 2.5 TEU trucks; 60 TEU, 75 TEU, and 144 TEU trains; and 200 TEU, 500 TEU, and 800 TEU container ships.
- The distance travelled is 1,000km for a long-haulage and 50km for a drayage.

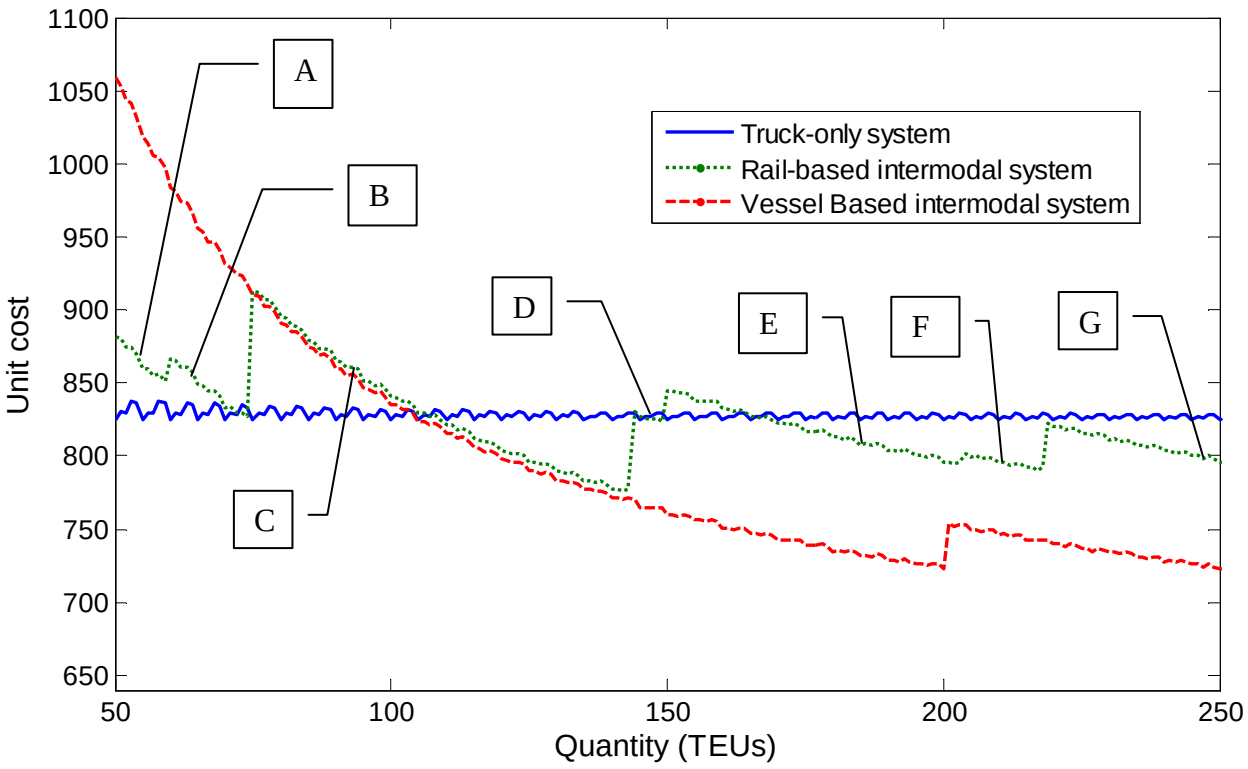


Figure 6.3 Comparison of minimum unit cost as quantity increases

In Figure 6.3, curves are broken when batch strategy is changed and accordingly the minimum unit cost is decreased. Vessel based intermodal system shows cost competitiveness after about 110 TEUs regardless of the batch strategy. For rail transport, the batch strategy changed seven times between the segments, indicated as A, B, C, D, E, F, and G in Figure 6.3. In segments A, B, and C, a 60 TEU train, a 75 TEU train, and a 144 TEU train were optimal, respectively. It is interesting that the 144 TEU train was more competitive than any combination of 60 and 75 TEU trains (somewhere in segment C) until reaching 144 TEU. In segment D, two 75 TEU train trips showed the minimum unit cost. The combination of a 144 TEU train and a 60 TEU train was found optimal in segment E (i.e., up to 204 TEUs of quantity). In segment F, the combination of a 144 TEU train and a 75 TEU train was optimal (i.e., up to 219 TEUs of quantity). From 219 TEUs of quantity, two 144 TEU trains showed the minimum unit cost. It is noted that very small fluctuations for both rail-based and vessel-based intermodal systems are caused by truck-drayage that also has batch strategies according to the assigned quantity. The non-continuous fluctuations of such graphs give the insight that many local minima in MMCFP are found when several batch strategies are considered. The total number of batch strategies is dependent on $|v|$ and $|k|$ where v is the number of vehicle size for each mode and k is the number of transport mode. Thus, as such variables increase, the local minima dramatically increase. More details are discussed in the next section.

6.4 Multimodal minimum cost flow problem and the GA-based heuristic algorithm

6.4.1 Formulation of a multimodal minimum cost flow problem incorporating economies of scale

Consider a network $G = (N, A)$, where N is a set of nodes and A is a set of arcs. There are four nodes in N: origin, destination, hubs in the origin area, and hubs in the destination area. These nodes are denoted as O, D, H_O, and H_D, respectively. The arcs are defined as a_{ij}^{k}, where i is the origin node, $i \in O$, j is the destination node, $j \in D$, k_n is a nth freight mode, and $k_n \in K$. Feasible routes are pre-defined as consecutive chains of individual arcs and denoted as r and specified in Figure 6.2, where r is an integer indicating the different combinations.

The objective function is as follows:

$$Z = \text{Min} \sum_{(i,j)\in A} \sum_{r\in R} \Phi_{ij}^{r} X_{ij}^{r} \tag{5}$$

Where X_{ij}^{r} is a container flow between i and j for r (TEU): Decision variable

Φ_{ij}^{r} is the minimum unit cost between i and j for r (€ / TEU)

Φ_{ij}^{r} is a function ruled by r. Depending on which r is assigned, the function value can be estimated. Thus, Eq. 5 is non-linear and even non-continuous. Generally, Φ_{ij}^{r} (unit: €/TEU) is a function of all drayage processes by all k, long-haulage by all k, necessary transshipments, and penalties for rail drayage. Specifically,

$$\Phi_{ij}^{r} = \delta_{initial} + TSc(truck, k_1) + C_{iho}^{k_1}(X_{iHo}^{k_1}, d_{iHo}^{k_1}, S^{kv}) \times d_{iHo}^{k_1} + TSc(k_1, k_2) + C_{hohd}^{k_2}\Big(\sum_{(i,j)\in A} X_{ij}^{k_2}, d_{HoHd}^{k_2}, S^{kv}\Big) \times d_{HoHd}^{k_2} + TSc(k_2, k_3) + C_{hdj}^{k_3}(X_{Hdj}^{k_3}, d_{Hdj}^{k_3}, S^{kv}) \times d_{Hdj}^{k_3} + TSc(k_3, truck) + \delta_{final} \tag{6}$$

Where

$k_n \in K$, k_1,k_2,and k_3 are the first, second, and third modes assigned, respectively

$\delta_{initial}$ is a penalty for rail drayage; a constant penalty if k_1 is rail (i.e., when r = 4, 5, 8, and 9), 0 otherwise (€ / TEU)

δ_{final} is a penalty of rail drayage, a constant penalty if k_3 is rail (i.e., when r = 3, 5, 7, and 9), 0 otherwise (€ / TEU)

TSc(k_1, k_2) is the transshipment cost between k_1 and k_2 (€ / TEU)

$C_{ij}^{k}(X_{ij}^{k}, d_{ij}^{k}, S^{kv})$ is the unit cost function embedding ESQ, ESD, and ESVS between i and j (€ / TEU–km).

There are four notable characteristics of Φ_{ij}^{r}. First, the unit of $C_{ij}^{k}(X_{ij}^{k}, d_{ij}^{k}, S^{kv})$ is €/TEU–km in order to include the effect of ESD in a given network. While ESD may not play a significant role in MMCFP since the distance is given, it is still worthwhile to include ESD because of (a) different levels of ESD for long distance transport gained mainly in the truck-only system and in non-road parts of the intermodal systems and (b) diseconomies of scale for short distance transport occurring mainly in short-distance drayage by trucks. Secondly, the optimal batch to find the minimum unit cost through testing all possible combinations of different vehicle sizes was considered to estimate $C_{ij}^{k}(X_{ij}^{k}, d_{ij}^{k}, S^{kv})$ as specified in the previous section. Note that the unit cost is not a fixed constant in this case but a function. The function values with the same demand (X_{ij}^{k}) and distance (d_{ij}^{k}) vary depending on how the different vehicle sizes (S^{kv}) are batched. Thirdly, transshipment costs between truck and rail, between rail and rail, and between truck and vessels are distinguished (EC, 2000). Thus, *TSc* is a function of modes involved. Finally, the demand in unit cost function for long-haulage, indicated as $\sum_{(i,j)\in A} X_{ij}^{k_2}$ in $C_{hohd}^{k_2}(\sum_{(i,j)\in A} X_{ij}^{k_2}, d_{HoHd}^{k_2}, S^{kv})$, is not for a single *OD* pair but the summation of all X_{ij}^{k2}. This allows the clear description of ESQ in long-haulage by non-road modes such as rail and vessel.

There are four constraints, as follows:

Constraint 1. Flow-conservation constraints (i.e., equality constraints)

$\sum_{r} x_{ij}^{r} = D_{ij}$, for all $(i,j) \in A$

Constraint 2. Mode availability constraints

$\sum_{r_k} \sum_{(i,j)\in A} x_{ij}^{r_k} \le u^{k}$, $r_k \subset r$, $k \in K$

Constraint 3. Hub capacity constraints

$\sum_{r_k} \sum_{(i,j)\in A} x_{ij}^{r_k} \le Hub^{k}$, $r_k \subset r$, $k \in K$

Constraint 4. Non-negativity constraints (lower bound)

$x_{ij}^{r} \ge 0$ for all r and $(i,j) \in A$

Where

D_{ij} is a given demand between i and j (TEU)

r_k is a k mode-related intermodal system (e.g., if k=1(truck), r_k = 1; if k=2(rail) r_k = 2, 3, 4, and 5; if k=3(vessel), r_k = 6, 7, 8, and 9)

u^{k} is k mode availability (TEU/week)

Hub^k is the capacity of hubs for transshipments for mode k (TEU/week) (e.g., if k=2, Hub^k is rail intermodal terminal capacity; if k=3, Hub^k is port capacity)

In *Constraint 2*, it is assumed that the rail-based intermodal system (r = 2) and the 2nd level rail-based intermodal systems (r = 3, 4, and 5) use the same freight train service and share the same limited capacity (i.e., train slots). The same assumption is similarly applied to four short sea shipping options (i.e., r = 6, 7, 8, and 9).

6.4.2 GA-based heuristic algorithm for solving a MMCFP

A Genetic Algorithm (GA) is a powerful optimization method of finding a near-optimal solution, especially for non-linear and even non-continuous functions such as the one proposed in this paper. The rationale for introducing GA for the proposed problem is that traditional linear and non-linear methods cannot solve such a problem. Specifically, due to the dependence of Φ_{ij}^r on X_{ij}^k and accordingly X_{ij}^r as presented in Eq. 6, the number of feasible system/route choices for each O-D set is not simply $X_{ij}^r \times r$. The numerous combinations of route options and batch strategies in the proposed model make it more complicated than a general MCFP. The complexity of the proposed problem and the reason to use GA are demonstrated with a simple example in Appendix 6A.

However, the Genetic Algorithm (GA) was not a perfect method that always guarantees the optimal solution as widely known. Nevertheless, as mentioned previously and shown in Appendix 6A, it seems to be a feasible method to find at least the near-optimal within reasonable computation time. The more serious issue in the GA is to handle constraints in OR problem (Michalewicz, 1995, Michalewicz and Schoenauer, 1996, Deb, 2000). In this study, a heuristic method to overcome such a weakness is developed. Specifically, this study attempted to overcome this disadvantage by modifying the initial population (Michalewicz and Fogel, 2000) and developing penalty functions (Michalewicz, 1995). The outcome of the developed GA-based heuristic approach is the near-optimal solution for route, mode, and vehicle size choices including batch strategy. The basic idea and mechanism of the GA can be found in Holland (1975). The settings we used in this study were

- Real encoding rather than Binary encoding
- Stochastic universal sampling
- Modified simple crossover
- Dynamic mutation
- Elitism

The procedure of the algorithm highlighting initial population generation ensuring the equality constraint is specified in Appendix 6B.

6.5 Case study

In this section, a GA is applied in a case study and a near-optimal solution is found in terms of system choice, route assignment, and batch strategy for given demand-capacity sets.

6.5.1 Study area network and OD pairs

The case study examines a multi-modal network between Western Europe and Eastern Europe. Figure 6.4 presents distances between six nodes and multi-modal links. Nodes 1, 2, 3, 4, 5, and 6 indicate Amsterdam, Brussels, Warsaw, Vilnius, Rotterdam, and Gdansk, respectively. The distances are estimated by using the shortest path finder of GIS (Geographic Information System) for each multimodal network. Using the node notation defined in the previous section, O = [1,2], D= [3,4], H_O =[5], H_D =[6].

The demands (container flows) in the *OD* sets were estimated based on the European Statistic Bureau (Eurostat, 2008). The current container flows for (1 → 3), (1 → 4), (2 →3), and (2 →4) are 315, 27, 217, and 13 TEUs respectively. The service capacity of truck, rail, and vessel are 400, 150, and 200 TEUs respectively. A project proposal for new short sea shipping between Rotterdam and Gdansk was used to reflect the capacity of vessels in service (Rotterdam, 2007). However, since the demand and service capacity could be uncertain to some extent, we examined three more cases: current demand with unlimited capacity (Scenario 2), double demand with doubled service capacity (Scenario 3), and double demand with unlimited capacity (Scenario 4).

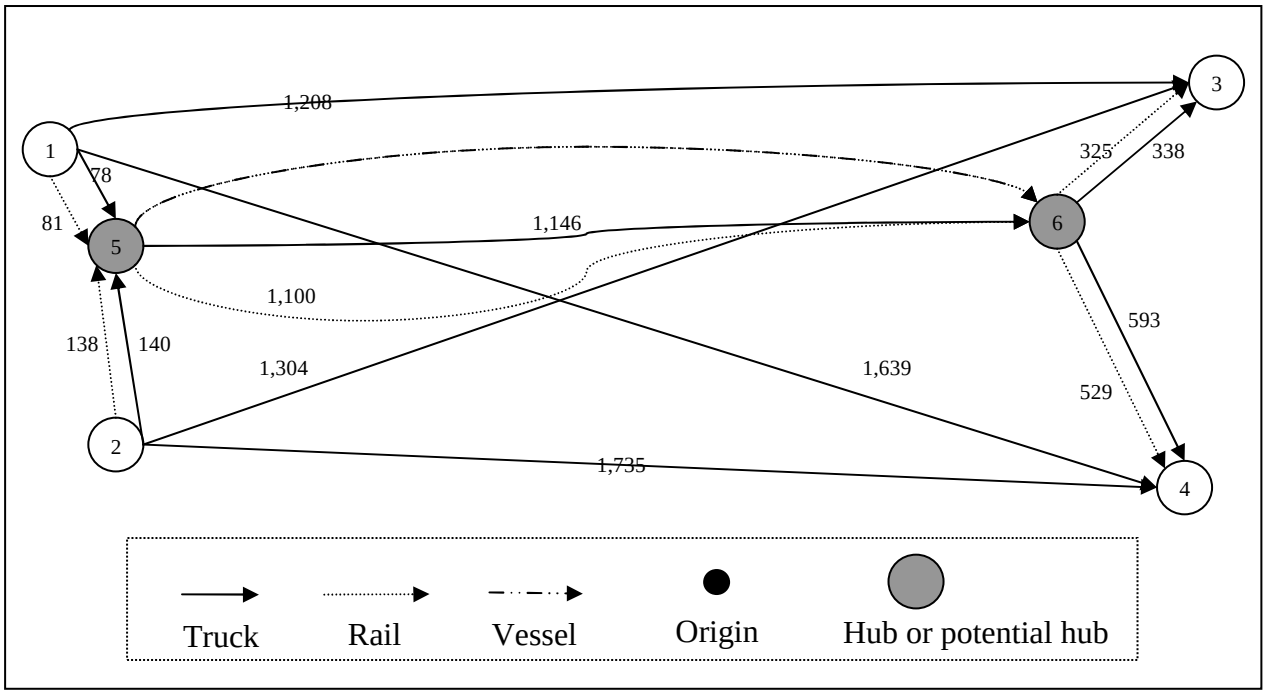


Figure 6.4 Distance (d_{ij}^k) in case study area (Unit: km)

6.5.2 Cost functions incorporating economies of scale ($C_{ij}^k(X_{ij}^k, d_{ij}^k, S^{kv})$)

It is a challenging task to develop the cost functions formulated in Eq. 6. The original equations for trucks and trains were obtained from Janic (Janic, 2007, 2008) while those for vessels were taken from Cullinane and Khanna (1999). $C_{ij}^k(X_{ij}^k, d_{ij}^k, S^{kv})$ for each mode (k) is estimated by modifying these three original cost functions as presented in Table 6.1. Note that the cost functions in Table 6.1 are used to plot for Figure 6.3.

Table 6.1 Unit cost function by mode and size of vehicles: $C^k(X, d^k, S^{kv})$

k	S^V		Unit cost function: $C^k(X, d^k, S^{kv})$
k=1	Basic formulation (Janic, 2007, 2008)		Cost (€/vehicle-km)[4] = $\alpha \times (d^1)^\beta$ Where α = 5.46, β = -0.278 $\Omega^1(X, D, S^{11}) = \gamma^1 \times (\frac{5.46}{2} \times (d^1)^{0.278})$ (€/TEU-km) $\Omega^1(X, D, S^{12}) = \gamma^2 \times (5.46 \times (d^1)^{0.278})$ (€/2TEU-km) $\Omega^1(X, D, S^{13}) = \gamma^3 \times (\frac{5.46}{2} \times 2.5 \times (d^1)^{0.278})$ (€/2.5TEU-km) Where γ^1, γ^2, and γ^3 are weight factors assumed as 1.0, 1.1 and 1.2, respectively.
	v=1	S^{11} = 1 TEU	$C^1(X, d^1, S^{11}) = 1.2 \times \frac{\alpha}{2} \times (d_{ij}^{\cdot})^\beta$ (€/TEU- km)
	v=2	S^{12} = 2 TEU	$C^1(X, d^1, S^{12}) = \frac{\alpha}{2} \times (d_{ij}^{\cdot})^\beta$ (€/TEU- km)
	v=3	S^{13} = 2.5 TEU	$C^1(X, d^1, S^{13}) = 0.9 \times \frac{\alpha}{2} \times (d_{ij}^{\cdot})^\beta$ (€/TEU- km)
k=2	Basic formulation (Janic, 2007, 2008)		Cost (€/ km-ton) = $\alpha \times (W^v \times d^2)^\beta$ where α =0.58, β=0.74, W is the total weight of a train; W^v = W_0^v(locomotive weight) +W_1^v(flatcars weight)+X_{ij}*14.3(loads weight) for v type of train. $\Psi^2(X, d^2, S^{2V}) = [0.58 \times (W_0^v + W_1^v + X * 14.3) \times d^2)^{0.74}] / X$ (€/ TEU-km)
	v=1	S^{21} = 60TEU; 1 locomotive with 20 railcars	$C^2(X, d^2, S^{21}) = [0.58 \times \{(89+20 \times 24+X \times 14.3) \times d^2\}^{0.74}] / X$
	v=2	S^{22} = 75TEU; 1 locomotive with 25 railcars	$C^2(X, d^2, S^{22}) = [0.58 \times \{(89+25 \times 24+X \times 14.3) \times d^2\}^{0.74}] / X$
	v=3	S^{23} = 144 TEU; 2 locomotives with 48 rail cars	$C^2(X, d^2, S^{23}) = [0.58 \times \{(89 \times 2+48 \times 24+X_i \times 14.3) \times d^2\}^{0.74}] / X$
k=3	Basic formulation (Cullinane and Khanna, 1999)		Cost (€/ TEU-km) = a constant for ship size
	v=1	S^{31} = 200 TEU vessel	$C^3(X, d^3, S^{31})$ = 0.08 (US $ /TEU mile) ≈ $0.8^5 \times 0.08 \times (1/1.609)$ = 0.04 (€/TEU-km)
	v=2	S^{32} = 500 TEU vessel	$C^3(X, d^3, S^{32})$ = 0.05 (US $ /TEU mile) ≈ $0.8 \times 0.05 \times (1/1.609)$ = 0.025 (€/TEU-km)
	v=3	S^{33} = 800 TEU vessel	$C^3(X, d^3, S^{33})$ = 0.034 (US $ /TEU mile) ≈ $0.8 \times 0.04 \times (1/1.609)$ = 0.02 (€/TEU-km)

6.5.3 Results

Table 6.2 shows the system/route choice and batch strategy to minimize the total logistics cost. The other scenarios in the other rows are discussed later. The first column is 4 OD pairs (i,j). *r* in the second column was defined in Figure 6.2 and specified in the third column in terms of freight transport modes between two nodes via hubs.

[4] Janic Janic, M. (2007) Modelling the full costs of an intermodal and road freight transport network, Transportation Research Part D, 12 (1), pp.33-44. assumed that a vehicle is capable of carrying 2 TEUs: either two 20-foot containers or one 40-foot container.

[5] 1 USD = 0.74 € in May 2009

Table 6.2 Route/system choice for four scenarios: Decision variables (X_{ij}^r) for all (*i,j*) and *r*

(i,j)	*r*	*Nodes and links* ①②③④: Nodes ❺❻: Hubs	Demand (TEU)	Batch Strategy: Truck pre-haulage	Train pre-haulage	Truck-only	Train long-haulage	Vessel long-haulage	Train post-haulage	Truck post-haulage
Scenario 1 (Base Scenario – Case study); Obj. value (Total Cost) = € 496,928										
(1,3)	1	① —Truck→ ③	315			C5				
(1,4)	1	① —Truck→ ④	27			C2				
(2,3)	3	② —Truck→ ❺ —Rail→ ❻ —Rail→ ③	59	C2			C7		C3	
	7	② —Truck→ ❺ —Vessel→ ❻ —Rail→ ③	143	C3				C3	C3	
	8	② —Rail→ ❺ —Vessel→ ❻ —Truck→ ③	15		C7			C3		C5
(2,4)	1	② —Truck→ ④	13			C1				
Scenario 2; Obj. value (Total Cost) = € 376,189										
(1,3)	1	① —Truck→ ③	28			C1				
	5	① —Rail→ ❺ —Rail→ ❻ —Rail→ ③	287		C5		C5		C2	
(1,4)	1	① —Truck→ ④	27			C2				
(2,3)	5	② —Rail→ ❺ —Rail→ ❻ —Rail→ ③	217		C2		C5		C2	
(2,4)	2	② —Truck→ ❺ —Rail→ ❻ —Truck→ ④	13	C1			C5			C1
Scenario 3; Obj. value (Total Cost) = € 877,539										
(1,3)	1	① —Truck→ ③	630			C5				
(1,4)	5	① —Rail→ ❺ —Rail→ ❻ —Rail→ ④	54		C7		C5		C5	
(2,3)	4	② —Rail→ ❺ —Rail→ ❻ —Truck→ ③	40		C3		C5			C5
	9	② —Rail→ ❺ —Vessel→ ❻ —Rail→ ③	393		C3			C6	C5	
(2,4)	5	② —Rail→ ❺ —Rail→ ❻ —Rail→ ④	26		C3		C5		C5	
Scenario 4; Obj. value (Total Cost) = € 657,184										
(1,3)	9	① —Rail→ ❺ —Vessel→ ❻ —Rail→ ③	630		C3			C2	C3	
(1,4)	3	① —Truck→ ❺ —Rail→ ❻ —Rail→ ④	54	C2			C5		C7	
(2,3)	7	② —Truck→ ❺ —Vessel→ ❻ —Rail→ ③	141	C3				C2	C3	
	9	② —Rail→ ❺ —Vessel→ ❻ —Rail→ ③	278		C3			C2	C3	
(2,4)	1	② —Truck→ ④	1			C7				
	2	② —Truck→ ❺ —Rail→ ❻ —Truck→ ④	11	C3			C5			C3
	4	② —Rail→ ❺ —Rail→ ❻ —Truck→ ④	14		C3		C5			C2

Truck
C1: 2.5 TEU truck(s)* → 2.0 TEU truck(s)* →1.0 TEU truck(s)
C2: 2.5 TEU truck(s)* → 2.0 TEU truck(s)
C3: 2.5 TEU truck(s)* → 1.0 TEU truck(s)
C4: 2.0 TEU truck(s)* → 1.0 TEU truck(s)
C5: 2.5 TEU truck(s) only
C6: 2.0 TEU truck(s) only
C7: 1.0 TEU truck(s) only

Rail
C1: 144-TEU train(s)* → 75-TEU train(s)* →60-TEU train(s)
C2: 144-TEU train(s)* → 75-TEU train(s)
C3: 144-TEU train(s)* → 60-TEU train(s)
C4: 75-TEU train(s)* → 60-TEU train(s)
C5: 144-TEU train(s) only
C6: 75-TEU train(s) only
C7: 60-TEU train(s) only

Vessel
C1: 800 TEU vessel(s)* → 500 TEU vessel(s)* →200 TEU vessel(s)
C2: 800 TEU vessel(s)* → 500 TEU vessel(s)
C3: 800 TEU vessel(s)* → 200 TEU vessel(s)
C4: 500 TEU vessel(s)* → 200 TEU vessel(s)
C5: 800 TEU vessel(s) only
C6: 500 TEU vessel(s) only
C7: 200 TEU vessel(s) only

For Scenario 1, the system choice in (1, 3) is truck-only system (r = 1) and the batch strategy was the 2.5TEU-trucks only (C5). The main reason that all 315 TEUs are assigned to truck-only system seems to be either the limited service capacities for non-road modes (150 TEUs

for rail and 200 TEUs for vessel), or the relatively long detour of the intermodal systems between Amsterdam and Warsaw (i.e. relatively short direct trucking distance). More specifically, as shown in Figure 6.4, the distance of truck-only system (r = 1) is 1208km while rail-based intermodal system (r = 2) and vessel based intermodal system (r = 6) are 1,516 km and 2,916km respectively. Such detours of intermodal systems crucially decrease the cost competitiveness. These longer distances of intermodal freight systems are usually compensated by ESQ gained in non-road long-haulage. However, in this case, ESQ occurred in (1, 3) does not seem to be sufficient to shift some quantity of 315 TEUs from trucks (r = 1) to other intermodal system (r = 2 to 9). As shown in (1, 4) and (2, 4), the quantity was not enough to achieve sufficient ESQ. If 27 TEUs in (1, 4) would be shipped by other intermodal systems. It could be successful but the ESQ was not sufficient to overcome the detour of intermodal systems. Needless to say, truck should be the best option for both (1,4) and (2,4). The 217 TEUs in (2, 3) are split into the three systems. In the case of r = 3, the quantity shipped was almost the capacity of a 60-TEU train. In the case of r = 7 and 8, the total demand of vessel in (5, 6) (i.e. 193 TEUs) is also near to the capacity of a 200-TEU vessel. One may wonder why not 60 TEUs for r = 3 in (2, 3) instead of 59 TEUs since it seems to be more efficient for r = 3 due to a full-loaded 60-TEU train in (5, 6). Since it was not possible to check the optimal solution, we tested some suspicious candidate solutions for (2, 3). For example, we tested

- 60 TEU (i.e. full loading of a 60-TEU train) for r = 3 and 142 TEU for r = 7 and 15 TEU for r = 8
- 60 TEU for r = 3 and 144 TEU for r = 7 and 12 TEU for r = 8
- 60 TEU for r = 3 and 144 TEU for r = 9 and 12 TEU for r = 6

The objective function values of those candidates was worse than the near optimal we found (€ 496,928).

The OD flows in Scenario 2 are same but the service capacity is increased to the infinite. The infinite service capacity indicates that non-road modes can be used without any constraints if they are more cost-effective than the truck-only system. Technically, releasing inequality constraints would result in a much larger search space for feasible solutions. This wider feasible space should lead to better solutions under these scenarios. Overall, €120,739 cost savings (€211 savings per TEU) is achieved. For arc (1, 3), 287 TEUs is shifted to a type of the intermodal system (r = 5). We hypothesized that the assigned 315 TEUs to the truck-only system in Scenario 1 might be caused by the limited service capacity of non-road modes and the detour in the route (1, 3). Scenario 2 clearly shows the intermodal options could be selected when service capacity increases despite of the high detours of the intermodal systems. The specific mechanism for this modal shift can be explained by the concept of consolidation at hubs. More specifically, 287 TEUs in (1, 3), 217 TEUs in (2, 3), and 13 TEUs in (2, 4) are consolidated at the hub 5 and co-shipped by a couple of trains. Also, 287 TEUs in (1, 3) and 217 TEUs in (2, 3) are consolidated at hub 6 and sent to node 3 together. These consolidations are confirmed in the batch strategy we found. For the train long-haulage, C5 is commonly found in (1, 3), (2, 3), and (2, 4): 144-TEU train only. For the train post-haulage, C2 is found.

Scenario 3 shows the impact of the double demand with the double capacity compared with Scenario 1. Overall, the total cost (objective function value) of Scenario 3 (€ 877,539) compared with that of S1 (€ 496,928) is less than double. In other words, economies of scale are more intensively gained in Scenario 3 than in Scenario 1 as quantity increases. When the

service capacity constraint is released in Scenario 4, the flows in arc (1, 3) are eventually shifted to an intermodal option. It indicates the advantage of economies of scale overcomes the disadvantage of the detours. The main contribution to this huge modal shift is the consolidations at several stages (e.g. rail at node 2; vessel and rail at hub 5; rail at hub 6).

6.6 Concluding remarks

Although previous studies have considered economies of scale, they either over-simplified the objective functions (i.e. linear function or even constant) or only included a single type of economies of scale: mainly ESQ and ESD obtained from the main long-haulage between hubs. The proposed approach explicitly incorporates ESQ for main long-haulage as well as ESD and ESVS in pre- and post-haulage and long-haulage. A GA-based heuristic algorithm was applied to solve the proposed MMCFP. The main added value of this study is to consider numerous feasible and realistic freight options in terms of quantity, vehicle size (v = 1 to 3), batch strategy (C1- C7), and multi modes (k = 1 to 3) and their combination (r = 1 to 8). Therefore, the feature outcome of the proposed model is completely new compared to other previous studies. We found system/route choice including the sequence of the modes along the route and the batch strategy for each mode selected. For simple example,

- The outcome in a type of previous studies is "truck → rail → truck",
- The outcome in another type of previous studies is "truck → rail → truck; rail is used between hubs", and
- The outcome in this study is "60 TEU truck → the combination of 144 TEU train and 60 TEU train → combination of 60 TEU train and 2.5 TEU trucks 5 times; 144 TEU train and 60 TEU train should be assigned between hubs".

More specifically, it is possible to find the multi-modal and multi-batch options between hubs as well as any two nodes. That is a key contribution of this paper when compared to other previous OR-based multimodal system/route choice problems incorporating economies of scale. Also, it is notable that, in this case, one unit modal shift in quantity in an arc could lead to the complete change of mode/route choice since all unit costs in entire network and batch strategy could be significantly changed. In other words, the final outcome such as the mode/route choices in the proposed MMCFP is a consequence of interrelationships among ESD for long-haulage as well as diseconomies of scale with respect to distance for drayage; increased demand made possible to use bigger sized vehicles, which is related to both ESQ and ESVS; the optimal batch strategy; and so on.

Nevertheless, this study is limited to clarify the individual impact of the three types of economies of scale on mode/route choice and batch strategy. In order to find out such impacts, a simple averaged unit cost function which does not incorporate the concept economies of scale can be compared with the proposed non-linear cost functions. This clarification will lead to an estimation of the trade-off between economies of scale obtained from long-haulage using non-road systems and diseconomies of scale due to terminal congestion/diseconomies of scale due to drayage distance. Finally, this study does not consider travel time. In the future, an added cost due to additional travel time based on value of time might be an acceptable approach.

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Appendix 6A: Rational to use GA

In this Appendix, the complexity of the proposed problem and the reason to use GA are demonstrated with a simple example. Assume r = 9 feasible routes (based on Figure 6.2) from node 1 to node 3 via origin hub 5 and destination hub 6. Also, consider four types of cost functions: (1) simple constant cost functions (based on Eq. 1), (2) constant hub-discount cost functions (based on Eq. 2), (3) demand-dependent hub discount cost functions (based on Eq. 3), and (4) the proposed demand-dependent cost function with multiple sized vehicle options (based on Eq. 4 or, specifically, Eq. 6). The type of problem needed to estimate the number of cases to assign might be $\sum_r X_{13}^r$ (a certain quantity) to 9 slots (where $0 \leq r \leq 9$, X_{ij}^r is a non-negative integer).

- When $\sum_r X_{13}^r = 1$, the four cases obviously have nine different costs for the nine options for assignment: ${}_9C_1$. The feasible assignments are
  - [1,0,0,0,0,0,0,0,0], [0,1,0,0,0,0,0,0,0], …[0,0,0,0,0,0,0,1,0], [0,0,0,0,0,0,0,0,1].
- When $\sum_r X_{13}^r = 2$, the four cases have 45 different costs for the nine options for assignment: $1\times{}_9C_1+1\times{}_9C_2$. The feasible assignments are
  - [2,0,0,0,0,0,0,0,0], [0,2,0,0,0,0,0,0,0], …[0,0,0,0,0,0,0,2,0], [0,0,0,0,0,0,0,0,2] when one option ($|r| = 1$) is exclusively chosen, or
  - [1,1,0,0,0,0,0,0,0], [1,0,1,0,0,0,0,0,0], …[0,0,0,0,0,0,1,0,1], [0,0,0,0,0,0,0,1,1] when two options ($|r| = 2$) are chosen.

In the first (1) and second (2) cost functions, the total cost for all the other cases (i.e., $\sum_r X_{13}^r$ = X, where X is a positive integer greater than 1) can be estimated through simple a arithmetic calculation once $\sum_r X_{13}^r = 1$ is separately estimated and saved. For example, the total cost for [1,2,3,4,5,6,7,8,9] can be easily estimated by multiplying 1,2,….9 by [1,0,0,0,0,0,0,0,0], [0,1,0,0,0,0,0,0,0], …, [0,0,0,0,0,0,0,0,1], respectively. No further complexity is required. In the third (3) and fourth (4) cost functions, the total cost for $\sum_r X_{13}^r$ = X should be independently estimated. In general, as one unit of demand increases, the total costs for all r should be estimated.

- When $\sum_r X_{13}^r = 3$, the four cases have nine different costs for the 9 options for assignment: $1\times{}_9C_1+2\times{}_9C_1+1\times{}_9C_1$. The feasible assignments are
  - [3,0,0,0,0,0,0,0,0], [0,3,0,0,0,0,0,0,0], …[0,0,0,0,0,0,0,3,0], [0,0,0,0,0,0,0,0,3] when one option ($|r| = 1$) is exclusively chosen, or
  - [2,1,0,0,0,0,0,0,0], [2,0,1,0,0,0,0,0,0], …[0,0,0,0,0,0,1,0,2], [0,0,0,0,0,0,0,1,2] when two options ($|r| = 2$) are chosen, or
  - [1,1,1,0,0,0,0,0,0], [1,1,0,1,0,0,0,0,0], …[0,0,0,0,0,1,0,1,1], [0,0,0,0,0,0,1,1,1] when three options ($|r| = 3$) are chosen.

In general, the number of the routing cases for one OD pair is $\beta_1\times{}_9C_1+ \beta_2\times{}_9C_2\ldots+ \beta_9\times{}_9C_9$, where β_i is the sequence number in Pascal triangles (i = 1, 2, … , 9). Using this formula, the number of cases between any two nodes is $\sum_{i=1}^{9} {}_{\sum_{r=1}^{9} X_{ij}^r}C_{i-1}\times{}_9C_i$. The number of cases are crucially dependent on $\sum_{r=1}^{9} X_{ij}^r$. For example, when $\sum_{r=1}^{9} X_{ij}^r$ = 10, 10^2, and 10^3, the number of cases for a

possible route combination are 7.6^4, 3.8^{11}, and 2.6^{19}, respectively. In addition, if we take the batch strategy into account, the number of cases is increased to $\left(\sum_{i=1}^{9} {}_{\sum_{r=1}^{9} X_{ij}^{r}} C_{i-1} \times_9 C_i\right) \times \left(2^N - 1\right)^K$, where N is the type of vehicle and K is the number of freight modes (see the algorithm for finding the minimum unit cost in the previous section). Furthermore, some inflows from the other nodes to hubs (e.g., X_{24}^{r} for any r) possibly change $C_{hohd}^{k_2}(\sum_{(i,j)\in A} X_{ij}^{k_2}, d_{HoHd}^{k_2}, S^{kv}) \times d_{HoHd}^{k_2}$ (Eq. 6). For example, if 1 TEU shifts from r = 3 to r = 7 for X_{13}, it not only causes changes in the minimum unit costs (Φ_{13}^{r}) of the two shifted r for r = 3 and r = 7 but also changes in the minimum unit costs for all the other intermodal options (r). Therefore, the number of different cases in the function type (4) that are proposed in this study is $\left(\sum_{i=1}^{9} {}_{\sum_{r=1}^{9} X_{ij}^{r}} C_{i-1} \times_9 C_i\right) \times \left(2^N - 1\right)^K \times OD$, where OD is the number of OD pairs in a given network. Compared to function type (3), there are obviously fewer feasible assignments than for function type (4) due to non-road drayage. If we ignore non-road drayage, $|r|$ is reduced from 9 to 3—that is, the number of cases related to non-road drayage is 6 (i.e., r = 3, 4, 5, 7, 8, and 9). In addition, if the batch strategy is not considered in cases with function type (3), the number of cases can be defined as $\left(\sum_{i=1}^{3} {}_{\sum_{r=1}^{3} X_{ij}^{r}} C_{i-1} \times_3 C_i\right) \times OD$, which is significantly less than the proposed function. Unless a meta-heuristic method such as GA is used, the proposed problem might not be solvable within a reasonable amount of time.

Appendix 6B: GA-based Heuristic Algorithm

Step 1: *Initialize* the parameters for given data such as generation number, population size, length of chromosome (which is equivalent to the number of decision variables in real-coded GA), *OD* demand matrix (D_{ij}), *OD* distance matrix d_{ij}^k for all (*i,j*) pairs and all modes in the cost function ($C_{ij}^k(X_{ij}^k, d_{ij}^k, S^{kv})$), the lower bound (i.e., *Constraint 4*), and constant penalty (***p***).

Step 2: *Generate* the initial population ($\tilde{X}_{ij}^r$) with two vectors: $\bar{X}_{ij}^r$ and $\hat{X}_{ij}^r$

Step 2-1: $\bar{X}_{ij}^r$ is a vector including *N* random real numbers, where *N* is the number of decision variables on arc (*i,j*), $0 \le \bar{X}_{ij}^r \le 1$. Note: *N* is determined by the number of |*r*| and *OD* pairs (for example, *N* = 36 if |*r*| = 9 as in Figure 6.2 and |*OD*| = 4 as in Table 6.2).

Step 2-2: $\hat{X}_{ij}^r$ is a vector including *N* random binary numbers, $\hat{X}_{ij}^r \in [0, 1]$. 1 is assigned as a component of $\hat{X}_{ij}^r$ if a random number is greater than 0.5; otherwise, 0 is assigned.

Step 2-3: The initial population ($\tilde{X}_{ij}^r$) is a vector placing $\bar{X}_{ij}^r$ and $\hat{X}_{ij}^r$ in the same raw in order.

Note: the number of raw of $\tilde{X}_{ij}^r$ is 2*N*.

Step 2-4: Generate the matrix $\tilde{X}_{ij}^r$ until it reaches the maximum population size.

Note: the matrix size of $\tilde{X}_{ij}^r$ should be *2N* multiplied by the maximum population size. It is assumed that the number of decision variables should be even.

Step 3: *Update* the initial population satisfying equality constraints (i.e., *Constraint 1*) for each arc (*i,j*) and generate the new population (X_{ij}^r).

$\breve{X}_{ij}^r$ is the element-wise vector multiplication for the real number side ($\bar{X}_{ij}^r$) and the binary number side ($\hat{X}_{ij}^r$) of the initial population ($\tilde{X}_{ij}^r$).

$X_{ij}^r = (\breve{X}_{ij}^r \times D_{ij} / \sum_r \breve{X}_{ij}^r)$, where $\sum_r \breve{X}_{ij}^r$ is the sum of $\breve{X}_{ij}^r$ for all *r* on (*i,j*) and D_{ij} is a given demand between i and j (TEU).

Note: a raw vector of X_{ij}^r is a candidate solution for (*i,j*) satisfying equality constraints and the size is *N*.

Step 4: *Calculate* the objective function (i.e., Eq. 5) for the population (X_{ij}^r) with $g = 1$ where *g* is generation number;

Save the objective function value for the g^{th} population (*Obj*(*g*)).

Step 5: *Check* for inequality constraints (*Constraints 3 and 4*);

for each arc (*i,j*)

If $\sum_{r_k} \sum_{(i,j)\in A} x_{ij}^{r_k} \le u^k$ and $\sum_{r_k} \sum_{(i,j)\in A} x_{ij}^{r_k} \le Hub^k$

Obj(*g*)= *Obj*(*g*)

Otherwise,

Obj(*g*)= *Obj*(*g*)+ Penalty (*p*)

Step 6: *Estimate* the fitness function.

Step 7: Increase the generation number ($g = g+1$) and *Run* Reproduce, Crossover, Mutation, and Elitism for X_{ij}^r.

Step 8: *Return* to Step 3 if *g* is less than the maximum number of generations.

Steps 2 and 3 are not normally included in prototypes of the GA procedure. These two steps are designed to generate the initial population and simultaneously ensure the equality constraint. These steps would be removed if another technique to handle equality constraints could be developed. In addition, Step 7 is not fully described here. For the details of Step 7, see two pioneer studies by Holland (Holland, 1975) and Goldberg (Goldberg, 1989).

Chapter 7
The trade-off between CO_2 emissions and logistics costs based on multi-objective optimization

Nam Seok Kim, Milan Janic and Bert Van Wee
Delft University of Technology

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Abstract

This paper examines the relationship between the freight transport costs and the Carbon-Dioxide (CO_2) emissions in given intermodal and truck-only freight networks. When the trade-off, which is represented as the relationship, is changed, the freight mode share and route choice are also modified. In order to show the ever-changing trade-off and mode/route choice, a decision-support tool is developed. The given intermodal freight networks represents different freight combinations (i.e. truck-only system, rail-based intermodal system, short sea based intermodal system). Since CO_2 constraints in logistics markets need to be realized in the near future, a modal shift in freight transport could be expected to reduce the CO_2 emissions within the reasonable cost/time constraints. The technique of multi-objective optimization is used as the core of the decision-support tool for clarifying the relationship. The developed tool is applied to a simplified freight transport network connecting two large European ports – the port of Rotterdam (The Netherlands) and the port of Gdansk (Poland). The initial solution, based on the minimization of freight costs, shows that the mode share of freight is local/regional freight transport situations, while the other solutions balanced with CO_2 emissions shows that the mode share is changed into intermodal freight system, which is based on the 'Hub-and-Spoke' network. In considering changing demands and capacities of

freight systems, five scenarios are tested in order to examine the impact of mode/route change on the trade-off. The results of scenario analyses show that the trade-off is significantly influenced by demands and capacities of systems.

Key words: multi-objective optimization, multimodal freight transport, logistics, Carbon-Dioxide (CO_2) emissions, mode choice, route choice.

7.1 Introduction

In most logistics systems, minimizing the cost/ time performance has always been the top priority objective. The efficiency-oriented logistics systems have created a high dependency on the truck-only system (the road freight market share amounts to about 44% in the European Union (EC/Eurostat, 2007, EC, 2002)). However, over the same time period, road freight transport has been one of the most rapidly growing CO_2 contributors, while other contributors have decreased, rather slowly though, over the past 10 years (EC/Eurostat, 2007, ECMT, 2006). Consequently, in order to reduce the CO_2 emissions from the road freight transport in Europe, international organizations as well as national and local governments have designed policies which aim to increase the market shares of the non-road freight transport modes, focusing on the inter-, or multi-, modal freight transport systems (EC, 2001, Bontekoning et al., 2004). A research question is then raised as to *what the desired (well-balanced) freight mode share is? To what extent should intermodal freight systems be desirable to ensure freight market (and, in this study, container transport studying particular) and to reduce CO_2 emissions from freight transport.* This study attempts to answer these questions by clarifying the relationship between the costs and the CO_2 emissions of different modes.

To estimate the share of particular freight transport modes, a decision-support tool based on the multi-objective optimization problem is developed. The detailed outcome being looked for is the ever-changing network assignment solution for each solution as well as the trade-off curve consisting of a certain number of assignment solutions. This outcome may be an answer to the research question asked above. The tool is applied to a simplified network consisting of two hubs and four spokes (i.e. 2 nodes for hubs and 4 nodes for local shippers/consignees).

7.2 Multimodal hub and spokes network representation

This Section describes the representation of multimodal hub-and-spoke networks, consisting of two kinds of nodes, hub cities and local cities, and two kinds of arcs, internal flows and external flows. Figure 7.1(a) illustrates the internal and external flows. The internal flows consist of explicit internal flows and implicit internal flows. Explicit internal flows indicate the flows from/to any nodes in the network excluding a dummy node, which is the representative node for other cities in the network regions. Implicit internal flows, which influence the network but are not specifically expressed in the network, indicate the flows from/to the dummy node. For example, the implicit internal flows might use long-haul in an intermodal freight system but the destination is not explicitly indicated in the network region. The external flows are coming/ outgoing from/to some places outside of the network. Specifically, if the supply of node 1 (O_1) is the sum of $X_{1external}$, X_{12}, and $X_{1dummty}$, only X_{12} is considered. This is illustrated in Figure 7.1(b), where one more hub city and some more local cities are added to Figure 7.1(a). The arcs do not represent the homogeneous infrastructure (e.g. highway). For example, $ARC_{hub1hub2}$ can be railway, short sea shipping and roadway.

$X_{hub1external}$ can be the short/deep sea lines. Figure 7.1(c) presents the comprehensive network considering all possible modes in the network. For example, the long haulage from hub1 to hub 2, flows on $ARC_{hub1hub2}$, is the summation of the flows of three systems: truck, indicated as superscription '1' of X; rail intermodal system, indicated as '1', and SSS (Short Sea Shipping), indicated as '3'. Specifically, $X_{34}+ X_{32} +X_{3dummy} = (X^1_{34}+ X^1_{32} +X^1_{3dummy}) + (X^1_{34}+ X^1_{32} +X^1_{3dummy})+(X^3_{34}+ X^3_{32} +X^3_{3dummy})$.

For the truck only system, every local shipper/consignees can send/receive flows directly by truck. For example, the linear line from node 1 to 4 is X^1_{14}. In the same way, all the other flows can be presented in the network region. It is notable that the basic unit of freight transport is "system" instead of "mode" in Figure 7.1(c), in order to represent both truck-only systems and inter- (multi-) modal systems. Thus, drayage and terminal transshipments are regarded as parts of intermodal systems.

7.3 Multi-objective optimization for freight cost and CO_2 emissions

The multi-objective optimization model is used as the core of the decision support tool for finding the optimal freight systems assignment (e.g. truck-only system, the rail-based intermodal system, and the vessel based short-sea system) and for estimating the trade-off between the freight costs and the CO_2 emissions. There are two types of multi-objective optimization problems that are applicable: preference-based and ideal (i.e. cooperative and competing, respectively)(Deb, 2002). The core of preference-based optimization problems is to internalize CO_2 emissions in the objective function. Thus, the solution is similar to one for single optimization problems. However, the ideal multi-objective optimization problem considers two issues (i.e. freight cost and CO_2 emission in this case) separately and estimates their relationship (i.e. trade-off). The relationship can be drawn as a trade-off graph and is called Pareto-optimal solutions (Deb). The problem with the preference-based approach is that it is extremely difficult to estimate the CO_2 price (i.e. a converting factor (e.g. euro / kg of CO_2)). Nevertheless, most of the previous research has treated this issue using constant converting factors expressed in monetary terms in the context of external costs and accordingly has remodeled such a multi-objective optimization problem as a single optimization problem. Janic (Janic, 2003) and Chang (Chang et al., 2008), for example, use the concept of external cost including air pollution, congestion, noise, and traffic accident in the optimization model. However, as mentioned, the conversion factor (i.e. the external cost) has not been fully agreed in the research community. In other words, even though CO_2 emissions might be treated as a component of external costs, converting the emission into monetary terms should be done very carefully. For such a reason, the ideal multi-objective optimization approach which is more flexible is chosen in this study. In addition, as shown later, the converting factor can conversely be approximated by this approach once the trade-off has been estimated. The ideal multi-objective is presented in its general form and then applied to the relationship between cost and CO_2 emissions in freight transport systems in the following Subsections.

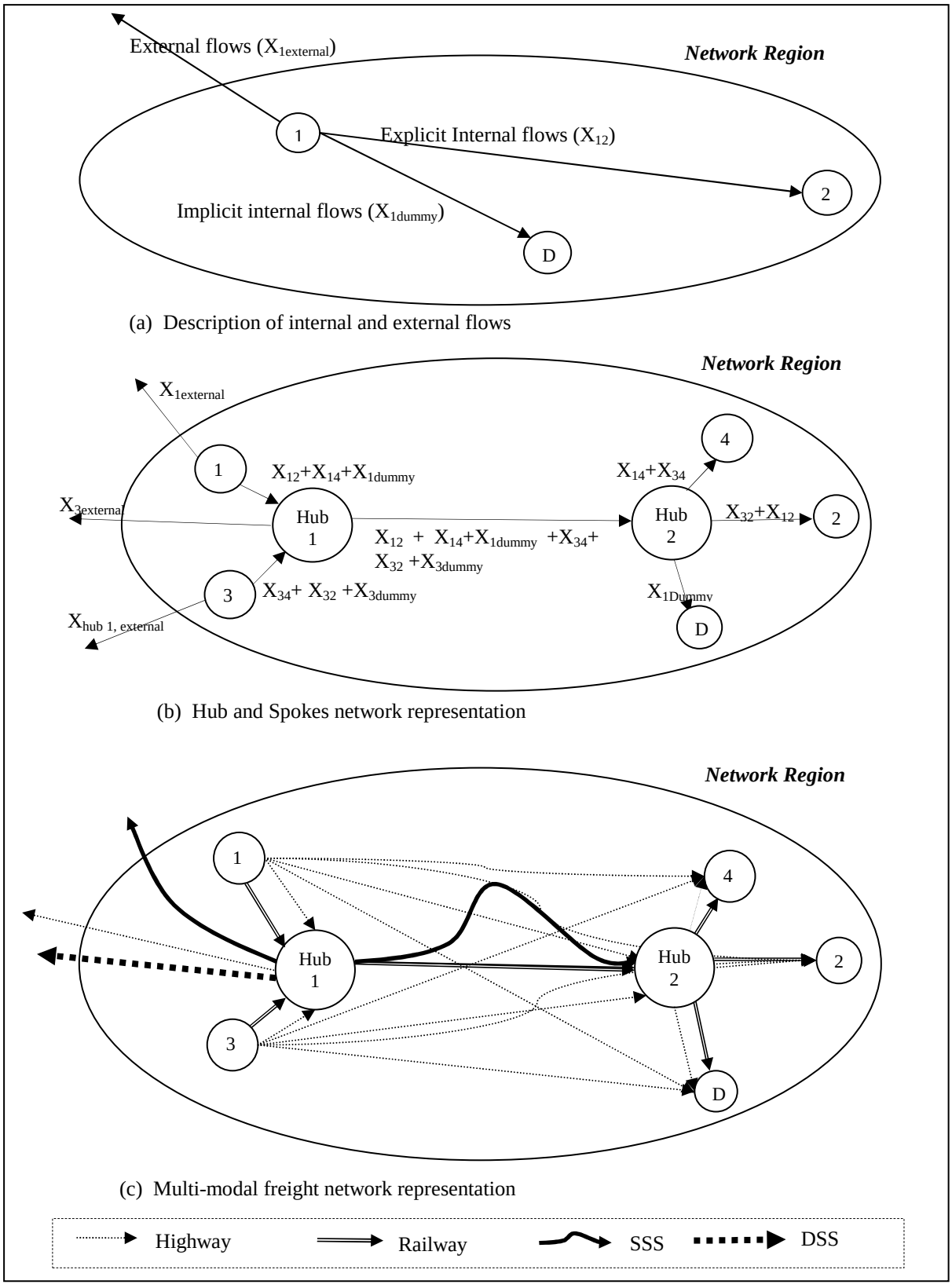

Figure 7.1 Freight network representation

7.3.1 General multi-objective optimization problem and Pareto optimal

Minimize/Maximize	$f_m(x)$,	m = 1,2,…,M;
s.t.	$g_j(x) \geq 0$,	j = 1,2,…,J;
	$h_k(x) = 0$	k = 1,2,…,K;
	$x_i^{(L)} \leq x_i \leq x_i^{(U)}$,	i = 1,2,…, N.

Where,

x is a vector of n decision variables: $x = (x_1,x_2,\ldots,x_n)^T$
$x_i^{(L)}$ and $x_i^{(U)}$ are the lower and upper bounds of x_i, respectively.
$g_j(x)$ and $h_k(x)$ are the constraint functions of J inequality and K equality, respectively

The $x_i^{(L)}$ and $x_i^{(U)}$ demarcates *a decision variable space D*. Thus, the number of axis of a decision variable space is N. *The multi-objective space, Z,* is the crucial difference between single objective optimization problem and multi-objective optimization problem since the latter has "multi-dimensional space" (for more details, see (Deb, 2002)).

Pareto optimal is defined as "a solution (call it A) to a multiple-objective problem is Pareto optimal if no other feasible solution is at least as good as A with respect to every objective and strictly better than A with respect to at least one objective" (Winston, 1994).

7.3.2 The relationship between cost and CO_2 emission

The aim is to determine an appropriate freight modal split which ensures minimum freight costs with the minimum level of CO_2 emissions, subject to the demand and the capacity. Thus, the final solution might not be a single point but a curve or a line. We found the multi-objective optimization problem highly suitable for our aim. The objective functions in the problem are to minimize the total system operational costs and the quantities of the CO_2 emissions. The optimization constraints are: (a) the flow conservation constraints, (b) the freight systems availability constraints, (c) intermodal freight conservation, (d) the non-negativity constraints, (e) the CO_2 emission restriction constraints, defined as quota, for both the particular routes and the transshipment points. Highlighting the CO_2 quota, Kim, et al. recently developed CO_2 limitations based on the Kyoto protocol and other traffic characteristics (Kim and Janic, 2008). The quota is defined as the *fixed target quantity* assigned to the freight transport after considering all other sources of emissions of CO_2 such as from passenger transport sharing the same transport infrastructure. However, the CO_2 quota in this paper is defined as the *relative magnitude updated iteratively* from the initial CO_2 mass when the freight cost is minimized.

Notation used in the model is as followed:

V is the set of nodes, i.e. the origins and destination of the freight transport flows;
A is the set of routes connecting the origin and destination nodes of the freight flows;
K is the set of the freight transport systems serving the given freight flows in the given region;
O (k), k∈ *K*, the set of origins of the freight system *k*;
D (k), k∈ *K*, the set of destinations of the freight system *k*;
o_{ij}^k, (*i*,*j*)∈ *A, k*∈ *K*, the demand of the freight system *k* from *i* to *j*;

u^k, $(i,j) \in A$, $k \in K$, the service capacity of freight system k on the system;

x_{ij}^k, $(i,j) \in A$, $k \in K$, the flow of the freight system k on the route (i,j) (i.e, the decision variable);

$C_{ij}^k(x_{ij}^k)$, $(i,j) \in A$, $k \in K$, the cost for transporting x_{ij}^k flow units by the freight system k on the route (i,j) ($/ton);

$Q_{ij}^k(x_{ij}^k)$, $(i,j) \in A$, $k \in K$, the CO_2 emissions from the transport system k on the route (i,j) (ton);

$Q_i^k(x_i^k)$, $i \in T(k)$, $k \in K$, the CO_2 emissions at the transshipment point k (ton);

B_{ij}, $(i,j) \in A$, the CO_2 emission quota for the route (i,j) including terminal operations (ton);

It is notable that A in the notation above is not the 'arc' that connects individual nodes. The 'route' can be a series of arcs.

Although objective functions and the related constraints are not purely linear if we fully formulate the related freight costs and CO_2 emissions, this study attempts to express them in a linear form and simplify the problem in order to avoid unnecessary complexities. Thus, the parameter estimation of C_{ij}^k and Q_{ij}^k is indeed crucial to finding the approximation of the Pareto optimal solution. The simplified objective functions and constraints are presented below.

The objective function 1 based on the total transport cost:

$$Z_1 = \text{Min} \sum_{k \in K} \sum_{(i,j) \in A} C_{ij}^k x_{ij}^k$$

The objective function 2 based on the CO_2 emissions:

$$Z_2 = \text{Min}\left[\sum_{k \in K} \sum_{(i,j) \in A} Q_{ij}^k x_{ij}^k + \sum_{k \in K} \sum_{i \in V} Q_i^k x_i^k + \sum_{k \in K} \sum_{j \in V} Q_j^k x_j^k \right]$$

Subject to

(a) The flow-conservation constraints:

$$\sum_{\{j \in V:(i,j) \in A\}} x_{ij}^k = o_{ij}^k \quad , (i,j) \in A \, , k \in K$$

(b) The freight mode availability constraints:

$$\sum_{\{j \in V:(i,j) \in A\}} x_{ij}^k \le u^k \quad , i \in V, k \in K$$

(c) The intermodal freight conservation constraints:

$$\sum_{\{j \in V:(i,j) \in A\}} x_{ij}^k \le u^k \quad , k=2 \text{ and } 4$$

$$\sum_{\{j \in V:(i,j) \in A\}} x_{ij}^k \leq u^k \qquad , k=3 \text{ and } 5$$

(d) The non-negativity constraints:

$$x_{ij}^k \geq 0$$

(e) The CO_2 emission quota constraints:

$$\left[\sum_{k \in K} \sum_{(i,j) \in A} Q_{ij}^k x_{ij}^k + \sum_{k \in K} \sum_{i \in V} Q_i^k x_i^k + \sum_{k \in K} \sum_{j \in V} Q_j^k x_j^k \right] \leq B_{ij}, \; (i,j) \in A, \; k \in K$$

According to (c) the intermodal freight conservation constraints, it is assumed that the rail-based intermodal system and the 2nd level rail-based intermodal system use the same freight train service and accordingly share the limited capacity (i.e. train slots). The assumption is similarly applied to two options of short sea shipping.

7.4 Solution procedure and model implementation

7.4.1 Procedure

Estimation of upper bound and lower bound of the second objective function

Step 0: Initialization: set all parameters, objective functions and constraints (a), (b), (c), and (d)

Step 1: Run linear programming for Z_1 excluding Z_2 and get the initial solution for Z_1

Step 2: Substitute the initial solution to the second objective function (Z_2) and assume the current value of Z_2 as the upper bound of constraint (e)

Step 3: Run linear programming for Z_2 with the same constraints excluding Z_1, get the initial solution for Z_2, and use the current Z_2 as the lower bound of constraint (e)

Estimation of Pareto optimal solution

Step 4: Set *Pareto Optimal set* = $\{\phi\}$ and the desired number of subset of Pareto Optimal points

Step 5: Estimate the increment of CO_2: increment = (upper bound – lower bound) / the number of Pareto Optimal points

Step 6: Update the constraint (e);

$$\left[\sum_{k \in K} \sum_{(i,j) \in A} Q_{ij}^k x_{ij}^k + \sum_{k \in K} \sum_{i \in V} Q_i^k x_i^k + \sum_{k \in K} \sum_{j \in V} Q_j^k x_j^k \right] =< \text{(Initial Upper bound – increment)}$$

Step 7: Run linear programming for *Z1* with the updated constraint and others

Step 8: Update the subset of *Pareto Optimal set* for (Z_1, Z_2), if all constrains and optimality conditions are satisfied and a solution is found

Step 9: If the current number of Pareto Optimal solution is less than the desired number of Pareto Optimal (in other words, the current upper bound is less than the global lower bound), go to Step 6

Step 10: end

Excel Solver was used to run LPs in the entire algorithms. The algorithms have been coded in Visual Basic. Lingo 11.0 was also used for the verification.

7.4.2 Case study

Study area

We explored a case study area where 3 different intermodal systems could be compared. In the study area, the freight systems may have the appropriate equipment for transshipment and can compete, at least potentially, with each other. The study area may have more than two major economic activity centers. As many manufacturing industries have recently been located in Eastern Europe, the port of Gdansk is one of the fastest growing ports, being a regional hub for Poland and Lithuania as well as connected to a freight rail-line. On the other hand, the Port of Rotterdam is one of the largest ports in Western Europe as well as a regional hub for the Netherlands and Northern Belgium. Thus, connecting two ports (i.e. rail and short-sea) as a long-haulage line, these two hubs are an appropriate study area satisfying the criteria mentioned above. Actually, this route has been recognized as one of the major freight corridors in Europe (Walker et al., 2004)

Ranking of cost and emissions

The freight transport cost and CO_2 emissions, as shown in Table 7.1, are estimated based on two European Commission researches: RECORDIT and MEET, respectively (EC, 2000, EC, 1999). Although there are many factors affecting CO_2 emissions, the most crucial one in the long-distance trips in this case study is the average cruising speed rather than the acceleration rate, cold start emissions, ambient temperature and so on. Thus, the CO_2 emissions are estimated by a function of cruising speed and distance traveled with the average values for other factors such as cold start emissions and ambient temperature. This case study assumes the average cruising speeds of trucks, railway, and short sea shipping to be 90km/h (60km/h in drayage), 90km/h, and 25km/h respectively. It is also worth noting that production emissions are included based on previous research (Kim and Van Wee, 2009, Facanha and Horvath, 2006, Spielmann and Scholz, 2005). Those performance measures (i.e. cost and CO_2 emissions) being used as parameters (i.e. C_{ij}^k and Q_{ij}^k) in linear programming are multiplied by the estimated shortest path distance based on different modal networks (i.e. road, rail, and short sea waterway) in GIS. Table 7.1 shows the complexity to decide *"What is the best option in the network in terms of one of two objectives?"* and the difficulty to generalize the freight costs for each freight system. In other words, one mode dominates one route (region), while it is not even comparative in another route (region). In addition, one mode is economically superior to the others in one route, while it can be significantly worse in the other route. One certain fact in the entire case study network is the worst freight system regarding CO_2 emissions is the truck-only system indicated as ① as shown in Table 7.1.

It is worth mentioning that there are three types of drayage in the mode choice sets in Table 7.1: truck-drayage, rail-drayage, and truck pickup/distribution. The rationale dividing these types is that the distance of drayage in the study area seems to be longer than the practical drayage distance (i.e. 50 km or so). The truck-drayage is defined as the movement from senders to a terminal or a port by trucks. It exists in the rail-based intermodal system indicated as ② and the short sea based intermodal system indicated as ③. Rail-drayage, indicated as ④ and defined as the rail-rail (or rail-short sea shipping) connection system from the local freight

train terminal to a hub terminal is shown in the 2nd level intermodal systems and the rail-short sea based intermodal system is indicated by ⑤. Thus, in the cases of the 2nd level intermodal systems, the truck pickup/distribution plays the role of picking up from the origin and distributing to destinations.

④ shows the quite competitive cost performance in terms of both freight costs and CO_2 emissions. Compared to ②, ④ has the lower freight cost and the lower CO_2 emissions although the terminal transshipment charges are twice as high. However, the route from Amsterdam to Warsaw was an exception. The rail- and short sea-based intermodal shortest path associated with the route both involve a considerable detour, while the truck-only system (①) has the shortest path without such a considerable detour. Thus, ① is the best option on the route 1-3 in terms of costs. In practice, there are several similar cases, in that ① has significant competitive advantage over the intermodal system, due to the detour on the given network.

Table 7.1 Ranking of cost and CO_2 emission in the freight network in case study

Origin – Destination	Best choice based on Freight Transport Cost					Best choice based on CO_2				
	Best choice	2nd	3rd	4th	Worst Choice	Best choice	2nd	3rd	4th	Worst Choice
Amsterdam – Warsaw(1-3)	① (€ 1,401)	④	②	⑤	③ (€3,108)	④ (2,026 kg)	②	⑤	③	① (5706 kg)
Amsterdam – Vilnius (1-4)	④ (€ 1,596)	①	②	⑤	③ (€3,501)	④ (2,251 kg)	⑤	②	③	① (7,742kg)
Amsterdam – Gdansk (1-6)	④ (€ 1,090)	②	①	③	⑤ (€2,607)	④ (1,435 kg)	②	⑤	③	① (5,271 kg)
Brussels – Warsaw (2-3)	④ (€ 1,484)	①	②	⑤	③ (€3,260)	④ (2,089 kg)	②	⑤	③	① (6,159 kg)
Brussels – Vilnius (2-4)	④ (€1,639)	①	②	⑤	③ (€3,653)	④ (2,314 kg)	⑤	②	③	① (8,195 kg)
Brussels – Gdansk (2-6)	④ (€ 1,169)	②	①	⑤	③ (€2,740)	④ (1,501 kg)	②	⑤	③	① (5,725 kg)
Rotterdam – Warsaw (5-3)	④ (€ 1,230)	②	①	⑤	③ (€2,917)	④ (1,703 kg)	②	⑤	③	① (5,852 kg)
Rotterdam – Vilnius (5-4)	④ (€ 1,385)	②	①	⑤	③ (€3,310)	④ (1,928 kg)	⑤	②	③	① (7,884 kg)
Rotterdam – Gdansk (5-6)	② , ④ (€ 915)		①	③, ⑤ (€2,397)		②, ④ (1,114 kg)		③, ⑤		① (5,413 kg)

Mode(System) Choice Sets
① Truck-only system
② Rail based Intermodal system (Truck drayage – Rail Long haulage – Truck drayage)
③ Short Sea based intermodal system (Truck drayage – Shortsea haulage – Truck drayage)
④ 2nd level Rail based Intermodal system
(Truck pickup – Rail drayage – Rail Long haulage – Rail drayage – Truck distribution)
⑤ Rail-Short sea based Intermodal system
(Truck pickup – Rail drayage – Short sea Long haulage – Rail drayage – Truck distribution)

Network assignment

The demand of containers in each node and furthermore the OD matrixes were estimated using freight transport demand statistics issued by Eurostat . The summation of the demands for each arc was used as the RHS constraints (o_{ij}^{k}). The external flows and implicit internal flows are not considered in the case study (e.g. external containers to be loaded/ unloaded in the Port of Rotterdam are not taken into account). The issue on setting up the capacity, in

particular for the road network, is quite challengeable because all situations on road links vary from country to country in Europe (e.g. the number of lanes, percentages of freights and passenger trips, the time variation, and so on). Thus, instead of setting up infrastructure capacity, the number of available freight vehicles in the logistics market is assumed to be that used in the RHS. For example, $x_{12}^{1}+x_{13}^{1}+\ldots.+ x_{99}^{1} \leq$ the number of trucks in the entire network region (i.e. the superscription indicates the freight system). This may be applied to each node if the market information is sufficiently satisfied.

Figure 7.2 (a) shows the demand. Each arc has three mode options. There are invisible arcs connecting spoke nodes (i.e. node 1, 2, 3, and 4) and hubs (i.e. 5 and 6). Those arcs have two mode options: road and rail, since 2nd intermodal systems are considered. The capacities for freight systems in the network are assumed to be 90TEU per day for rail, 200 TEU per day for short sea service, and 500 TEU for a truck-only system, reflecting the current freight system. Figure 7.2(b) is the first container assignment solution minimizing the freight cost in the network by the single LP running (i.e. Step 1 in the previous Section). This solution may represent the current freight market share if the inputs (i.e. demand and capacity) are accurate and the decisions in logistics are only made to minimize the freight cost. In addition, this solution is totally independent of the relation to CO_2 since currently there is no direct regulation of CO_2 emissions in the case study area. Figure 7.2(c) shows the assignment of containers in terms of minimizing the CO_2 emissions generated from the freight systems in the entire network (i.e. Step 3 in previous Section). There are only a few shifts from one system to another in order to reduce CO_2 in the entire network. Specifically, for the arc (2, 3), 185 containers transported by road in Figure 7.2(b) are reduced to 153 in Figure 7.2(c) and are shifted to short sea shipping. However, since the short sea shipping has the capacity (i.e. 200 TEU per day), 25 containers from node 5 to node 4 are shifted from short sea shipping to rail, in that $X_{54}^{5} + X_{54}^{4}$ in Figure 7.2(b) is equal to X_{54}^{4} in Figure 7.2(c). In terms of satisfying the flow conservation constraint (a), this model appears to find the lowest costs as well as ensuring the lowest CO_2 emissions. As shown in Table 7.1, the truck-only system from 1 to 6 seemed to be the optimal choice in terms of costs if the rail-related services are excluded. This small change in the case study was caused by the capacities of each freight system being quite tight (i.e. total demands and capacity are assumed as 783 and 790 respectively). In other words, there is no room significantly to update the network too much. It was also shown that the binding constraints in Figure 7.2(b) were the truck-only system and the intermodal rail system while in Figure 7.2(c) it was rail based intermodal systems and short sea intermodal systems. It is also worth noting that the flows with superior truck-only system costs in arc (1,3) are supposed to shift to less CO_2-emitting systems in Figure 7.2(b). However, the capacities of other intermodal systems are full. It is recognized that the capacity and demand of intermodal systems seems to be crucial in terms of minimizing CO_2 emissions. This issue will be fully discussed in the scenario analysis.

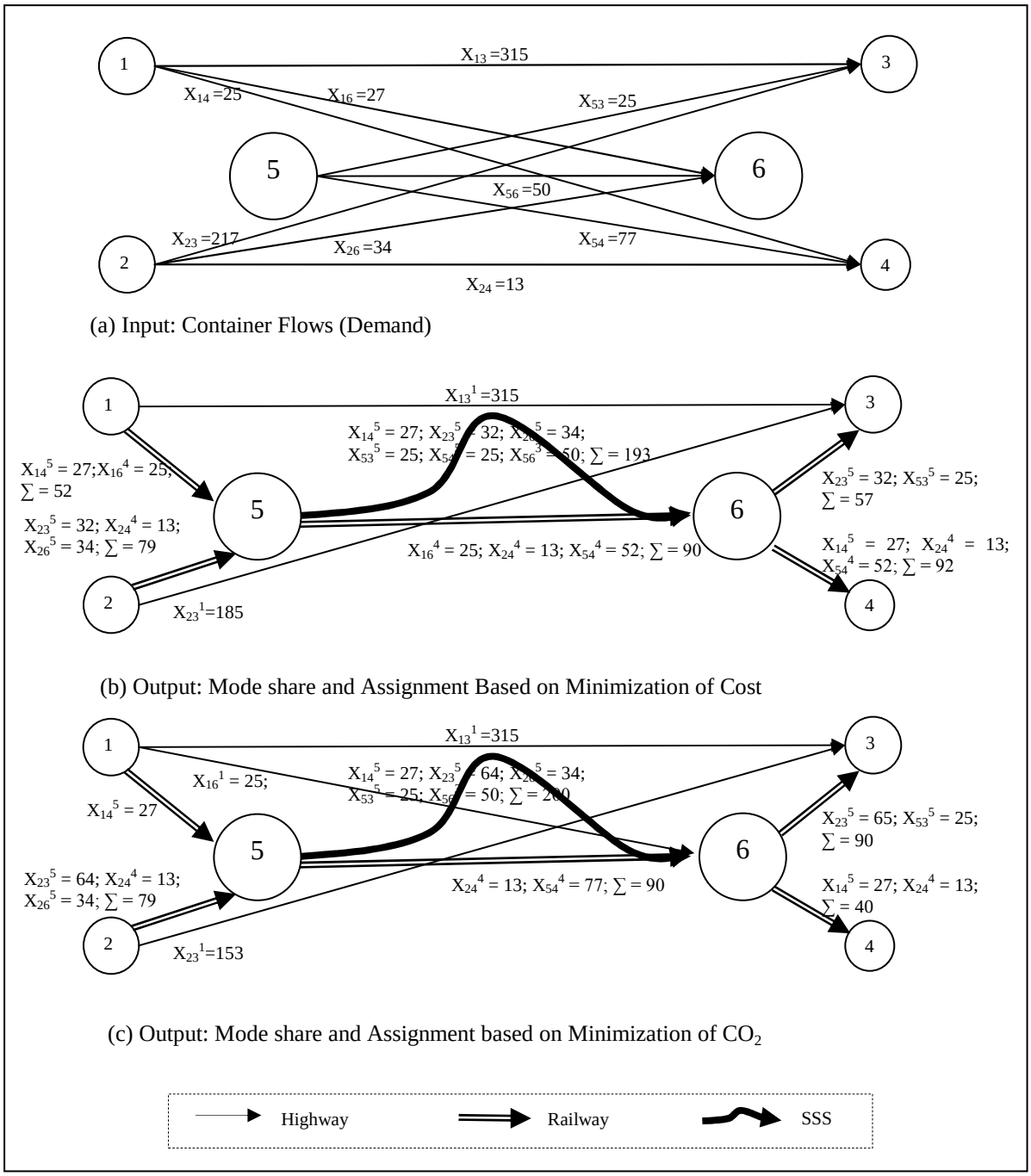

Figure 7.2 The given flows and initial assignment solutions

Pareto optimal (Trade Off)

The solutions to the assignment problem estimated previously were the marginal points as shown in the Figure 7.3: the minimization of freight transport system costs (i.e. upper left side) and the minimization of CO_2 emissions (i.e. lower right side). Figure 7.3 shows 50 solutions, which are not a full set of Pareto optimal solutions but a subset. However, the algorithm can estimate less than 50 since there might be non-feasible solutions in iterations. The relationship between costs and CO_2 emissions in the entire network is not exactly linear. The linearity of Pareto Optimal is not necessary even if all the objective functions are linear. Specifically, the changed amount of costs is not necessarily proportional as the allowed CO_2 emissions are decreased.

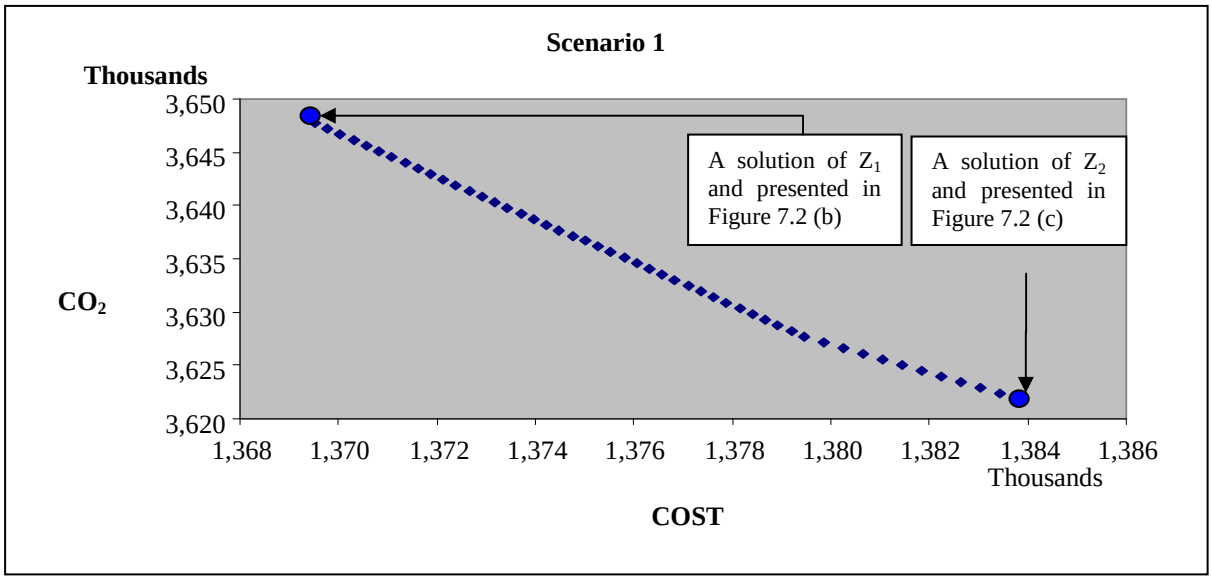

Figure 7.3 Pareto optimal solutions for scenario 1

7.5 Scenario analysis

7.5.1 Input scenarios

In order to examine different market situations, 6 different scenarios related to demand and capacity are shown in Table 7.2. Scenario 1, whose Pareto optimal was already presented in Figure 7.3, is more or less the base scenario to compare with the others. Thus, Scenarios 2 and 3 are the attempts to examine the change of relationship between freight costs and CO_2 emissions as the capacities of specific freight system(s) are changed. More specifically, the two different demand scenarios are applied to the three different capacity options: current capacity (i.e. 500 TEU for trucks, 90 TEU for rail, and 200 TEU for vessels), three times increased rail capacity (i.e. 500 TEU for trucks, 270 TEU for rail, and 200 TEU for vessel), and infinite capacity option.

In Scenario 4 to 6, the fixed number of containers (i.e. 87 containers) is the total number of containers divided by the number of nodes in the network region. These scenarios have been designed in order to avoid the effect of one exceptional route, which is Amsterdam to Warsaw. The route has greater demand (i.e. 315 containers) compared to other nodes and an exceptionally cheaper truck-only system cost compared to other arcs. In order to generalize, even though the demand might be correlated with the costs, it is assumed that the same amounts of containers are transported.

Table 7.2 Scenarios in terms of OD flows and service capacity

	Description	OD Sets				Total Demand	Service Capacity	
S 1	The demand based on economical activity (Ams – War / Bru – War) and the capacity reflecting current market situation (2 train services per week / 1 short sea service per week)		Warsaw	Vilnius	Gdansk		Mode	
		Amsterdam	315	27	25	783	truck	500
		Brussels	217	13	34		rail	90
		Rotterdam	25	77	50		vessel	200
S 2	The demand based on economical activity (Ams – War / Bru – War) and the extended intermodal capacity (3 train services per week / 1 short sea service per week)		Warsaw	Vilnius	Gdansk			
		Amsterdam	315	27	25	783	truck	500
		Brussels	217	13	34		rail	270
		Rotterdam	25	77	50		vessel	200
S 3	The demand based on economical activity (Ams – War / Bru – War) and infinite capacity		Warsaw	Vilnius	Gdansk			
		Amsterdam	315	27	25	783	truck	infinite
		Brussels	217	13	34		rail	infinite
		Rotterdam	25	77	50		vessel	infinite
S 4	The fixed demand for all origins and the capacity reflecting the current market situation (2 train services per week / 1 short sea service per week)		Warsaw	Vilnius	Gdansk			
		Amsterdam	87	87	87	783	truck	500
		Brussels	87	87	87		rail	90
		Rotterdam	87	87	87		vessel	200
S 5	The fixed demand for all origins and extended capacity (3 train services per week / 1 short sea service per week)		Warsaw	Vilnius	Gdansk			
		Amsterdam	87	87	87	783	truck	500
		Brussels	87	87	87		rail	270
		Rotterdam	87	87	87		vessel	200
S 6	The fixed demand for all origins and infinite capacity		Warsaw	Vilnius	Gdansk			
		Amsterdam	87	87	87	783	truck	Infinite
		Brussels	87	87	87		rail	Infinite
		Rotterdam	87	87	87		vessel	Infinite

7.5.2 Results

The trade-off graphs (i.e. Pareto optimal) in Figure 7.4 have the same scale of x- and y- axis. Figure 7.3 has been changed to the first graph (Scenario 1) in order to compare with other scenarios. It can be seen that pairs of two scenarios, (S1 and S4), (S2 and S5), and (S3 and S6), have similar shapes. Comparisons and interpretations are as follows:

- S1 vs S2 — The increment of CO_2 emission constraint of S1 and S2 is 527.16 and 10,941.28 respectively. (the increment is defined in Step 5 in the previous Section). The vertical length (i.e. CO_2) and horizontal width (Cost) of two graphs can be explained by the amount of increment. The greater increment means a longer and wider graph, which indicates that the changeable amount of cost and CO_2 in S2 is relatively greater than in S1. When it comes to absolute comparison, it makes sense that S2, adding two more railway services per day on the long-haulage arc (5, 6) provides a more economical and less CO_2-emitting service than S1 in the entire network region.

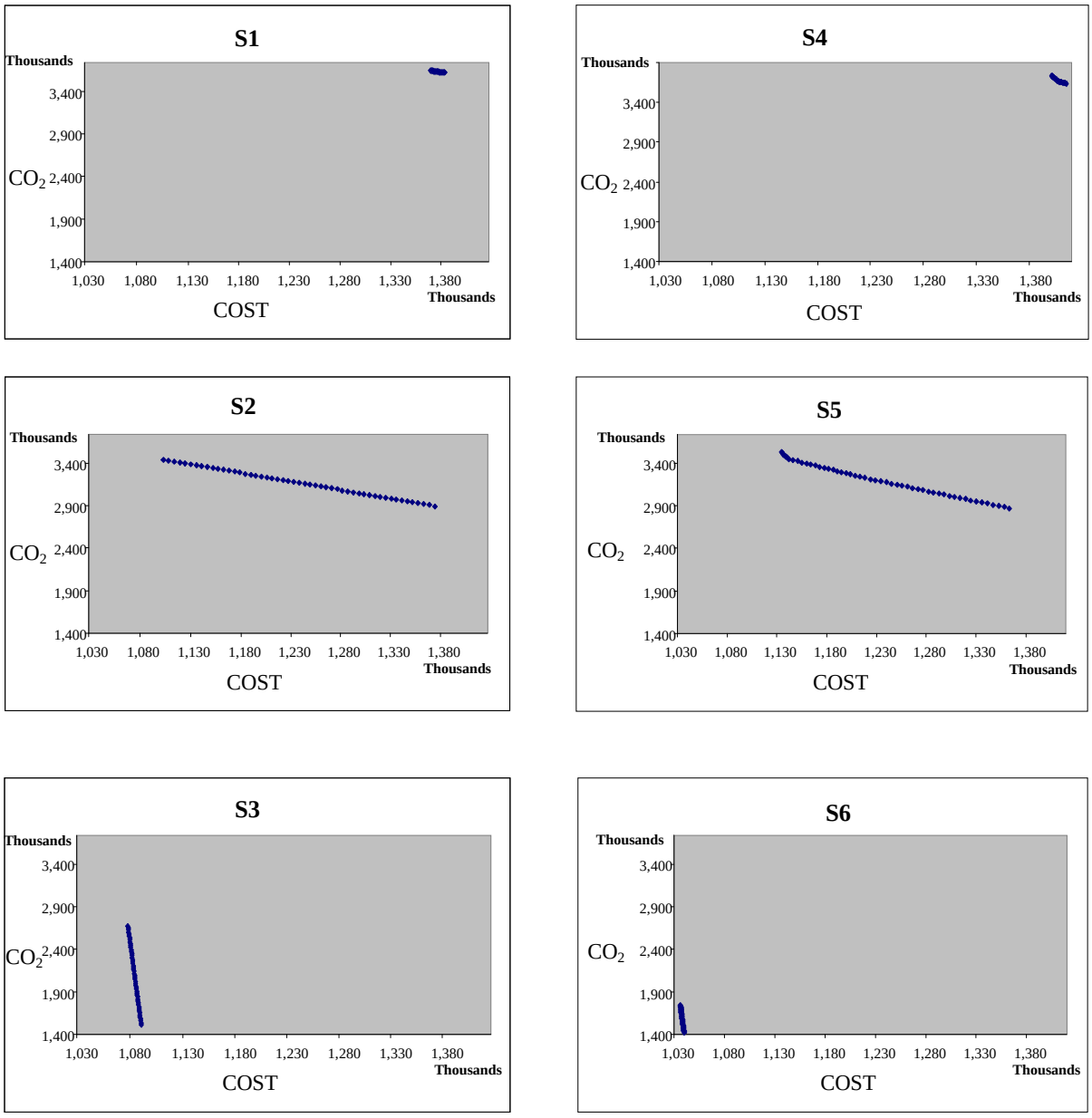

Figure 7.4 Scaled Pareto Optimal Solution on given network and demand

- S1 vs S2 vs S3 S3 shows that both costs and CO_2 are reduced as the system capacity is infinitely increased. Actually, the graph does not seem to happen in reality due to congestion on the highway and the queues of containers in the port/terminals. Nevertheless, it is worth observing that the slope of the graphs is very different compared to S1 and S2. The shape indicates that it is feasible to reduce CO_2 emissions drastically as a relative small amount of costs are paid in the region where the intermodal system capacities are sufficient and other external impacts are negligible.
- S1 vs S4 The slope of S4 is steeper than of S1 because the concentration of demand in the area where a cheaper truck service (i.e. flows from Amsterdam) is provided is relaxed.

- S2 vs S5 The graph shapes are almost similar apart from the left upper part of S5, the minimized cost with the loosed CO_2 constraints. This part indicates the slightly expensive freight costs because the costs are increased across the entire network through the uniform distribution of the demand (i.e. 87 containers for all nodes) in that some flows use uneconomical freight systems. The steeper slope at the beginning is because the truck-only system services rapidly shift to the intermodal systems. As the uncompetitive expensive truck services in terms of route are removed from the network and the CO_2 emissions constraints get tighter, the slope in S5 is stabilized as S2.
- S3 vs S6 In general, both costs and CO_2 are considerably decreased. The main reason is the initial unbalanced demand flows on the arc (5, 6).

7.6 Discussion of results

The comparisons of scenarios in Figure 7.4 make the evaluation of current tax policy possible. As mentioned previously, scenario 1 has been constructed based on the current demand and capacity in the case study area. The slopes of each scenario in Figure 7.4 could be an indication of the CO_2 tax price per ton since it is almost a line, which can be approximated in any point. Simple linear regressions are run in order to draw the generalized lines for 6 scenarios. Table 7.3 presents the scenarios, the estimated linear regressions and R^2, and CO_2 price per ton (€/ton of CO_2). According to R^2 values and t-values in the basket (e.g. [-92.62]), the regression lines fit well. However, it is surprising that CO_2 price ranges from 11 € / ton to 5,350 € / ton in terms of the input scenarios. Considering the practically recommended CO_2 price ranging 7 € / ton to 45 € / ton for 2010 (Maibach et al., 2008) even though the approach for the estimation is different from this study, the CO_2 price estimated in this study seems to be over-estimated. However, the opposite case is also possible in that *the current recommended CO_2 price could be seriously underestimated.*

Table 7.3 Estimation of CO_2 price per ton

	Demand	Linear Regression Equation	R^2	CO_2 price per ton (€ / ton)
S 1	Current OD flows Base capacity	Cost = 3,319,039 – 5.35 CO_2 [-92.62]	0.994	5,350
S 2	Current OD flows Increased Rail Service	Cost = 2,810,750 – 0.496 CO_2 [-7945.5]	1.000	496
S 3	Current OD flows Infinite	Cost = 1,107,040 – 0.011CO_2 [-89079.5]	1.000	110
S 4	Equal flows in all O-D Base capacity	Cost = 1,833,786 – 0.125 CO_2 [-23.4]	0.919	125
S 5	Equal flows in all O-D Increased Rail Service	Cost = 2,414,230 – 0.368 CO_2 [-82.2]	0.993	368
S 6	Equal flows in all O-D Infinite	Cost = 1,055,150 – 0.011 CO_2 [-24828.1]	1.000	11

7.7 Conclusions and further study

The quantitative relationship between CO_2 and freight costs has been gaining in importance in the logistics field due to global warming as well as rapidly increasing fuel costs. This study is an effort to estimate the relationship using the LP-based algorithm. This study clearly shows the trade-off curve generated by developing a decision-support tool. Since each solution composing the trade-off curve has the unique network assignment as well as modal share rate, the point (or range) could be found which fits with the social needs or decision makers' wishes. Furthermore, examining six scenarios with different O-D sets and capacity constraints shows that the trade-off curves have almost a linear relationship in that *freight costs should be paid more as CO_2 emissions should be reduced*. However, the quantity of the relationship varies, ranging from 5,350€ / ton to 11€ / ton in terms of the input scenarios. In other words, the cost of CO_2 emissions cannot be estimated *in general* while it can be estimated *only if* several necessary conditions are fully considered (i.e. O-D sets, capacity and availability of freight systems, cost structure, CO_2 estimation and so on). The study also shows that increasing the lower CO_2 emitting system's capacity would reduce the CO_2 emissions. In addition, this study has newly extended the concept of intermodality into 2nd level intermodal systems assuming that drayage can be performed by rail and considered as a different option.

Nevertheless, this study may be incomplete since one of the most crucial decision factors in logistics decision making, minimizing the lead time or ensuring Just-in-time (i.e. reliability), is not taken into account. The third/fourth objective functions could compensate for this incompletion in a future study. The objective functions minimizing those temporal concepts might be non-linear functions. In addition, the actual cost function and emissions function are not really linear. Although the unit-based performance measures are used as in this study, more precise formulations will lead this simple linear problem with feed-back to non-linear optimization problem. Accordingly, non-linear programming (NLP) would be a better option to finding a more accurate solution. Thus, more complicated algorithms such as evolutionary and generic algorithms should be used in order to estimate the full set of Pareto optimal solutions. As mentioned previously, the Pareto optimal estimated in this study was a subset. There are some more details to be improved on in a future study. RECORDIT showed that the different type of loading units often caused the considerable different total costs. Thus, although the two types of containers are converted into TEU in this study, the attention of loading units should be paid. It is because the double size of the loading unit does not guarantee double weight, which crucially affects the costs as well as the CO_2 emissions. Road traffic congestion is also an important factor affecting both costs and CO_2 emissions. Specifically, congestion is mainly associated with the total traveled time for logistics cost and accelerating/decelerating and the number of stops for CO_2 emissions from freight transport. The severe road congestion in certain long-distance corridors would make the truck-only system less competitive than intermodal freight systems. The congestion in intermodal terminal/port, one of the factors making the intermodal system less competitive, also would be considered in future study.

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Chapter 8
Summary and conclusions

"Cogito, ergo sum[1]"

René Descartes (1596-1650)

8.1 Findings and contributions

A simple version of the initial research question could be "*Is the intermodal system better than the truck-only system?"*. The adjective "better" is specified as "environmentally better" and "economically better" in Part 1 and 2 respectively. Even though the questions were simple, the answers were not so simple: *in some conditions, the intermodal system is better; in others the truck-only is better.* Therefore, the more specific question asked in the introduction to Part 1 and 2 was *Under what conditions is the intermodal system more competitive than the truck-only system in economic and environmental terms?* Once the conditions that make the intermodal more competitive had been found, we could also find the differences in quantity: "*how much the intermodal system is better*". In part 1 the difference was the reduction of CO_2 mass (tonne) while in part 2 it is the total cost saving (€) as well as the mode/route share (%). In Part 3, the initial questions presented in the introduction were "*What is the relationship between CO_2 emissions generated in the logistics chain and logistics costs? In order to decrease one unit of CO_2 emissions through shifting freight mode (system), how much does*

[1] A Latin philosophical statement which means "I think, therefore I am".

the shift cost?". The difference in quantity is the trade-off between the costs and the CO_2 emissions.

Addressing the research questions, the main findings and contributions are summarized for each Chapter as follows:

- *Chapter 3*
  Although some statistics and earlier studies reported that rail transportation emits fewer greenhouse gases and air pollutants than road transportation, these have not been comparable because truck-only systems are based on a door-to-door trip, whereas rail systems are based on a terminal-to-terminal trip only (EC, 1999, 2003a, 2002). In addition, techniques to assess emissions from transport modes have been developed which focus only on one individual transport mode (EC, 1999). Therefore, Chapter 3 is designed to assess CO_2 emissions from freight systems rather than individual freight modes. The main contributions are as follows:

  - The framework development (Figure 3.2 and 3.3 in Section 3.3)
  - The numerical formulation (Section 3.4)
  - The Semi-Life Cycle Assessment (LCA) modelling (Section 3.2) including
    - Four different electricity generation scenarios (100% of coal and oil, 50% coal and oil and 50% nuclear power, and 100% nuclear power)
    - Transmission loss of electricity
    - Impact of terminal operations on CO_2 emissions

  The main conclusion was that rail-based intermodal freight systems emit less CO_2 than truck-only systems in general, regardless of the type of locomotives, except in the case of an intermodal system based on an electric-powered train using 100% coal and oil for electricity generation (See the Figure 3.6). Thus, without consideration of the source of electricity, it is not possible to assert that the intermodal is always more sustainable than the truck-only system, at least in terms of CO_2 emissions. The average cruising speed was also a key factor in determining whether the intermodal is more environmentally sustainable than the truck-only system: When the cruising speed was assumed to be 50km/h, the truck-only system was the most CO_2 emitting system. In the other proposed cruising speed with 10km/h step increases (e.g. 60, 70, 80, and 90 km/h), the electric-powered train based intermodal system with the electricity generation of 100% coal and oil was the system which emitted the most CO_2.

- *Chapter 4*
  This Chapter was designed for extending the methodology of Chapter 3 by:
  - Summarizing the research gap of CO_2 emissions assessment in the field of the intermodal study focusing on EC studies (EC, 1999, 2000, 2003b, 2005)
  - Examining a case study with practical geographical and operational data
  - Considering the average percentage of source for electricity generation (i.e. 35% nuclear, 30% coal/oil, 14.5% hydro, and 9% natural gas) in EU15 (EC, 1999)
  - Adding a vessel-based intermodal system and comparing with the other intermodal systems and truck-only system

This Chapter confirmed the findings of Chapter 3: the intermodal freight systems emitted less CO_2 than the truck-only system, except when based on an electric-powered train where the electricity was 100% generated by coal/oil (Figure 4.4 in Section 4.3). In addition to this confirmation, the vessel-based intermodal system (indicated as Alt 7 in Figure 4.4) showed a similar level of CO_2 emissions of the diesel powered train based intermodal system (indicated as Alt 2) and slightly less CO_2 emitting than the electric powered train based intermodal system with the average percentage of electricity generation in Europe (indicated as Alt 3). Furthermore, a significant insight into an environmental aspect of waterborne vessels was found: the vessel size is a key factor when comparing the vessel-based intermodal system with other freight systems (i.e. as the size of vessel increases, the per ton CO_2 emissions decreases).

- *Chapter 5*
  Since it is not possible to estimate the definitive break-even distance that is a measure of the economic feasibility of the intermodal freight system, this Chapter developed a Monte Carlo simulation model that generates random numbers in a certain range for several factors. The main contributions of this Chapter are that:
  - The intermodal break-even distance are clearly redefined (Section 5.3)
  - The distance-dependent cost functions are tested (Section 5.4)
  - The random effect of shipper-receiver pairs and terminal costs are examined (Section 5.4)
  - The terminal shape and the location of the intermodal terminal are examined in a sensitivity analysis (Section 5.5), and
  - The break-even distances either investigated or estimated in previous studies are synthesized (Appendix 5B)

  We reviewed more than 15 previously published studies examining the break-even distances for the intermodal freight transport system as shown in Appendix 5B. To the best of our knowledge, this Monte-Carlo simulation approach was a new method to estimate the economic feasibility under several different conditions without a loss of generality and to produce the intermodal mode share (%) in each simulation trial.

  The specific findings are that a one percent change in the increased truck rate or decreased rail rate is almost respectively seven times, three times, and twice as effective as a one percent change in the handling costs at terminals, rail distance, and drayage costs. Furthermore, we found that neither the oval-shaped market area nor a terminal relocation attracts customers to intermodal systems in general. When two options are combined, the synergic effect is significant.

  To sum up, the intermodal system is not always more economically beneficial than the truck-only system. It is only better under conditions which consist of several variables. This study examines the variables and gives insight into how to increase the intermodal share.

- *Chapter 6*
  This study developed a framework incorporating economies of scale into the multimodal minimum cost flow problem in the network. The main contribution is as follows:

- Three types of economies of scale were presented graphically (Figure 1 and Appendix 6A) and mathematically (Appendix 6B): ESQ (Economies of Scale in terms of Quantity), ESD (Economies of Scale in terms of Distance), and ESVS (Economies of Scale in terms of Vehicle Size).
- Special attention was paid to drayage in the modeling perspective: the penalty for the 2nd level of intermodal system (i.e. truck – rail - long-haulage rail – rail - truck) shown in Figure 6.3 and the corresponding choice sets Figure 6.4 (i.e. conventionally only truck - long-haulage rail – truck is available).
- Technically, a Genetic Algorithm-based heuristic algorithm was developed in order to solve non-continuous and non-convex objective functions which cannot be solved by traditional LP (Linear Programming) /non-LP techniques. In addition, the proposed heuristic algorithm also overcomes the inherent difficulty to handle the constraints (i.e. one demerit of GA is to handle the equality/inequality constraints) (Michalewics, 1995).

In general, the findings in this chapter are that GA is applicable to the non-continuous and non-convex multimodal minimum cost flow problem so as to obtain the near-optimum solutions. The huge savings of the cost per TEU were observed with increases in demand as well as in service capacity, such as frequency for non-road modes. This finding led to the answer of the research question: the intermodal system is more economically competitive than the truck-only system if economies of scale are fully taken into account.

- *Chapter 7*
  This chapter examined the relationship between the freight transport costs and the CO_2 emissions in the given intermodal and truck-only freight networks. To the best of my knowledge this was a new approach to estimate the price in order to reduce CO_2 emissions in freight market by one tonne. Also, the decision making model developed in this chapter provides decision makers with a set of Pareto optimal solutions (i.e. several different options for routing and freight mode choice). In addition, in considering the changing demands and capacities of freight systems, five scenarios are tested in order to examine the impact of mode/route change on the trade-off between the freight transport costs and the CO_2 emissions. The results of scenario analyses show that the trade-off is significantly influenced by demands and capacities of systems. As shown in Table 7.3, the different demand/capacity scenarios resulted in CO_2 prices ranging from 11 €/tonne to 5,350 €/tonne. This wide range in CO_2 prices were caused by different levels of sensitivity to demand and capacity. Nevertheless, the finding provides insight into the different amounts of CO_2 costs that could be charged in different freight corridor/network having different demand/capacity if it was implemented.

8.2 Limitations and future studies

A valuable finding of this dissertation is that there are a lot of unknown factors which determine whether or not an intermodal system is more competitive than a truck-only system. The uncertainty caused by these unknown factors is the main limitation of this dissertation in general. Thus, this dissertation, in order to handle such unknown factors, has simplified the system, assumed some factors based on market observation/previous studies, or even ignored

unmanageable factors. One may say that this is the difference of either "deterministic versus Stochastic" or "Static versus Dynamic" models. The position of this dissertation is on the side of deterministic and static models apart from Chapter 5 which includes stochastic aspects.

Below we list the most important limitations of the chapters of this dissertation.

- Chapter 3

A set of limitations is recognized:

  - The average distance of drayage used (i.e. 50km per one-end) was more or less arbitrary although it reflects the logistics market situation in Europe
  - Utilization and loading factors are simply assumed and empty back haul was not taken into consideration
  - Different detour factor (larger for rail than for road) could be used.
  - The non-CO_2 related environmental impacts of nuclear power: nuclear power hardly produces CO_2 emissions but has other environmental impacts (e.g. related to nuclear waste).

The first limitation above was resolved in the case study by using real distance data in the Geographic Information System in Chapter 4. The average distance of drayage was also treated with the Monte-Carlo simulation model in Chapter 5, although the research objective was different from Chapter 3.

- Chapter 4

A useful further study focusing on one of the limitations of this chapter is addressed: trucks used for drayage have different characteristics than those used for long-distance haulage in most cases. In particular, drayage trucks tend to be older and less fuel efficient. In addition, when waterborne transport is compared with other transport systems, the inclusion of vehicle/vessel size could result in important changes in CO_2 emissions.

- Chapter 5

This Chapter treated the uncertainty issues such as drayage distance, shipper/receiver location, terminal location, and so on by using a Monte-Carlo simulation. The limitations are:

  - The radius defining the origin and destination market size ($\boldsymbol{R_o}$ and $\boldsymbol{R_d}$) were assumed to be equal. This leads to the recommendation to examine the impact of two different market sizes in future study.
  - This chapter only takes into account the economies of distance. The economies of scale based on quantity (i.e. cheaper rates as quantity increase) and vehicle size (i.e. cheaper rate as vehicle size increase) could also be another important factor although it is expected that there may be a correlation with economies of distance (Other economies of scale, for example, in terms of quantity and vehicle size are tested in Chapter 6).

- Chapter 6

The main limitation of this chapter might be the proposed unit cost functions for each transport mode. On the one hand, these are well modelled. However, the sources of each cost function differ by mode, potentially leading to inconsistencies (for trucks and trains, Janic (2007, 2008) and for waterborne vessels, Cullinane and Khanna (1999)). To the best of my knowledge, to date there is no study to model the comparable unit cost functions

incorporating different economies of scale for different transport modes. This is a good future research topic since each transport mode has different levels of economies of scale. (e.g. waterborne vessels are more sensitive to vessel size (up to 8,000TEU) than to distance while trucks are more sensitive to distance than to the size of the vehicle (at most 2.5TEU)). In addition to the limitation related to the unit cost function, we recommend examining the individual impact of each economy of scale since this Chapter only provided the whole impact of three economies of scale (ESQ, ESD, and ESVS). The final limitation is a kind of inherent shortcoming of the genetic algorithm that tends to find the near-optimal instead of the global optimum. Alternatively, other methods such as simulation annealing, Tabu search, and other efficient heuristics could be developed for better solutions in shorter time in future.

- Chapter 7

Even though the temporal concept such as minimizing the lead time and ensuring Just-in-time (i.e. reliability) is also not taken into account in this Chapter, the proposed multi-objective optimization problem might be the appropriate format to incorporate them. Specifically, the third/fourth objective functions addressing such issues would be newly added in the problem in a future study. In addition, for computational simplicity, the economies of scale proposed in Chapter 5 and 6 are not taken into account in the multi-objective optimization.

In addition, the Pareto optimal solutions estimated in this study was a subset (i.e. the number of solutions are only 50). The number of solutions can be either increased or decreased according to the research objective of the future study. If the objective functions are fairly complicated, smaller numbers of Pareto optimum solutions are recommended due to computational time. Otherwise, more solutions could be a good option since the number of Pareto optima is equal to the number of options that policy makers can choose.

There are three limitations that are generally applicable to this dissertation and corresponding future studies: (1) the size of the network in this dissertation (mainly Chapter 4, 6, and 7) is quite small: 6 nodes (Amsterdam, Brussels, Vilnius, Warsaw), 2 terminals (Rotterdam and Gdansk), connecting links regarding only three transport modes (trucks, rail, and short sea shipping). Examining the cost model (Chapter 6), CO_2 emissions assessment models (Chapter 4) as well as the trade-off model (Chapter 7) in a larger network is necessary to test the model's robustness. (2) This dissertation does not include the temporal concept for several reasons. The first reason is that the travel time, delay time, and Just-in-time policy are highly dependent on uncertain situations which are the main issue in stochastic models. For example, the delay time due to congestion is hardly generalized in deterministic models. The exclusion of the temporal concept might be justified by the fact that there are still a lot of cost-oriented shippers/receivers in logistic markets. One of the benefits of excluding such factors was that the environmental and economic impacts could be individually highlighted. In addition, the estimation of the value of time and the value of CO_2 emissions are still open to debate as shown in Tol (2005). For this reason, the author has intentionally attempted to avoid the conventional method of valuing time as well as CO_2 emissions. The consequence of such effort was to develop the method of the trade-off between costs and non-monetary values as shown in Chapter 7. The trade-off is estimated based on the multi-objective optimization method that seems to be an appropriate format for including the temporal variable such as delay time, travel time, and Just-in-time without loss of generality. (3) Not only in this

dissertation but also in general, the data collection and market observation is one of the most important processes in any freight transport/logistics research. This dissertation used the very limited data relying on scientific journal articles and government reports rather than on field data. This needs to be fortified in the future.

8.3 Epilogue

This dissertation contains three large "Parts". In every Part, the role of the truck-only system was always the "counterpart" of the intermodal system. The policy rationale to encourage the intermodal system is that this freight system is, at least potentially, better than the truck-only system. However, I've found many reports/articles whose purposes are to only optimize/improve the intermodal system without a comparison with its counterpart. I believe the encouragement of the intermodal system is only justified when it performs better in environmental or other policy relevant aspects than its counterpart. If the truck-only system was better than the intermodal system for some reason, why not use trucks and even encourage them? In addition, if the environmental benefit from the intermodal system is very minor and the economic loss of it is considerable, does our society still want to encourage the intermodal system? I got the impression in some of the previous intermodal related studies that these are predetermined to encourage the intermodal system, and only focus on ways to enhance the efficiency. This feature has driven me to doubt whether the intermodal system is really better than the truck-only system.

The overall result shows the phenomenon that two freight systems are competing in environmental and economic terms. Since this dissertation includes several factors that are commonly used and interrelated in every Chapter (e.g. drayage distance, long-haulage distance, demand, capacity, frequency of freight trains, the location of terminal, and travel speed/time), the degree of freedom in the model proposed in each Chapter is very high. In general, this is why we cannot say that one freight system is always better than the other. Thus, all the answers for the corresponding initial research questions might be "conditional". The superiority of the intermodal system that is valid under certain conditions leads to the issue of transferability. Therefore, the author would like to suggest readers who want to use some parts of this dissertation to pay special attention to local/regional geographic, economic, and logistics conditions.

This kind of uncertainty also makes policy making to reduce CO_2 emissions in the field of freight transport related to multimodal transport difficult. I hope that this dissertation contributes to helping to uncover this uncertainty and accordingly to increase the quality of the related policy making. Furthermore, I hope that this dissertation contributes towards making our society more sustainable in the future.

Finally, an experimental policy concept is attached to this dissertation in Appendix B: CO_2 quota. I excluded it in the main body of the dissertation because its focus is slightly different to that of the main story of this dissertation and because it is based on a conference proceeding, not a journal paper. If the reduction of CO_2 emissions would be the top priority rather than cost saving and the Just-In-Time constraint, this new and quite aggressive methodology could be considered.

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Samenvatting en conclusies

Resultaten en bijdragen

De oorspronkelijke onderzoeksvraag kan teruggebracht worden tot de volgende vraag: "*Is een intermodaal vervoersysteem beter dan een vervoersysteem waarin al het vervoer over de weg (per truck) plaatsvindt?"*. *Het bijvoeglijk naamwoord* "beter" heeft hier betrekking op "beter voor het milieu" (zoals uitgewerkt in Part 1) en "beter in economische zin" (zoals uitgewerkt in Part 2). Dit lijken eenvoudige vragen, maar de beantwoording daarvan is niet zo eenvoudig: onder bepaalde voorwaarden is een intermodaal vervoerssysteem beter en onder andere voorwaarden is een wegvervoersysteem beter. Dit verklaart de meer specifieke vraag in de inleiding van Part 1 en Part 2 "*Onder welke voorwaarden is het intermodale vervoerssysteem concurrerender dan een systeem met alleen wegvervoer als we kijken naar de economische en milieuprestaties van beide vervoerssystemen?"* Zodra de voorwaarden waaronder intermodaal vervoer concurrerender is bekend zijn, dan kunnen we antwoord geven op de vraag "*hoeveel is het intermodale vervoerssysteem beter dan wegvervoer?"*. In Part 1 werd ingegaan op de mogelijke reductie in CO_2 uitstoot (in tonnen), terwijl in Part 2 ingegaan werd op de mogelijke reductie in totale kosten (in Euro), alsmede op de marktaandelen (modal split en route %). In Part 3 waren de oorspronkelijke onderzoeksvragen als volgt "*Wat is de verhouding tussen de CO_2-emissies zoals die in de logistieke keten ontstaan en de logistieke kosten?" en "Hoeveel kost het per eenheid CO_2 om de emissies* van *CO_2-emissies te verlagen via een shift van wegvervoer naar intermodaal vervoer?*". Door de antwoorden op elkaar te betrekken wordt het mogelijk om aan te geven wat het kost om X ton goederen van weg- naar intermodaal vervoer te verschuiven, welke vermindering van de CO_2-emissies daarmee bereikt kan worden en meer in het algemeen welke trade-off er bestaat tussen logistieke kosten en CO_2 -uitstoot.

De beantwoording van deze onderzoeksvragen heeft geleid tot een aantal belangrijke bevindingen en bijdragen aan het wetenschappelijke discours. Per hoofdstuk kunnen deze als volgt samengevat worden:

- *Chapter 3*
  Er bestaan statistieken en eerdere studies die aangeven dat railvervoer minder broeikasgassen en luchtvervuiling produceert dan wegvervoer. Het gaat hier echter om niet-vergelijkbare grootheden, omdat de emissiegegevens van wegvervoer gebaseerd zijn op deur-tot-deur vervoer, terwijl de emissiegegevens van railvervoer gebaseerd zijn op interterminal vervoer (EC, 1999, 2003a, 2002). Daarnaast zijn er technieken ontwikkeld om emissies van individuele vervoersmodaliteiten te onderscheiden (EC, 1999). Chapter 3 richt zich daarom op het bepalen van de CO_2-emissies van vrachtvervoersystemen en niet op individuele modaliteiten. De belangrijkste bijdragen van de studie zijn de volgende:

  - Het ontwerpen van een raamwerk (Figure 3.2 en 3.3 in Section 3.3)
  - De analytische formulering (Section 3.4)
  - De Semi-Life Cycle Assessment (LCA) modellering (Section 3.2) inclusief
    - Vier verschillende scenario's voor de electriciteitsproduktie (100% met kolen en olie, 50% met kolen en olie en 50% met nucleaire energie en 100% nucleaire energie)
    - Transmissieverliezen bij electriciteitsgebruik
    - De invloed van terminalactiviteiten op de CO_2-emissies

  De belangrijkste conclusie is dat op railvervoer gebaseerde intermodale goederenvervoersystemen in het algemeen, ongeacht het type locomotieven, minder CO_2 produceren dan wegvervoerssystemen. Een uitzondering is een intermodaal vervoerssysteem waarbij gebruikt maakt wordt van electrische locomotieven die electriciteit gebruiken die voor 100% met kolen en olie geproduceerd is (zie Figure 3.6). Dit geeft aan dat niet zonder meer geconcludeerd mag worden dat intermodaal vervoer in alle gevallen minder CO_2 genereert. Altijd zal aangegeven moeten worden welke brandstofmix voor de productie van electriciteit gebruikt is. Een andere factor die bepalend is voor de (relatieve) duurzaamheid van een vervoerssysteem is de gemiddelde snelheid: Bij 50km/h produceert een truck de meeste CO_2. Wanneer deze snelheid in stappen van 10 km/h toeneemt (bijvoorbeeld 60, 70, 80 en 90 km/h), dan zal een trein met een locomotief die electriciteit gebruikt die geproduceerd is met een brandstofmix van 100% kolen en olie, de meeste CO_2 uitstoten.

- *Chapter 4*
  In dit hoofdstuk wordt de methodologie van Chapter 3 op de volgende manier uitgewerkt:
  - Ontdekken van de 'gaten' in het bestaande EC onderzoek naar de CO_2-emissies van intermodaal vervoer (EC, 1999, 2000, 2003b, 2005)
  - Opzetten van een casestudie waarin echte geografische en operationele data gebruikt worden
  - Bepalen van de gemiddelde brandstofmix van electriciteitscentrales in de EU-15 (35% nucleair, 30% kolen/olie, 14.5% hydro, en 9% gas; EC, 1999)
  - Toevoegen van short seavervoer en dit vergelijken met weg-rail- en wegvervoersystemen.

  Dit hoofdstuk bevestigde de uitkomsten van Chapter 3: een intermodaal vervoerssysteem genereert minder CO_2 dan een wegvervoerssysteem. Een uitzondering is een intermodaal vervoerssysteem waarbij gebruikt maakt wordt van locomotieven

die electriciteit gebruiken die voor 100% met kolen en olie geproduceerd is (zie Figure 4.4 in Section 4.3). Daarnaast blijkt short seavervoer (zie Alt 7 in Figure 4.4) een vergelijkbare CO_2- uitstoot te hebben als een intermodaal vervoerssysteem dat gebruik maakt van diesellocomotieven (zie Alt 2) en iets minder CO_2 uit te stoten dan een intermodaal systeem dat gebruik maakt van electrische locomotieven die gebruik maken van d gemiddelde brandstofmix van Europese electriciteitscentrales (zie Alt 3). Een andere belangrijke uitkomst van dit onderzoek is dat de omvang van een zeeschip bepalend is voor de CO_2-emissies: als de scheepsomvang toeneemt, dan dalen de CO_2-emissies per ton.

- *Chapter 5*
  Aangezien het niet mogelijk is om een sluitend antwoord te geven op de vraag wat de break-even afstand is en daarmee van de markt van een intermodaal vrachtvervoersysteem, hebben wij in dit hoofdstuk een Monte Carlo simulatiemodel gebouwd dat in staat is om (binnen bepaalde grenzen) willekeurige waarden te genereren voor verschillende factoren. De belangrijkste bijdragen van dit hoofdstuk zijn:
  - Het duidelijk herdefiniëren van de intermodale break-even afstand (Section 5.3)
  - Het testen van de afstandsafhankelijke kostenfuncties (Section 5.4)
  - Het analyseren van willekeurige verlader-ontvanger paren en terminalkosten (Section 5.4)
  - Het analyseren van de vorm van en de locatie van een intermodale terminal via een gevoeligheidsanalyse (Section 5.5), en
  - Synthese van de in eerdere studies bepaalde break-even afstanden (Appendix 5B).

  Wij hebben meer dan 15 eerder uitgevoerde studies onderzocht teneinde de break-even afstanden voor intermodale vrachtvervoersystemen te kunnen bepalen (zie Appendix 5B). De hierbij gebruikte Monte-Carlo simulatie is nog niet eerder voor deze toepassing – het schatten van het intermodale marktaandeel onder verschillende condities en deze uitkomsten te generaliseren - ingezet.

  Volgens onze berekeningen is 1 % stijging in de kosten van truckvervoer of 1 % daling van de kosten van railvervoer ongeveer respectievelijk 7 maal, 3 maal en 2 maal zo effectief als 1 procent verandering in de terminal handlingkosten, de afstand per rail en de kosten van voor- en natransport per truck. Verder vonden wij dat noch het 'ovale marktgebied' noch een terminalverplaatsing potentiële klanten warm maakt voor intermodale vervoersystemen. Wanneer twee sturingmogelijkheden gecombineerd worden, dan is het synergie-efect wel significant.

  Samengevat: het intermodale vervoersysteem is niet altijd rendabeler als een wegvervoersysteem. Dit is alleen het geval wanneer meerdere variabelen gecombineerd worden. In deze studie zijn deze variabelen onderzocht en daarmee is het inzicht in de mogelijkheden om het marktaandeel van intermodaal vervoer te vergroten toegenomen.

- *Chapter 6*
  In deze studie is een raamwerk ontwikkeld waarmee schaalvoordelen (economies of scale) gerelateerd kunnen worden aan de kosten van en vervoersstromen binnen een multimodaal vervoersysteem. De belangrijkste bijdragen zijn de volgende:
  - Drie typen schaaleffecten werden grafisch (Figure 1 en Appendix 6A) en wiskundig weergegeven (Appendix 6B): de ESQ (schaaleffecten in termen van hoeveelheid), ESD (schaaleffecten in termen van afstand), en ESVS (schaaleffecten in termen van voertuiggrootte).
  - Speciale aandacht is hierbij gegeven aan de modellering van het voor- en natransport: zo werden de extra kosten van zgn. secundaire intermodale systemen (d.w.z. truck – rail – lange afstandsvervoer per rail – rail - truck) (zie Figure 6.3 en de daarmee overeenkomende keuzesets in Figure 6.4 (d.w.z. truck - lange afstandsvervoer per rail – truck) bepaald.
  - In technische termen, er werd een 'Genetic Algorithm-based heuristic algorithm' ontwikkeld om niet-continue en non-convexe doelfuncties op te lossen via traditionele LP (Linear Programming) of niet-LP methoden. In aanvulling daarop, dankzij dit 'heuristic algorithm' was het ook mogelijk om inherente beperkingen van GA (bijv. hoe om te gaan met equality/inequality constraints) te omzeilen (Michalewics, 1995).

  In het algemeen geven de bevindingen van dit hoofdstuk aan dat GA gebruikt kan worden om semi-optimale oplossingen te vinden voor complexe multimodale vervoerssystemen. Er kan sterk bespaard worden op de kosten per TEU wanneer de vraag, de capaciteit en de frequentie van intermodaal vervoer toenemen. Op basis van dit inzicht kan de onderzoeksvraag beantwoord worden: een intermodaal vervoersystem is concurrerender dan een wegvervoersysteem wanneer schaalvoordelen volledig meegewogen worden.

- *Chapter 7*
  In dit hoofdstuk is the relatie tussen de vervoerskosten en CO_2-emissies voor gegeven intermodale en wegvervoernetwerken bepaald. Dit is een nieuwe benadering om de prijs per ton van CO_2-emissies te kunnen bepalen. Ook werd een model voor besluitvormers ontwikkeld waarmee zij een set van Pareto optimale oplossingen (d.w.z.. verschillende opties voor routekeuze en modal choice) kunnen analyseren. In aanvulling daarop werden vijf scenario's ontwikkeld om te bepalen wat de invloed van veranderingen in de modaliteit of routekeuze is op de trade-off tussen vervoerskosten en CO_2-emissies. De scenario-analyses laten zien dat deze trade-off significant beïnvloed wordt door de vraag en aanbod binnen een vervoersysteem. Zoals in Table 7.3 is te zien, variëerden de CO_2-prijzen tussen 11 €/ton en 5,350 €/ton. Deze ruime marge wordt veroorzaakt door de verschillende gevoeligheden voor vraag en aanbod. Niettemin, de uitkomsten dragen bij aan het inzicht in de mogelijkheden om de CO_2-kosten door te berekenen in de verschillende vervoerscorridors en - netwerken.

Beperkingen en toekomstige studies

Een belangrijke uitkomst van deze dissertatie is dat er veel onbekende factoren zijn die bepalen of een intermodaal vervoersysteem concurrerender is dan wegvervoer. De onzekerheid over deze onbekende factoren is de belangrijkste beperking van deze dissertatie.

Vandaar dat wij in deze dissertatie, teneinde met deze onzekerheid om te kunnen gaan, de vervoersystemen vereenvoudigd hebben, waarbij we sommige factoren hetzij aan andere studies ontleend hebben, dan wel de niet te bepalen factoren buiten beschouwing hebben gelaten. Dit is in feite het verschil tussen “deterministische versus stochastische” of tussen “statische versus dynamische” modellen. Wij kiezen hierbij de kant van de deterministische en statische modellen behalve in Chapter 5 dat stochastische aspecten bevat.

Hieronder gaan we per hoofdstuk in op de belangrijkste beperkingen van deze dissertatie.

- Chapter 3

De volgende beperkingen gelden hier:

- De gemiddelde afstand in het voor- en natransport (50km per enkele reis) is min of meer arbitrair gekozen, hoewel deze overeenkomt met de marktsituatie in Europa
- Gebruiks- en beladingsfactoren zijn verondersteld, terwijl leegrijden ('return trip') niet meegenomen is in de analyse
- Er zouden andere omrijfactoren (groter voor rail- dan voor wegvervoer) kunnen worden gebruikt.
- De niet-CO_2 gerelateerde milieu-effecten van nucleaire energie zijn niet meegenomen: nucleaire energie produceert nauwelijks CO_2 in directe zin, maar er zijn andere milieunadelen (bijv. gerelateerd aan restafval).

De eerste beperking werd opgelost door in de casestudie echte afstandsgegevens uit een GIS systeem te halen (zie Hoofstuk 4). De gemiddelde afstand in het voor- en natransport is via het in Chapter 5 ontwikkelde Monte-Carlo simulatiemodel bepaald, hoewel het researchdoel verschilde van dat van Chapter 3.

- Chapter 4

Een beperking van dit hoofdstuk is dat trucks die voor voor- en natransport worden gebruikt meestal verschillen van trucks die voor lange afstandsvervoer worden gebruikt. De eerste categorie trucks is meestal ouder en minder energie-efficiënt. Daarnaast, wanneer short sea vervoer wordt vergeleken met andere vervoersystemen, dan is de scheepsomvang bepalend voor de (verandering in) CO_2-emissies.

- Chapter 5

In dit hoofdstuk werden onzekere factoren zoals voor- en natransport afstand, locaties van verladers/ontvangers, terminal locatie enz. bepaald via Monte-Carlo simulatie. De volgende beperkingen gelden hierbij:

- De omvang van de markten (oorsprong ($\boldsymbol{R_o}$ en bestemming $\boldsymbol{R_d}$) werd gelijk verondersteld. In een toekomstige studie zou de impact van een verschillende omvang van de markten meegenomen kunnen worden.
- Er is alleen ingegaan op ‘economies of distance’. Schaalvoordelen gebaseerd op hoeveelheid (d.w.z. de vervoerskosten dalen als de vervoerde hoeveelheden toenemen) en grootte van het voertuig (d.w.z. de vervoerskosten dalen als de voertuigomvang toeneemt kunnen een belangrijke invloed hebben om de uitkomsten van de berekeningen. Er is echter ook reden om aan te nemen dat EOS en EOD correleren (zie verder Chapter 6).

- Chapter 6

  De belangrijkste beperking in dit hoofdstuk ligt in de voorgestelde kostenfuncties per eenheid voor elke vervoersmodaliteit. Aan de ene kant zijn deze goed gemodelleerd. Echter, de bronnen van deze kostenfuncties verschillen per modaliteit, wat kan leiden toe inconsistenties (voor trucks en treinen zie Janic (2007, 2008) en voor watervervoer zie Cullinane en Khanna (1999)). Tot nu toe is er geen studie die vergelijkbare kostenfuncties per eenheid voor verschillende EOS voor de verschillende transportmodaliteiten modelleert. Dit is een interessant onderwerp voor verdere studie, omdat elke transportmodaliteit verschillende EOS kent (bijv. de kosten van watervervoer zijn gevoeliger voor de scheepsomvang (tot 8,000TEU) dan voor afstand, terwijl trucks gevoeliger zijn voor afstand dan voor voertuiggrootte (tot maximaal 2.5 TEU)). In aanvulling op deze beperkingen bevelen wij aan om de impact per schaalfactor (ESQ, ESD, ESVS) te bepalen, en niet zoals hier gebeurd is, voor het totaal van deze drie. De laatste beperking is er een die inherent is aan GA. Hierbij wordt een bijna-optimaal i.p.v. een globaal optimum bepaald. Als alternatief kunnen andere methoden, zoals 'simulation annealing', 'Tabu search' en andere efficiënte heurististieken gebruikt of ontwikkeld worden om dit probleem op te lossen.

- Chapter 7

  Hoewel tijdsaspecten, zoals minimale lead time en just-in-time (betrouwbaarheid) niet in dit hoofdstuk meegenomen zijn, kan het voorgestelde 'multi-objective optimization problem' het juiste kader bieden om de tijdsfactor wel mee te nemen. De derde en vierde doelfuncties kunnen in een toekomstige studie gebruikt worden om hier dieper op in te gaan. In aanvulling daarop en om de berekeningen te vereenvoudigen, is bij het bepalen van de schaalvoordelen in Chapters 5 en 6 geen gebruik gemaakt van 'multi-objective optimization'.

  De vijftig Pareto optimale oplossingen die in deze studie gevonden zijn vormen een deel van de mogelijke uitkomsten. Dit aantal kan zowel vergroot of verkleind worden afhankelijk van de onderzoeksdoelen van toekomstige studies. Als de doelfuncties relatief complex zijn, dan is een kleiner aantal Pareto optimale oplossingen wenselijk om de computertijd te verkorten. Anderzijds is uitbreiding van het aantal oplossingen aan te bevelen, omdat beleidsmakers dan meer keuzemogelijkheden hebben.

Er zijn drie beperkingen die in meer algemene zin voor deze dissertatie en ook voor toekomstige studies gelden: (1) de omvang van het netwerk in deze dissertatie is erg beperkt (zie Chapters 4, 6 en 7): er zijn 6 knooppunten (Amsterdam, Brussels, Vilnius, Warsaw), 2 terminals (Rotterdam en Gdansk) en verbindingen via slechts 3 transportmodaliteiten (truck, rail en short sea). Teneinde de robuustheid van deze modellen te kunnen bepalen is een nadere beschouwing van het kostenmodel (Chapter 6), van de beoordeling van de CO_2-emissies (Chapter 4) en van het trade-off model (Chapter 7) nodig in het kader van een groter netwerk. (2) Deze dissertatie houdt om verschillende redenen geen rekening met het tijdsaspect. De eerste reden is dat de reistijd, de vertragingen en het just-in-time beleid sterk afhankelijk zijn van onzekerheid; het belangrijkste onderdeel van stochastische modellen. Om een voorbeeld te geven, vertragingen door congestie worden nauwelijks gegeneraliseerd in deterministische modellen. Het uitsluiten van het tijdsaspect kan gerechtvaardigd worden door te wijzen op het feit dat er nog steeds veel verladers/ontvangers zijn die op de kosten letten. Een van de voordelen van het weglaten van dit soort factoren is dat de milieu- en economische aspecten afzonderlijk naar voren konden komen. In aanvulling daarop, de tijdswaarde en de

waarde van CO_2-emissies zijn nog steeds niet bepaald (zie Tol (2005)). Daarom hebben wij ervoor gekozen om de conventionele methode om zowel de tijd als de CO_2-emissies te waarderen te vermijden. Een consequentie van deze keuze was dat wij een methode moesten ontwikkelen om kosten en niet-monetaire eenheden tegen elkaar af te wegen (zie Chapter 7). Bij deze trade-off hebben wij gebruik gemaakt van de 'multi-objective optimization method'. Volgens ons is dit de juiste methode om met tijdsfactoren om te gaan zonder verlies van de mogelijkheid tot generalisatie. (3) Niet alleen in deze dissertatie, maar ook in het algemeen blijken dataverzameling en marktonderzoek tot de meest belangrijke onderzoeksprocessen te behoren. Voor deze dissertatie kon helaas slechts gebruik gemaakt worden van een beperkte dataset bestaande uit wetenschappelijke tijdschriften en overheidsrapporten en niet van veldwerk. Voor verdere studie zijn meer gegevens nodig.

Epiloog

Deze dissertatie bestaat uit drie grote delen. In elk deel is de rol van het wegvervoer altijd de tegenhanger van het intermodale systeem. De ratio om intermodaal vervoer te stimuleren is dat het intermodale vervoersysteem, ten minst in potentie, beter is dan een wegvervoersysteem. Echter, wij hebben veel studies bekeken die er uitsluitend op gericht waren om het intermmodale vervoersysteem te optimaliseren of verbeteren zonder dat zij intermodaal vervoer en wegvervoer met elkaar vergeleken. Wij zijn echter van mening dat bevordering van het intermodaal vervoer alleen te rechtvaardigeen is wanneer intermodaal vervoer qua milieuprestaties of andere voor het beleid relevante aspecten beter scoort dan wegvervoer. Als het wegvervoer om een bepaalde reden beter is dan intermodaal vervoer, is het dan niet logisch om wegvervoer te gebruiken en ook te stimuleren? En, als de milieuvoordelen van intermodaal vervoer vrij beperkt zijn en de kosten van een modal shift aanzienlijk zijn, is het dan logisch dat een samenleving intermodaal vervoer stimuleert? Wij kregen de indruk dat sommige eerder uitgevoerde studies naar intermodaal vervoer bevooroordeeld zijn en daarbij alleen focussen op manieren om de efficiëntie van intermodaal vervoer te verbeteren. Dit brengt ons er toe om te twijfelen of intermodaal vervoer werkelijk beter is dan wegvervoer.

Dit brengt ons bij het fenomeen van twee vrachtvervoersystemen die met elkaar concurreren als het gaat om hun milieu- en economische prestaties. Aangezien deze dissertatie meerdere factoren bevat die in elk hoofdstuk terugkomen (zoals de afstand in voor- en natransport, de afstand van lange afstandsvervoer, de vraag, het aanbod, de frequentie van vrachttreinen, de terminallocatie en de trip snelheid en duur), is het aantal vrijheidsgraden in ons model erg groot. Dit is de algemene verklaring waarom wij niet kunnen zeggen dat een van de twee vervoersystemen altijd beter is dan het andere. Daarom zijn alle antwoorden op de bijbehorende initiële onderzoeksvragen “conditioneel”. In die situaties waarin het intermodale vervoersysteem superieur is, geldt dit onder bepaalde voorwaarden. Dit brengt ons bij het onderwerp overdraagbaarheid van uitkomsten. Wij raden de lezers die bepaalde delen van deze dissertatie voor hun eigen onderzoek willen gebruiken aan om zich hierbij af te vragen of hun lokale/regionale geografie, hun economische situatie en logistische eisen voldoende overeenkomen met de in deze dissertatie gebruikte condities.

Het uitblijven van 'zekere' uitkomsten maakt het leven van beleidsmakers die beogen om de CO_2-emissions van vrachtvervoer te verminderen niet eenvoudig. Wij hopen dat deze dissertatie bijdraagt aan het verder in kaart brengen van deze onzekerheid en daarmee

bijdraagt aan het verbeteren van de kwaliteit van het beleid op dit terrein. Verder hopen wij dat deze dissertatie bijdraagt aan het duurzamer maken van onze samenleving in de toekomst.

Tenslotte hebben wij een experimenteel beleidsconcept voor CO_2 quota in Appendix B opgenomen. Dit is niet in de hoofdtekst opgenomen, omdat het een iets andere focus heeft als die van de hoofdtekst en omdat het op een congrespaper is gebaseerd en niet op een paper in een journal. Als de beperking van CO_2-emissies de hoogste prioriteit zou hebben in plaats van kostenbesparing en just-in-time, dan zou deze nieuwe, redelijk agressieve aanpak gekozen kunnen worden.

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Appendix A:
A Review of network representation of intermodal and truck-only freight transport systems for freight service network design problems

Nam Seok Kim and Bert Van Wee
Delft University of Technology

Appendix A is a revised version based on a conference proceeding presented at NECTAR [1] (Network on European Communications and Transport Activities Research) conference in Arlington (USA) from June 18th to June 20th, 2009.

Abstract
Intermodal freight transport systems have emerged as alternative systems for truck-only systems. The increased research interest has promoted developing optimization models using OR (Operational Research) techniques for intermodal freight transport. In this paper we present several types of intermodal optimization network design problems and describe the complexities inherent to intermodal freight systems. Focusing on network representations, the possibility of reducing these complexities is also discussed. In particular we discuss two types of frequently used network representations, and conclude that one of them is good enough to find optimal solutions when only intermodal systems are considered while the other representation is appropriate if the aim is to find the optimal solution for both intermodal as well as truck-only systems as a counterpart. In addition, this study presents three generic methods to overcome the complexities relating to intermodal models: the decomposition of networks, description of economies of scale, and the introduction of non-road options.

[1] http://nectar.gmu.edu/ or http://www.nectar-eu.org/

Introduction

The mainstream of network optimization modeling approaches for freight transport focuses on uni-modal freight transport systems rather than intermodal freight transport systems. However, intermodal systems have recently received growing attention as a preferable alternative to truck-only freight systems in terms of economic competitiveness, environmental concerns, and traffic congestion alleviation (EC, 2001, 2005, USDOT, 1991). Thus, research interest in improving the intermodal freight system has been growing rapidly. However, the intermodal freight transport research is a "*pre-paradigm research field*" (Bontekoning et al., 2004). Therefore several research gaps still exist. Macharis and Bontekoning (2004) reported that several types of problems related to intermodal freight have been modeled and are potentially able to be modeled by using operational research (OR) techniques. However, again, when intermodal freight systems are modeled as OR problems, it is undoubtedly "*still a very young domain*" as indicated by Crainic and Kim (2005).

Among the OR problems concerning the intermodal system, this study includes so-called "*service network design problems*" (Crainic and Kim, 2005) or "*intermodal operators*" problems (Macharis and Bontekoning, 2004). The general aims of service network design problems are to find the optimal route and mode choice (Crainic and Rousseau, 1986, Min, 1991, Barnhart and Ratliff, 1993, Oh, 1993, Haghani and Oh, 1996, Guélat et al., 1990, Chang, 2008), or to find hub locations (O'Kelly and Bryan, 1998, Yaman et al., 2007), minimizing the total cost in a given network. Note that mode choice is not the same as system choice. The system is defined as all the process from shippers to receivers by more than two transport modes via terminals (Janic and Reggiani, 2001, Kim and Van Wee, 2009). Thus, the choice set of the freight system includes both truck-only and intermodal freight systems rather than individual transport modes only. The output might be the freight system choice and – related to this choice - the route choice in the network. In order to compare intermodal with truck-only systems it is necessary to represent both systems in one network and mathematically formulate them consistently in one objective function. However, intermodal systems inherently have different characteristics compared to truck-only systems. Intermodal freight systems include multiple modes and multiple steps (collection/distribution [2] by trucks, transhipment, and long-haulage by non-road modes) and therefore are much more complex than the door-to-door delivery of truck-only systems when it is modelled as an OR problem. Each stage (i.e. drayage, long-haulage, and terminal operation) of the intermodal chain has different characteristics. For example, per tonne-kilometre drayage cost is normally expensive[3] and there is a relatively higher risk of empty back-haul. In the case of long-haulage, non-road systems are usually relatively cheap due to the economies of scale, but may face diseconomies of scale due to the potential delay in the transshipment process.

In order to properly embed the above-mentioned issues in service network design problems, and eventually to determine the quality of the model, the network representation plays an important role. However, due to the complexities of the intermodal system, the multi-modal networks in literature are represented in different ways than uni-modal networks. It is obvious that the objective functions and the network representation depends on several issues: the planning level (i.e. strategic, tactical, and operational level), the selection of the chain to be optimized (i.e. the entire chain or a part of the intermodal chain), the modes/systems

[2] Often referred to as drayage or pre-and end-haualge.

[3] The unit costs for drayage differ from those for truck-only system (long distance road haulage) (EC, 2001). In addition, the unit costs for drayage are estimated in terms of the transport time while the unit costs for long-haulage trucking is estimated in terms of the distances travelled (Van Duin and Van Ham, 2001). Janic (2008) attempted to develop an unified regression model for both drayage and long distance trucking.

considered in the model, the consideration of economies of scale in the hub-and-spoke network, and so on. This paper aims to describe the complexities that intermodal freight systems inherently have, to review OR literature focusing on network representation, and to explore the possibility to overcome complexities related to intermodal freight transport systems.

We do not consider the problems of hub location, local drayage optimization, intermodal terminal optimization (COFC/TOFC) or the problem of hub-and-spoke networks with extensive stopovers. In the network design problem treated in this study, the number of hubs and the locations are given and there are no extensive stopovers. In addition, we do consider the more complicated types of intermodal systems as options (e.g. truck-rail-rail (or vessel)-rail-truck; the so-called 2nd level of intermodal chain). In other words, rail can play a role in drayage.

In the next Section, we summarize the complexities of the intermodal network design problem. In Section 3, we present ways to represent both uni-modal and inter-modal networks. Then, based on the definition of an intermodal freight system, the most comprehensive intermodal network representation is distinguished. Furthermore, we review several intermodal network representations. In Section 4, some modeling ideas to overcome the complexities of multi-modal networks are presented. Finally, Section 5 presents the conclusions.

Complexities of the multimodal Network Design Problem

Table A.1 shows the characteristics of both intermodal and truck-only systems.

Table A.1 Characteristics of both systems

	Intermodal system	Truck-only system
Mode	Multiple modes	Single mode (i.e. truck)
Network level	A combined network - *Microscopic*[4] level of road network for drayage - *Macroscopic* level of non-road network for long-haulage	*Macroscopic* level of road network
Stage in the intermodal chain	Multiple stages - Drayage - Long-haulage - Transshipment	Single stage Long-haulage
Total Distance	Summation of shortest paths in terms of the stage (i.e. drayage and long-haulage)	Simple shortest path
Unit Cost	More expensive trucking cost of (drayage) Cheaper cost of long-haulage by non-road mode due to economies of scale and distance	Decreased as distance increases. Almost fixed rate above a certain distance. (economies of distance only)
Total Travel Time	Relatively slower than truck-only system	Relatively faster than intermodal system
Configuration	hub-and-spoke (mostly)[5]	Door-to-door Line-haul

Based on these characteristics we derive six issues that we refer to as complexities[6] causing difficulties to model the service network design problem in intermodal networks.

[4] Microscopic level of road network refers to the urban/regional network while macroscopic indicates national/international network in this context.

[5] For other types of networks, see Figure 3.2 in Kreutzberger (2008).

Ⅰ. Intensive interrelationship between the different planning levels[7];
Ⅱ. Different stages such as drayage, long-haulage, and terminal process;
Ⅲ. Multiple types of infrastructure (i.e. road, rail, and waterway) dedicated for different transport modes (i.e. truck, rail, and vessel respectively);
Ⅳ. Nodes in terms of origin/destination as well as terminals;
Ⅴ. Economies/diseconomies of scale and trade-off between economies and diseconomies of scale.
Ⅵ. Competition between uni-modal (i.e. truck-only system) and multimodal systems

First of all, the issue on the intensive interrelationship between the different planning levels makes modeling intermodal freight more complicated than a uni-modal system. Even though, in general, the categorization into the 3 *planning levels* (strategic, tactical, operational) have allowed for reasonable local optima and contributed to alleviate the complexities in OR models (Macharis and Bontekoning, 2004, Crainic and Kim, 2005, Crainic and Laporte, 1997, Crainic, 2000), this categorization ironically avoids modeling a comprehensive (over all three planning levels) intermodal service network design problem. Even though such planning interrelationship occurs in OR problems in general, it is more complex for intermodal systems than for uni-modal systems since intermodal freight systems generally can have multiple objectives at each planning level. It is therefore crucial to identify the objective that should be reached by the overall optimum. For example, the optimal solution of the intermodal chain at the operational level might be different from the optimal solution at the tactical and strategic levels. The ***first*** complexity issue correlates with the ***second*** and ***third*** issues since the particular stages in the intermodal chain relate to different planning levels in many cases (e.g. drayage at the operational/tactical level and long-haulage at the tactical/strategic level). In addition, different modes are used at different levels (e.g. drayage by truck and long-haulage by non-road modes). It is obvious that optimizing local/regional problems at an operational/tactical level does not guarantee the global optimum of national/international problems at the strategic level. The ***second*** and ***third*** issues are also interrelated. Specifically, a certain transport mode can play more than two roles. In a given truck network, for example, trucks are used for both the drayage part of the intermodal system but also as the only mode for truck-only systems, while rail or barge might mainly be used only in long-haul in intermodal systems (Janic and Reggiani, 2001). Thus, for these three issues, trucking optimization for drayage is found using the local/regional road network at the operational/tactical level, which needs a more detailed network than the network that is to be used at the regional/international level (Morlok et al., 1990). In case of long-hauling truck-only systems a detailed local/regional network may not be needed. In practice, at any planning level drayage is a crucial part to determining whether an intermodal system is economically feasible (EC, 2000, Nozick and Morlok, 1997, Morlok et al., 1990). The EU project RECORDIT specifically shows that the drayage costs may cover even more than 30% of the total door-to-door trip costs despite the relatively short distance (EC, 2000). Of course optimizing the drayage process only does not guarantee the feasibility of an entire intermodal

[6] The complexity does not mean 'computational complexity', which is normally used in OR research field.
[7] The focus at the *strategic* level is on decisions for the construction/expansion/modification of physical infrastructures targeting more than 10 years in future. The decision at the *tactical* level is to find optimal or alternative ways to enhance the system without significantly changing infrastructures. The targeting time period is usually less than 1 year. The decision at an *operational* level focuses on the daily or hourly task. (for more details on the classification, see Crainic and Laporte (1997)).

freight system. Trains and barges use only railway and inland waterway networks respectively and require (separate) networks at the regional/international level in order to estimate the accurate transport distance, which is one of the most crucial factors for total freight costs. The remainder of the ***second*** issue is that the terminal process is also a factor affecting the complexities since a different combination of modes may need different roles of terminals with different terminal costs and process time. The ***Fourth*** issue is about how to set up nodes. Most previous studies assume that only origins and destinations generate demand (i.e. inflows and outflows), and that terminals (or hubs) have capacity. However, hubs can also be origins and destinations, and origins and destinations may have capacity limitations as well. Thus, distinguishing the general nodes (origins/destinations) and the hubs is often inappropriate in modeling. Another important issue associated with nodes setting is to generate options for economies of scale, which is related to the ***fifth*** issue. The ***fifth*** issue is how to properly treat the economies and diseconomies of scale and the trade-offs between them in given intermodal networks. Economies of scale for uni-modal systems in hub-and-spoke systems are dealt with by O'Kelly and Bryan, and Racunica and Wynter (O'Kelly and Bryan, 1998, Racunica and Wynter, 2005). However, these authors could not properly show the ***sixth*** issue: How can multi-modal transport compete with truck-only systems? One may argue that it is possible to consider (optimize) the intermodal and the truck-only system independently in separate networks, and then compare the results. However, it is obvious that two different systems are interrelated in a given network. In other words, truck-only options might become less profitable as intermodal systems become more profitable, because options to realize economies of scale for truck-only systems will then be reduced. Therefore the interactions are also very important issues that should be included. Moreover, the trade-off between economies of scale being achieved by the use of non-road modes and diseconomies of scale due to terminal processes (i.e. congestions) is also a part of the ***fifth*** issue. These complexities undoubtedly result in difficulties to be formulated and solved in the network design problem.

Intermodal network representation

This Section presents types of intermodal networks and reviews the literature focusing on network representation.

Types of intermodal network representation

There is no prototype of network representation for intermodal service network design problem. It varies depending on the aim of study, data collected, modeler's point of view. However, there are still common components that are necessary to be embedded in OR problems: nodes and arcs.

In order to explicitly know what should be included in the intermodal network representation for an OR problem, some definitions of intermodal freight system (i.e. combined freight transport[8]) should be reviewed (2001, ECMT, 1998):

- Definition 1. "Multi-modal transport is a carriage of goods by **at least two different transport modes**."

[8] Combined transport is often used as synonym of intermodal transport Kreutzberger, E., 2008, The innovation of Intermodal Rail Freight Bundling Networks in Europe: Concepts, Developments, Performances. *Ph.D*, Delft University of Technology.. It seems to use these two expressions before year of 2000. Since 2000, "Intermodal" transport seems to dominate "combined".

- Definition 2. “Intermodal Transport is the movement of goods (**in one and the same loading unit or vehicle**), which uses successfully several modes of transport without handling of the goods themselves in transshipment between the modes”

- Definition 3. “Combined transport is a transport in which the major part of the (European) journey is carried out by **rail, inland waterways or sea** and in which any initial and/or final leg carried out by **road** are **as short as possible**”

Definition 1 is simple and straightforward. However, as Janic and Reggiani (2001) mentioned, the substantial processes such as loading units are missed. Definition 2 is a more focused one for loading units and transshipment process. Definition 3 is a policy oriented definition with the focus of the `non-road’ transport modes used.

Depending on the point of view, network representation varies. In general, one may attempt to transfer infrastructures (i.e. road, rail, and waterway) and locations (i.e. shippers, receivers, and transshipment points) on a drawing paper in simplified way. In this case, subjective intension should be avoided. However, a modeler enables either to adjust, add, or remove some attributes of network. In this study, we attempt to emphasize the intermodal transport policy on network representation. In order to transplant the policy direction on the intermodal network, definition 3 is fully reflected when the intermodal network is represented. Especially, the expression ‘initial and/or final leg carried out by road are as short as possible’ in definition 3 may indicate the minimal usage of the truck system due to the reasons mentioned previously: economic competitiveness, environmental concerns and traffic congestion alleviation. Nevertheless, it is obvious to consider definition 1 and 2.

Four criteria can be derived from definitions to find the most comprehensive intermodal network representation, overcoming the complexities mentioned previously. Then, the criteria are linked to at least one of the complexities as referred to above. If at least one of the criteria is not satisfied we do not consider a network representation as intermodal one in this study.

- Is it possible to describe both directed and consolidated (i.e. hub-and-spoke) flows and compare them? (associated with complexities Ⅳ, Ⅴ, and Ⅵ above)
- Is it possible to describe all freight mode (system) options in a network? (associated with Ⅲ and Ⅵ)
- Is drayage by truck? (associated with Ⅲ and Ⅳ)
- Can the stages in the intermodal chain be described properly (associated with Ⅱ)

One may discuss criterion C since definition 1 and 2 do not explicitly express that drayage should be by truck. For example, it is obviously true that containers that arrive at a port by container ships or barge can be directly transshipped to rail or maritime vessels. However, it can be assumed that such containers are initially collected by trucks in origin area and brought to the port. In addition, even if the containers are transshipped from a seagoing container ship to rail or maritime vessels, it can also be assumed that the final leg is by truck. Thus, even though trucks are not really shown in the intermodal network, it can be assumed that the initial/final drayage should be treated by trucks. That is the crucial reason why we consider

definition 3. However, an exception is observed; some factories that are located along railway tracks possess and operate their own private non-road infrastructures as well as rolling stock (e.g. trains and rail cars). Although trucks are not necessarily utilized in this case as either drayage or long-haulage of intermodal systems, it is the merest case. We exclude this exception and consider that intermodal systems always need 'truck drayage', indicated in criterion C.

Six types of network representation can be derived - see Figure A.1. Some of them are seemingly intermodal. However, if the criteria based on definition 1 above are used, genuine intermodal network representations can be distinguished. Figures A1(a), (b), and (c), are uni-modal representations (e.g. road transport), the three others intermodal.

From the perspective of the criteria we now reflect on the intermodality issues of the representations in Figure A.1. In the representation of Figure A.1(a), neither consolidation nor intermodality exists: criteria A, B, and D are violated. In Figure A.1(b), consolidation occurs but a comparison with direct flows is not applicable: criterion A is partially achieved but B and D are violated. Previous studies on the LTL (Less than TruckLoad) problems fully describe and successfully optimize such a network (For more information on problems in Figure A.1(a) and (b), see (Crainic and Kim, 2005, Croxton et al., 2003, Croxton et al., 2007, Magnanti and Wong, 1984, Balakrishnan and Graves, 1985). The comparison between consolidated and direct flows can be achieved in the representation of Figure A.1(c). In this representation consolidation occurs, but intermodality does not: criterion B is violated.

In Figure A.1(d) to (f), multiple transport modes can be drawn. According to the definition of an intermodal freight system, Figure A.1(d) shows the concepts of both inter-modality and consolidation. However, it is not possible to compare them with direct flows (i.e. truck-only system) as represented in Figure A.1(b): criterion A is violated. Figure A.1(e) would be the best network representation according to *definition 1*, However, the initial and/or final leg in Figure A.1(e) is not carried out by road. As a result criterion C is violated.

Figure A.1(f) satisfies all the criteria although it does not seem to be a complete network representation. One may argue that Figure A.1(f) is even a limited version of Figure A.1(e). However, the more constrained version is the most realistic representation of intermodal networks when policy direction is considered. In order to clarify the difference between Figure A.1(e) and (f), initial and final legs by "trucks" are attached in Figure A.1(e) as shown in Figure A.2. Figure A.2 is a complete version of the intermodal network representation which is basically the same as Figure A.1(f). Through this extension, 2nd level of intermodal freight system with non-road connection (i.e. non-road drayage) to the main hub is modeled later.

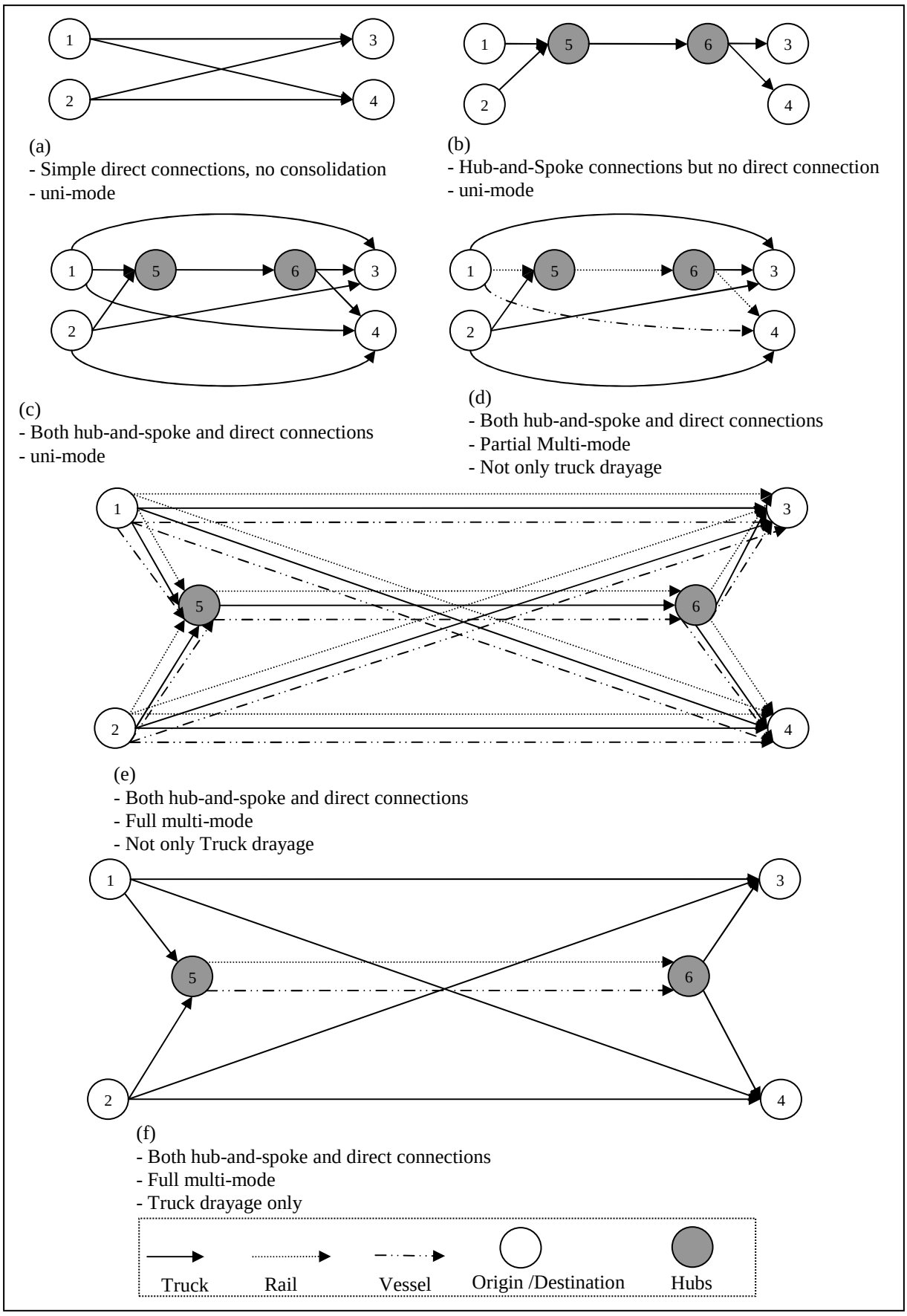

Figure A.1 Network representations of uni- and inter-modal systems

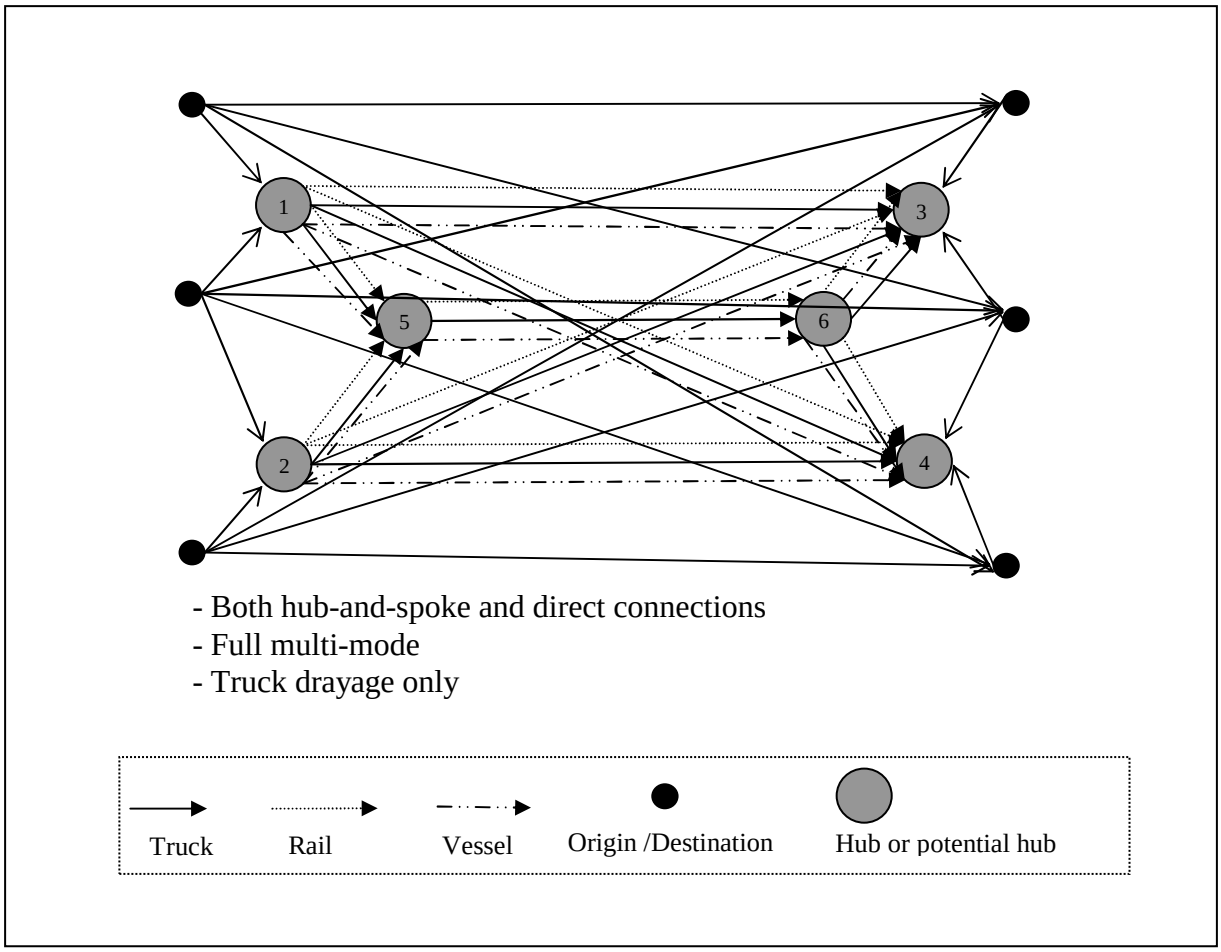

Figure A.2 Complete network representations of intermodal system

As briefly mentioned previously, the drayage part plays a crucial role in the economic feasibility of an intermodal system compared to a truck-only system. Therefore the drayage part should be clearly included in network representations as is the case in Figure A.1(f) or Figure A.2. These two Figures are the only acceptable representation satisfying the definition and related criteria. However, several authors use the other network representations as visualized in Figure A.1 (d) to (f) and label them as "intermodal". Literally, it is correct since there are more than two transport modes in the network representations. However, they are not suitable for finding the best freight system/route considering all theoretical possible unimodal and intermodal options.

Previous intermodal freight studies

Barnhart and Ratliff (1993) used the concept of *shortest path algorithm* and *matching problem* (in graph theory) and tested it in a small network (i.e. 5-6 nodes and 6-11 links), which matches Figure A.1(f). This approach can fully describe the competitiveness between intermodal and truck-only systems between two hubs (i.e. terminals). Their study is one of only few studies that exactly address the drayage operation by truck in the intermodal chain.
Min (1991) and Chang (2008) developed a multi-objective optimization problem to find the best routes in an international intermodal network. However, in their network representation nodes are connected by a link that only allows for one transport mode to be used. The network does not allow 'multiple' modes from a node. In addition, since the drayage distances and

costs are relatively low because their study focuses on *international* intermodal networks (i.e. long-distance), the focus was not on building a generic intermodal network including a detailed road network for drayage but to find the best international routes considering the economies of scale of long-haulage. Therefore the network representations in this case is a bit simpler than the generic intermodal freight model that, for example, includes more detail with respect to the road network for drayage to also cover the domestic journey.

Figure A.1(e) seems to be an appropriate network representation satisfying both consolidation and intermodality. However, it is just a full representation allowing all transport modes between all OD pairs rather than the constrained drayage by trucks reflecting definition 2. An example of a study that uses the model represented in Figure A.1(e) is Boardman et al. (1997). This model fully embeds the transfer costs into a network analysis using an intermodal freight optimization model in a systematic way. Based on market research they explicitly take into account the transfer cost and transfer time for transshipments between different modes. More specifically, \$150 and \$225 for transfer cost and 4 and 3 hours transfer time was examined for transshipment between truck and rail, and truck and air respectively, in Atlanta, U.S. However, it is unclear if and how they included the drayage costs. They might be included in the fixed cost of the non-road modes, or excluded. Then, it would make sense if Boardman et al. (1997) used Figure A.1(e) rather than Figure A.1(f), since the drayage stage by trucks is not clarified.

Crainic and Rousseau (1986) developed a multi-commodity, multi-modal service network design using the network representation of Figure A.1(e). Their work is theoretically capable of dealing with competition between intermodal and truck-only systems, and includes a representation of the drayage operation. It is worthwhile briefly summarizing their formulation since their work has been recognized as a pioneering study in this field. They used a directed network $G = (V,A)$, where V is the set of nodes or vertices and A is the set of arcs or links. The set of nodes consists of three subsets: O, the set of origin; D, the set of destination nodes; and H, the set of hubs (i.e. intermodal terminal). In the case study commodities P, are added the network $G = (V,A,P)$. Then, two decision variables are defined: (1) service frequency decision variables, represented by a binary integer $\boldsymbol{y_s}$, assigned when a certain service in set S is chosen and otherwise 0), and (2) volume of product p, positive real or integer number h_l^p in itinerary[9] $l \in L^P$ and $p \in P$. The formulation is then:

$$Min \sum_{s \in S} F_s(y) + \sum_{p \in P} \sum_{l \in L^P} C_l^p(y,h) + \phi(y,h)$$

S.t. $\quad \sum_{l \in L^P} h_l^p = d_p \qquad p \in P$

$y_s = 0 \text{ or } 1 \qquad s \in S$

$h_l^p \geq 0 \qquad l \in L, p \in P$

Moreover, the concept of economies of scale can be added to the formulation above as shown in Chang's study (Chang, 2008). However, although Crainic and Rousseau (1986) developed a generic formulation and elegant solution method, they could not show the nature of modal competitiveness between intermodal freight systems and truck-only systems. Their focus was on railway and its quality control such as frequency, consolidation, and delay. There was no drayage and also none of the considerations necessary to fully describe an intermodal freight system. The drayage may not have been added due to the fact that the drayage used a different network (i.e. road network), which is much more spatially detailed and complex than the railway network. Accordingly, comparisons between rail and a truck-only system could not be

[9] Service $s \in S$ is defined as the full possible set of predefined routes with different modal combinations. An itinerary for commodity p, $l \in L^P$, is defined as a set of possible service processes between two terminals (e.g. consolidation, transfer, classification, and in intrinsically the time consumed).

made. Even though drayage (assuming a detailed road network) and a truck-only system is included in the set of service (*S*), it is time consuming to estimate accurately C_{ilj}^{p}, in $F_s(y)$ which is a summation of the costs of successive different freight transport modes (e.g. drayage from i to terminal 1 by truck, long-haulage terminal 1 to terminal 2 by rail, and drayage from terminal 2 to j by truck). In other words, there might be too many path options in the set of pre-defined paths (i.e. set *S*).

Excellent work on multimodal representation was also done by Guélat et al. (1990)**.** They attempted to represent a physical network as closely as possible in an OR perspective and developed a normative model for a multi-modal freight transport system at the strategic level. The network representation they proposed does have some similarity to the version of Crainic and Rousseau (1986) discussed above. As explicitly mentioned by Guélat et al. (1990) this model does not include the mode choice component. In other words, this model may not clearly overcome the competition issue indicated in the complexity Ⅵ.

Oh (1993) and Haghani and Oh (1996) also developed a model for an intermodal OR problem with multiple sub networks. The number of these sub networks equals the number of transport modes in entire network. Aggregating the sub-networks the entire network is similar to Figure A.1(e). One advantage of this model is that if some irrelevant arcs are removed from the sub-networks, the network presentation is the same as in Figure A.1(f). We call those problems that can be solved only by using the representation of Figure A.1(e) ***"pure intermodal problem"***.

According to definition 3 of the intermodal freight system, Figure A.1(f) (or Figure A.2) is the most appropriate intermodal representation. It includes competition between multimodal and truck-only systems and is fully capable of examining consolidation as well as economies of scale, e.g. because that transport operator/terminal operator gives some quantity related discounts. Van Duin and Van Ham (2001), Kim et al. (2008) and Kim et al. (Kim et al., 2009) use this network (i.e. Figure A.1(f)) to describe all the processes including drayage by trucks, long-haulage by non-road modes, and consolidation in the intermodal network by estimating the full costs for all routes. More specifically, they include the pre-estimated fixed cost at the combined modes level (i.e. system level) rather than at the individual mode level in the objective function. This pre-estimation of freight costs makes it possible to include modal/route choice in complex freight networks including the truck-only and intermodal system. In other words, they used a network representation ***G=(N,E, S)*** rather than ***G=(N,E,M)*** where N is a set of nodes, E is a set of arcs, S is a set of pre-defined systems including intermodal freight systems and truck-only systems and M is a set of individual freight modes. This approach is straightforwardly applicable to small networks and is fully capable of including competitiveness between multimodal and truck-only systems. However, if the number of nodes (including hubs) is large, such a pre-estimation process will be very time-consuming because of the complicated cost structures that include freight mode(s), commodities, economies of scale, and transfer costs.

Both Grünert et al. (1999) and Grünert and Sebastian (2000) consider both an air and road network which is a variant of Figure A.1(f). They called their macroscopic network GANT (Global Area Transportation Network). Later they added LATN (Local Area Transportation Network), which consists of a set of nodes and arcs at the local level (i.e. microscopic network). They decompose the network according to three criteria: transportation mode, type of operation, and aspect of the task to be performed. More specifically, the network is distinguished into drayage on the road network and long-haulage both on the air network and the road network. They considered both road and non-road (i.e. air transport) options for long-haulage. However, according to them, truck-only systems are considered to be an option only if air transport is not available. The truck-only system mainly plays a supportive role for air-

transportation in their study. In other words, the first major decision, “the assignment of requests to either air or ground transportation” is pre-selected. It might relate to the characteristics of the air transport system, which in most cases is not a competitor for the road system.

However, for rail-intermodal systems, truck-only systems should be compared with the rail-intermodal systems without the pre-selection process because the two systems compete. Note that there are similar approaches to combine local networks within a global network (for example, (Ballis and Golias, 2004, Southworth, 2000). The contribution of these studies is that they overcome the first complexity: Intensive interrelationship between the different planning levels. We call those problems, which are analyzed on Figure A.1(f) (or Figure A.2), ***“comprehensive intermodal problems”***. Such problems can compare intermodal systems with truck-only systems. A synthesis according to Figure A.1 and the criteria developed previously is presented in Table A.2.

Table A.2 A synthesis

Researchers (year)	Figure A.1	Criteria A	Criteria B	Criteria C	Criteria D
		Is it possible to describe both directed and consolidated (i.e. hub-and-spoke) flows and compare them?	Is it possible to describe all freight mode (system) options in a network?	Is drayage by truck?	Can the stages in the intermodal chain be described properly (e.g. transshipment cost)
Barnhart and Ratliff (1993)	Figure A.1(f)	Yes	Yes	Yes	
Boardman et al. (1997)	Figure A.1(e)		Yes	No	Yes
Crainic and Rousseau (1986)	Figure A.1(e)	No	Yes	No	Yes
Chang's study (Chang, 2008)	Figure A.1(e)	No	Yes	No	Yes
Guélat et al. (1990)	Figure A.1(e)	No	Yes	No	Yes
Oh (1993) and Haghani	Figure A.1(e)		Yes		
Van Duin and Van Ham (2001)	Figure A.1(f)	Yes	Yes	No	Yes
Kim et al. (2008)	Figure A.1(f)	Yes	Yes	Yes	Yes
Kim et al. (Kim et al., 2009)	Figure A.1(f)	Yes	Yes	Yes	Yes
Grünert et al. (1999)	Figure A.1(f)	No	No	Yes	Yes
Grünert and Sebastian (2000)	Figure A.1(f)	No	No	Yes	Yes

To sum up, the identified limitations of the studies presented in this overview can be summarized as follows:

Figure A.1(e) is good enough to find the optimal solutions for pure intermodal problems.
Figure A.1(f) should be used to find the optimal solution for comprehensive intermodal problems that includes the competitiveness with the truck-only system.
The flexibility of the network representation as found in literature to extend the intermodal system into a 2nd level of intermodal system is limited (i.e. transition from Figure A.1(f) to Figure A.2.).

Suggestions for overcoming complexities of service network design problems

In this Section, we attempt to overcome some of the limitations indicated in the previous Section. The first suggestion is to simplify the estimation of cost through chain decomposition, the second is to extend the inter-modal network design problem into the 2nd level of an intermodal system through introducing what we call the penalty concept, and the third is to allow non-road modes to be included as options for drayage.

Decomposition of chains

The complexity being caused by the different stages in a network (i.e. drayage, long-haulage, and terminal processes) and different modes are discussed above. In addition, competition between intermodal and the truck-only system is also a modeling challenge. The key factor in modeling is how to define the most fundamental units: the distance for different networks (i.e. road and non-road) and the unit costs for the different stages and modes. Specifically, a question, which is formulation-related, arises: How to bring all cost components for both intermodal and truck-only systems together in an OR mathematical formulation in a consistent way? (i.e. for the truck-only system, the quantity shipped is multiplied by the unit cost while the intermodal system needs to consider three stages (drayage, long-haulage, and transshipments) with different unit costs, dependent on quantity shipped and distance). To answer this question we need to clarify the inconsistency between the two systems. Since intermodal systems have the advantage of economies of scale, a hub-and-spoke network configuration should be represented in order to consolidate shipments. To represent all relevant options in the same network the long-haulage road network as a competing option should be considered. So, the road network should be represented at two levels: First, for drayage at the local/regional level (e.g. urban/local road network), and second, for long-haulage with much less detail than for drayage. In the case of long haulage a representation only at the highest level (e.g. expressways in Europe or interstate highways in U.S.) is generally sufficient. In a mathematical formulation, it is very challenging for problem solving to combine such different configurations (i.e. direct or Hub-and-spoke) and levels (i.e. local/ regional and international/ inter-state). These issues on inconsistency and the configurations are associated to four of the complexities mentioned in section 2: Ⅰ,Ⅱ,Ⅲ and Ⅵ. We suggest a decomposition of the chain to overcome these complexities. Figure A.3 shows the proposed decomposition.

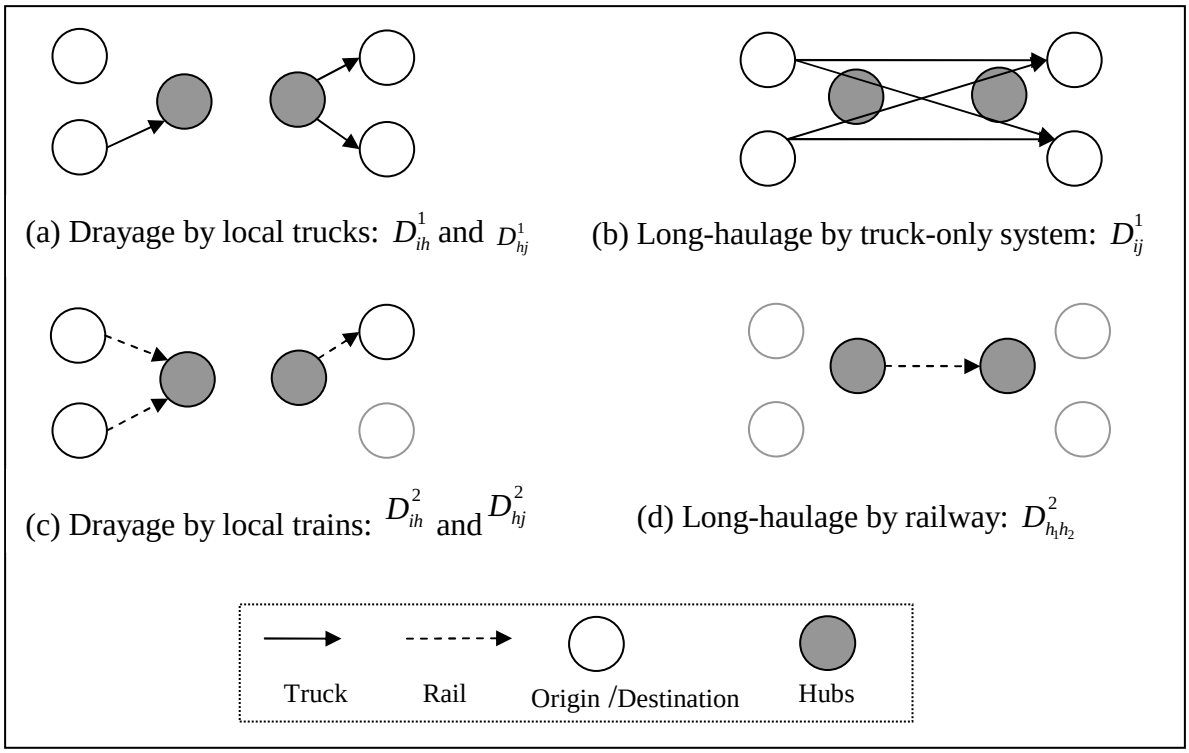

Figure A.3 Network decomposition in terms of mode and stage in the entire network

More specifically, throughout the decomposition, the total distances for each system option (i.e. combination of modes and terminal process) are efficiently estimated as followed:

Shortest distance from origins to destination on road network (i.e. k=1): $D_{ij}^{k_{Long-haulage}}$

Shortest distance from origin terminal(s) to destination terminal(s) on non-road network *k* [1]: $D_{h_1h_2}^{k_{Long-haulage}}$

Shortest distance from origins/destination terminal to origin terminal/ destination on road network (k=1) for drayage vice versa: $D_{ih1}^{k_{drayage}}$ and $D_{h2j}^{k_{drayage}}$

Shortest distance from origins/destination terminal to origin terminal/destination on *k* non-road network[2]: $D_{ih1}^{k_{drayage}}$ and $D_{h2j}^{k_{drayage}}$

Where, D_{ij}^k is the distance between i and j by mode k (k=1 for road, k=2 for rail, k=3 for vessels)

The shortest paths can be estimated using GIS (Geographic Information System) or in the classical algorithmic way using network data. For estimating rail shortest paths, a railway network should be available.

[1] Note that non-road networks such as the rail network is less dense than the road network, and does not connect all locations.

[2] In the case that the **hub** rail terminal that is closest to the origin is quite far from the origin, a shipper may choose to use rail for drayage (i.e. the closest **local** rail terminal – the closest **hub** rail terminal) rather than long-distance drayage by trucks. If so, fixed cost for pre-drayage by truck from the origin to the **local** rail terminal (i.e. a penalty) should be included. This concept will be fully discussed in "2nd level of intermodal system" later).

There are three different kinds of unit costs that should be estimated. The unit cost C^k (where k is the transport mode) is a marginal cost including economies of scale.

Unit cost for the road network: $C^1 = \phi(D, X, V)$

Unit cost for the rail network: $C^2 = \phi(D, X, V)$

Unit cost for the terminal operation between truck and rail: $TS^{12} = \varphi(K_1, K_2, X)$

Where, $\phi(D, X, V)$ is a function of distance (D), demand (X), and vehicle type (V); $\varphi(K_1, K_2, X)$ is a function of two freight modes and demand.

Next, the total costs of different modes (k) can be calculated and compared. Note that the distances and the costs shown above are at the individual mode level rather than at the system level. Then, the system options (r) should be defined. An example set of the freight system is as follows:

r = 1; **truck**-only system
r = 2; **truck**-rail-**truck**
r = 3; **truck**-*sub-rail*-rail- *sub-rail* -**truck**
r = 4; **truck**- *sub-rail* -rail-**truck**
r = 5; **truck**-rail- *sub-rail* -**truck**

Regardless of the system options initial and final legs are by truck. In the cases of r=3, 4, and 5, *sub-rail* is used as drayage. Note, such a sub-rail will be called as non-road drayage or rail drayage later in this paper. Of course, more choice sets can be predefined. The solution of decomposition of chains is capable of handling a large number of nodes and arcs. The time consuming process of the pre-calculation of cost matrices, is automatically overcome. It is notable that Grünert et al. (1999), Grünert and Sebastian (2000), Oh (1993) and Haghani and Oh (1996) also use a similar decomposition concept. However, the decomposition they use is limited to 'truck-rail-truck' (i.e. r=2) only.

Economies of scale

O'Kelly and Bryan (1998) formulated economies of scale well for hub location problems and Racunica and Wynter (2005) developed O'Kelly and Bryan's formulation more realistically. However, two important issues are missed in both studies. One is the competitiveness between intermodal and truck-only systems in a given network and the other is the trade-off between advantages due to economies of scale for non-road transport (i.e. rail and vessel) and related terminal costs (i.e. potential diseconomies of scale). In addition, the truck system also has so-called "economies of distance" which should also be included. These can be included if the unit cost functions for transport and transshipment include both economies of scale and economies of distance, as well as diseconomies of scale for transshipment costs. This approach may lead to a better solution since all factors associated with both economies and diseconomies of scale and distance are explicitly included in the OR formulation (i.e. objective function and constraints).

Extension to 2nd level of intermodal system

Kim et al. (Kim et al., 2009) have already used the concept of 2nd level intermodal systems referring to the fact that railway can play a role in drayage as well as in long-distance transport. As a result they consider five transport options: the truck-only system, the 1st level intermodal system (i.e. truck-rail-truck and truck-vessel-truck), 2nd level intermodal system (i.e. truck-rail-rail-rail-truck and truck-rail-vessel-rail-truck). This subsection presents a simple method that can be used in order to consider non-road drayage when a non-road mode plays a role for drayage.

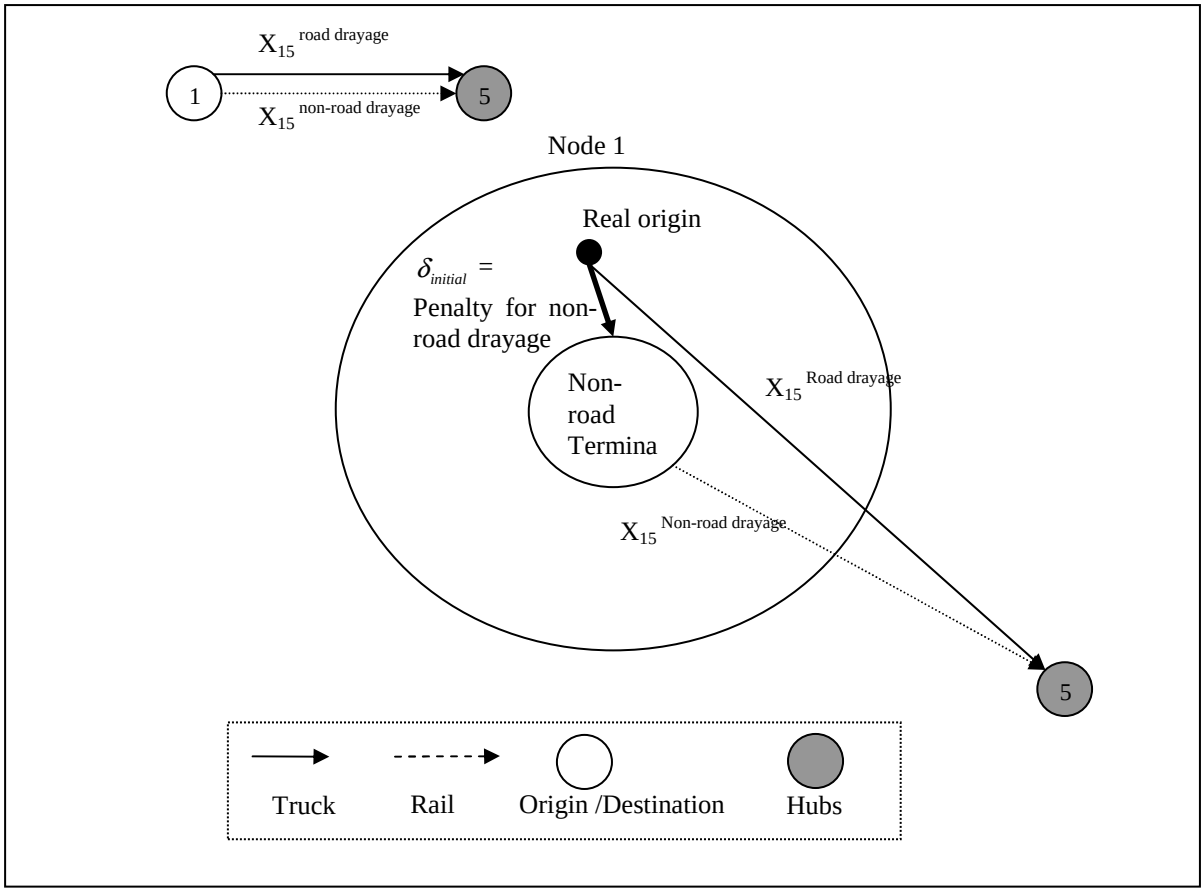

Figure A.4 Difference between road drayage and rail drayage

Before explaining Figure A.4 we first refer back to the representations in section 3. As mentioned there the initial and/or final leg in Figure A.1(e) is carried out by not only road but also non-road. Figure A.1(f) satisfies all the criteria as presented in that section. The crucial difference between Figure A.1(e) and Figure A.1(f) is the availability of drayage by non-road modes such as railway. In order to use Figure A.1(e), an assumption associated to the penalty for non-road drayage is required. Figure A.4 can be used for that assumption. The origin node (node 1) with two flows ($X_{15}^{\text{road drayage}}$ and $X_{15}^{\text{road drayage}}$) extracted from Figure A.1(e) is magnified in Figure A.4. A real origin indicated as the black dot circle may send $X_{15}^{\text{road drayage}}$ through the road network to node 5 while the $X_{15}^{\text{non-road drayage}}$ should stop at the non-road terminal, be transshipped to the non-road mode, and head to node 5 on the non-road network. The penalty $\delta_{initial}$ should be posed for the non-road drayage process. Therefore, if one may want to use the network representation with full modal availability as Figure A.1(e), the

penalty $\delta_{initial}$ can be applied for the associated route. If only road drayage is available in the given network, Figure A.1(f) can simply be used.
One more important issue associated with the 2nd level of the intermodal system is the relation to the p-hub location problem. The purpose of the p-hub location problem, which is slightly different from "*service network design problems"* (Crainic and Kim, 2005) or "*intermodal operators*" problems (Macharis and Bontekoning, 2004), is to find the optimal hub location from the predefined p hub sets (where p is the number of hubs in a given network) (O'Kelly, 1987, Aykin, 1990, Sohn and Park, 2000). However, again direct links between non-hubs (origin and destination) have not been found in any types of hub-location problems. When the i^{th} level of the intermodal system, which is not realistic in practice however, is considered in a given network, the problem can also have the potential to embed the p-hub location problem in a network design problem.

Conclusions and further Studies

Some complexities in OR modeling for intermodal network design problems have been presented. Based on the complexities and the definition of intermodal systems, four criteria are set up. The criteria enable a better intermodal network representation to be found than those usually found in the literature. We present three network representations for uni-modal networks and three for intermodal networks. When the intermodal chain itself is optimized (i.e. a pure intermodal problem), Figure A.1(e) is appropriate. However, when the intermodal chain is optimized and compared with truck-only systems, Figure A.1(f) or Figure A.2 should be used to select the optimized network between several types of intermodal options and the truck-only option.
Since the network representation is just a starting point for the formulation of OR problems, we suggest three ideas focusing on the problem formulation. The first idea is to decompose the intermodal chain and include the truck-only system in the choice set. Secondly, the inclusion of economies of scale and distance by mode and stage are suggested, though we did not fully explain the modeling implications. Thirdly, the possibility to extend the options for solutions to the 2nd level of the intermodal system (e.g. truck – rail – rail – rail - truck) is explored. To the best of our knowledge optimization models and related network representations that allow the optimization of transport over all theoretically possible (unimodal and intermodal) solutions cannot be found in literature yet. With our paper we aim to have contributed to this challenging research domain.

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Appendix B:
A methodology to establishing “CAP” in CAP-And-TRADE program for intermodal freight corridors

Nam Seok Kim and Milan Janic
Delft University of Technology

Appendix B is a revised version based on a conference proceeding presented at 10th TRAIL World Congress in Rotterdam (Netherlands) from October 14, 2008 (ISBN 978-90-5584-107-3)

Abstract

This paper develops a methodology for establishing the cap side for CO_2 emissions in inland freight transport at corridor levels within the scope of the cap-and-trade program in Europe. In particular, it presents a framework based on the concept of quota in order to allocate CO_2 emissions from inland transports at a country level to several transport corridors. The main impact expected if the quota system is working properly is that the freight modal shift toward less CO_2 emitting freight modes (or systems). This proposed quota, which is more microscopic than the quota in the cap-and-trade program which was already internationally agreed, would represent the total allowed CO_2 emissions for all freight transport modes operating in the corridor during a given period of time. On the other hand, the proposed quota may have some potential side effects. Such potential freight market distortions are also carefully discussed and furthermore some management and enforcement methods are also briefly discussed.

Introduction

When some symptoms of global warming were discovered in the 1970s, the United Nation began to identify the relationship between man-made carbon dioxide (CO_2) and global warming (IPCC, 2008). In 1992, at the Earth Summit, in Rio De Janeiro, several developed and developing countries signed an agreement to reduce anthropogenic CO_2 (IPCC, 2008). Later in the third Conference of the Parties of the United Nations Framework Convention on Climate Change (UNFCCC), at Kyoto, in 1997, the so-called Kyoto protocol was agreed upon. This protocol explicitly indicates that 36 developed countries in 1998 (41 developed countries including the EU as a country in 2004), classified as an Annex I country, are required to reduce greenhouse gas emissions to the level indicated in UNFCCC and Kyoto protocol (UNFCCC, 2006, 2008, UN, 1998). The protocol includes a mandatory CO_2 emissions reduction for clusters of countries. Despite such efforts, the European Environment Agency (EEA) shows that the European Union has not yet achieved the reduction target. More specifically, the total Greenhouse Gas Emissions equivalent in Europe, expressed in million tonnes (Mt) of CO_2, and the achieved reduction as of 2004 are as follows (UNFCCC, 2008, EC/Eurostat, 2007, EEA, 2006):

- EU-15 : 4279.0 Mt (1990: based year) and 4227.0 Mt (2004), - 1.2 % (*Changes in emissions)*
- EU-25 : 5429.4 Mt (1990: based year) and 5258.2 Mt (2004) , - 3.2 %
- EU-27 : 5796.0 Mt (1990: based year) and 5487.9 Mt (2004), - 5.3 %

It is notable that the 8% target reduction rate of the Kyoto protocol has not been achieved in any of the groups. The rationale that EU could count the mass of CO_2 into these groups is based on the Burden Share Agreement in Europe in 1998 (EC, 1999). This agreement aims to consider various national circumstances such as energy sources, dependency of fossil fuel, and industry. As a result, the adjusted reduction targets for CO_2 emissions are assigned to European countries (EC, 2006). Accordingly, European commissions, as well as each individual European country, have established the strategy to reduce CO_2 emissions and attempting to identify the most severe CO_2 contributors, according to the trend of CO_2 emissions by sectors. The European Union recognizes that greenhouse gas emissions, including CO_2 from transport, have increased at the fastest rate compared with any other sector over the past decade (see Figure B.1).

Two principal approaches for reducing CO_2 emissions in transport are recognized: taxes and subsides suggested by Pigou and the property rights by Coase (Chichilnisky and Heal, 1995, Pasour, 1996). The former can be explained as “government could use taxes and subsidies to internalize such external effects.” The latter points out “the possibility of bargaining in coping with externality problems” represented as the Cap-and-Trade program (UN, 1998, Pasour, 1996, OECD, 2001). The current situation on this issue in Europe can be evaluated as *internationally* agreeing on the Cap-and-Trade program based on Coase’s approach and as *domestically* preparing to pose a carbon tax based on Pigou’s suggestion. However, there is still a debate about which approach is more appropriate at a certain geographical level. Instead of claiming which option is better, this study attempts to fortify the “Cap” side of the Cap-and-Trade program, based on Coase’s approach.
The research gap in the Cap-and-Trade program might be the lack of consideration for inland international CO_2 control. More specifically, this research aims to answer the following question: “*If the Cap-and-Trade program is implemented at the international corridor level,*

how can "Cap" of CO_2 emissions for intermodal freight corridors be established?" In this paper, the freight transport is highlighted rather than passenger transport since the latter does not seem to be properly controlled. Carbon tax, based on Pigou's approach, as tested by Hensher is seemingly a good option at least for passenger transport (Hensher, 2008). However, it is still doubtful that freight transport is sensitive enough to such a carbon tax. This skepticism leads authors to consider Cap-and-Trade problem for freight transport.

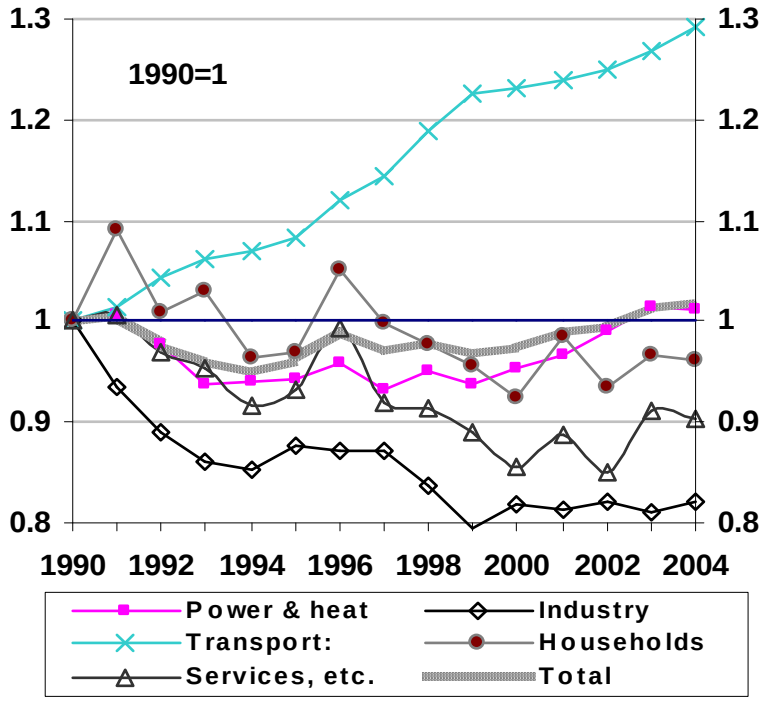

Figure B.1 Trend of CO_2 emissions in Europe by Sector, 1999-2004 (Source: Euro Stat (2007))

The "Cap" is defined as the capacity of the Cap-and-Trade program and is referred to **"**quota**"** in this paper. Even though there is no solid consensus on the definition of quota in transport, the OECD attempted to position it in the scope of the program and define it in the box below. It is notable that "regulation" underlined in the box below means the right to use certain freight modes based on the environmental performance.

The main expected impact of the quota is that the freight modal will shift toward less CO_2 emitting freight modes. The proposed CO_2 quota, which is presented in the next section, is more microscopic and more tangible than the quota from the Cap-and-Trade program upon which has already been internationally agreed. It would represent the total allowed CO_2 emissions for *all freight transport modes* operating *in certain corridors* during *a given period of time*. Under such circumstances, the particular modes would share this quota according to their CO_2 emission performance.

There are some assumptions throughout this paper. Two general assumptions are that the CO_2 emissions and CO_2 quota hereafter refers to the CO_2 equivalent emissions (i.e. Greenhouse Gas Emissions including carbon dioxide, methane, nitrous oxide, sulphur hexafluoride, hydro fluorocarbons, and perfluorocarbons) and the CO_2 equivalent quota, respectively. In addition, the trend of energy use will not be quickly changed in the future. It is also assumed that governments set limits for the CO_2 emissions from transport at a country level and decide the

target amount of CO_2 emissions for both domestic and international flows according to the country's strategy. The last assumption is, as mentioned previously, that this study only considers *international freight flows*.

Four main families of tradable permits

1. *Quotas (Cap and trade or minimum limits and trade); a quantified ceiling or floor assigned to agents for a give period.*
2. *Emission reduction credits: acknowledgement at the end of the period of the achievement of an emission or abstraction level below the one which had been authorized for a given agent.*
3. *Averaging: the competent authority sets average limit values for an entire range of similar products manufactured by firms within the same industrial branch.*
4. *Transferable usage rights: formally regulates access to resources that are feely available, organizing* ***the regulation of the use of resources*** *whose ownership is shared, or in the case of building and construction rights, alleviating the private property restrictions from the standpoint of environmental objectives.*

Source: OECD (2001)

In the next Section, methodology and data are presented. The detailed CO_2 quota at the corridor level is designed in the generic way. Then, necessary data sets required for realizing the CO_2 quota are fully described. The data as well as expected outcome are numerically defined. In Section 3, the methodology developed in Section 2 is numerically formulated. Finally, CO_2 quotas for the transport sector at both the country and corridor levels are estimated. Some limitations and further studies are discussed in Section 4. Especially, some caveats for the proposed quota approaches, and ideas to overcome them, are highlighted. The study is concluded in Section 5.

Methodology and data

This Section consists of three parts. First, we define the proposed *corridors* which are used as the spatial unit in this study, and accordingly define the proposed CO_2 quota *at the corridor level*. Then, a generic methodology to initially establish the limits of the allowed CO_2 emissions (i.e. *CO_2 quota*), based on the Kyoto protocol, is presented with necessary data. Finally, the concepts are formulated.

CO_2 Quota at the proposed corridor level

The CO_2 quota *in general***,** which is *at the country level*, is defined in this paper as the CO_2 mass allowed to be emitted in a country, obeying the Kyoto Protocol, regardless of the source of CO_2. This CO_2 mass for the country can be divided into the allowed CO_2 masses for different contributing sectors. Contrary to other sectors it is a rather complex task to set a CO_2 quota *for the transport sector* following a strict quota rule since transport is not a stationary CO_2 source and often crosses borders. Therefore, CO_2 quota for the transport sector could be set at a more detailed level rather than at the country level. This paper suggests setting up the CO_2 quota *at corridor level*.

A corridor is defined as a transport axis with the same direction (e.g. west-east or north-south) from one location to another location, often crossing country borders (EC, 2005). A corridor

can be multi-modal (e.g. having both roads and railroads, or even barge or short sea shipping) (EC, 2002). The shortest path algorithm in the GIS (Geographic Information System) is often used to find the most plausible path in order to draw corridors. Since some factors can cause a change in the characteristics of such corridors, three significant factors influencing corridors are taken into account: infrastructures (e.g. road, railway, and inland waterway), traffics demand, and country borders.

According to these factors, we propose the corresponding criteria for subdividing corridors. First, if the *road* traffic route has the same direction as the *railways*, the two routes are regarded as one corridor. Since road and rail can not always be parallel, it might be sometimes vague to define the width of the corridor. However, this criterion should be kept because two transport modes with the same direction share some flows and often compete with each other. Thus, if both road and railway are possibly used between the same origin and the same destination, regardless of the width, the two different infrastructures (i.e. road and railway) are regarded as a corridor. Secondly, since transport flows from one place to the other is in constant change due to local traffic, the corridor can be subdivided into several different sub-corridors if the characteristic of traffic flows are significantly different. A criterion for the corridor subdivision according to the traffic flows' change is the existence of the margining. If two same level of highways, for example, are merged into one, the corridor should be divided. Lastly, a corridor should be divided by country because each country has a different allowable CO_2 emissions mass (i.e. CO_2 quota) based upon the different target CO_2 emission reduction rates. Figure B.2 shows an example to clarify the corridor as defined above.

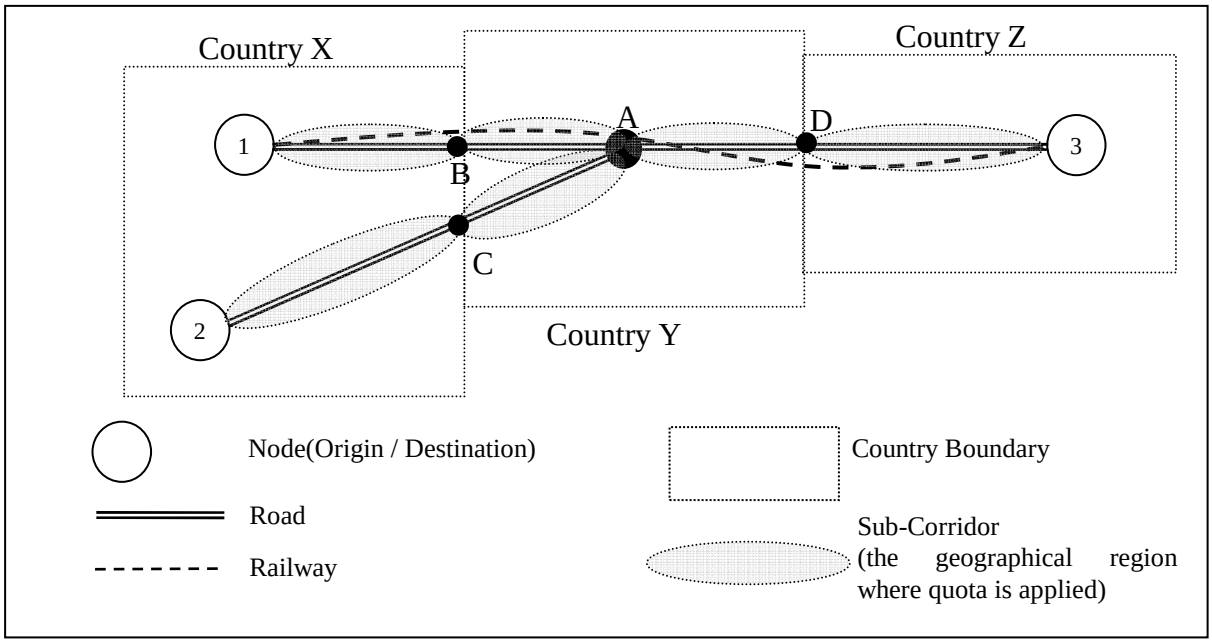

Figure B.2 Corridor selection for setting up CO_2 emissions quota

There are three nodes (i.e. node 1, 2, and 3; point A, B, C, and D are not actual nodes). The shortest paths are found to transport between node 1 and node 3 and between node 2 and node 3 for available transport modes. There seems to be three corridors in Figure B.2 (i.e. Arc^{road}_{13}, $Arc^{rail}_{13,}$ and Arc^{road}_{23}). However, according to the criterion 1, the both road and rail connecting node 1 and node 3 (i.e. Arc^{road}_{13} and Arc^{rail}_{13}) should be regarded as a corridor. According to the second criterion, since the traffic flows might have a different pattern after

Arc^{road}_{23} is merged into Arc^{road}_{13} at point A, the two corridors are subdivided into three sub-corridors (i.e. Arc_{1A}, Arc_{2A}, and Arc_{A3}). According to the last criterion, the corridors are finally disjointed by the country boundary into 6 sub-corridors ($Arc^{country\_X}_{1B}$, $Arc^{country\_X}_{2C}$, $Arc^{country\_Y}_{BA}$, $Arc^{country\_Y}_{CA}$, $Arc^{country\_Y}_{AD}$, and $Arc^{country\_Z}_{D3}$). Consequently, the CO_2 quota *at the (sub-) corridor level* is defined as the allowable CO_2 mass to be generated from such corridors described in Figure B.2. Hereafter, 'the corridor level' will be used as the 'sub-corridor level' without distinction.

Data needs (factors that influence the CO_2 quota at corridor level)

The issue of the initial distribution has been on the research agenda (Raux and Marlot, 2005). However, to our best knowledge, it has not been done at a domestic level or a domestic level combined with an international level. Figure B.3 presents the methodology for an initial distribution of CO_2 emissions at the corridor level. More specifically, based on Kyoto protocol and BSA (Burden Share Agreement), setting the target amount of CO_2 by country should be the step to set the quota at the corridor level (UNFCCC, 2006, UN, 1998, EC, 2006). Then, the target amounts of CO_2 in the transport sector (i.e. CO_2 quota in transport sector) by country are estimated. In the reminder of this section, the quota at the corridor level is estimated based upon several detailed factors that vary between corridors such as freight/passenger rate, modal split, international/domestic flow rate, the direction of flows, and the number of lanes of the corridor.

Traffic volumes and road hierarchy (# of vehicles): Traffic flows are classified into three classes based on OD (Origin-Destination) pairs:

- International traffic flows assuming that all international flows use the defined corridors;
- Domestic traffic flows entering and leaving the defined corridors;
- Domestic traffic flows in terms of local traffic using lower level roads, which are excluded in the analysis.

Freight and passenger traffic ratio (%): The different types of traffic flow patterns described above consist of freight and passenger flows. The application of the ITS (Intelligent Transportation system) data collection technique makes it possible to estimate this ratio at the corridor level. However, in most cases, the freight and passenger traffic ratio is not available at the corridor level. In the worst case, the freight and passenger ratio at the national level can be generalized.

Modal share: Modal share is also a significant factor affecting the CO_2 quota development at the corridor level. It is required to set up the initial allowable CO_2 amount at the corridor level. Although, for example, the modal split might be changed after some flows of long-haulage truck are shifted to the rail system, the quota at the corridor level might not be changed. Thus, the CO_2 quota will be the fixed one initially, but it can be updated at the tactical term (e.g. quarterly) in order to balance the share rate and increase/decrease the capacity of freight systems.

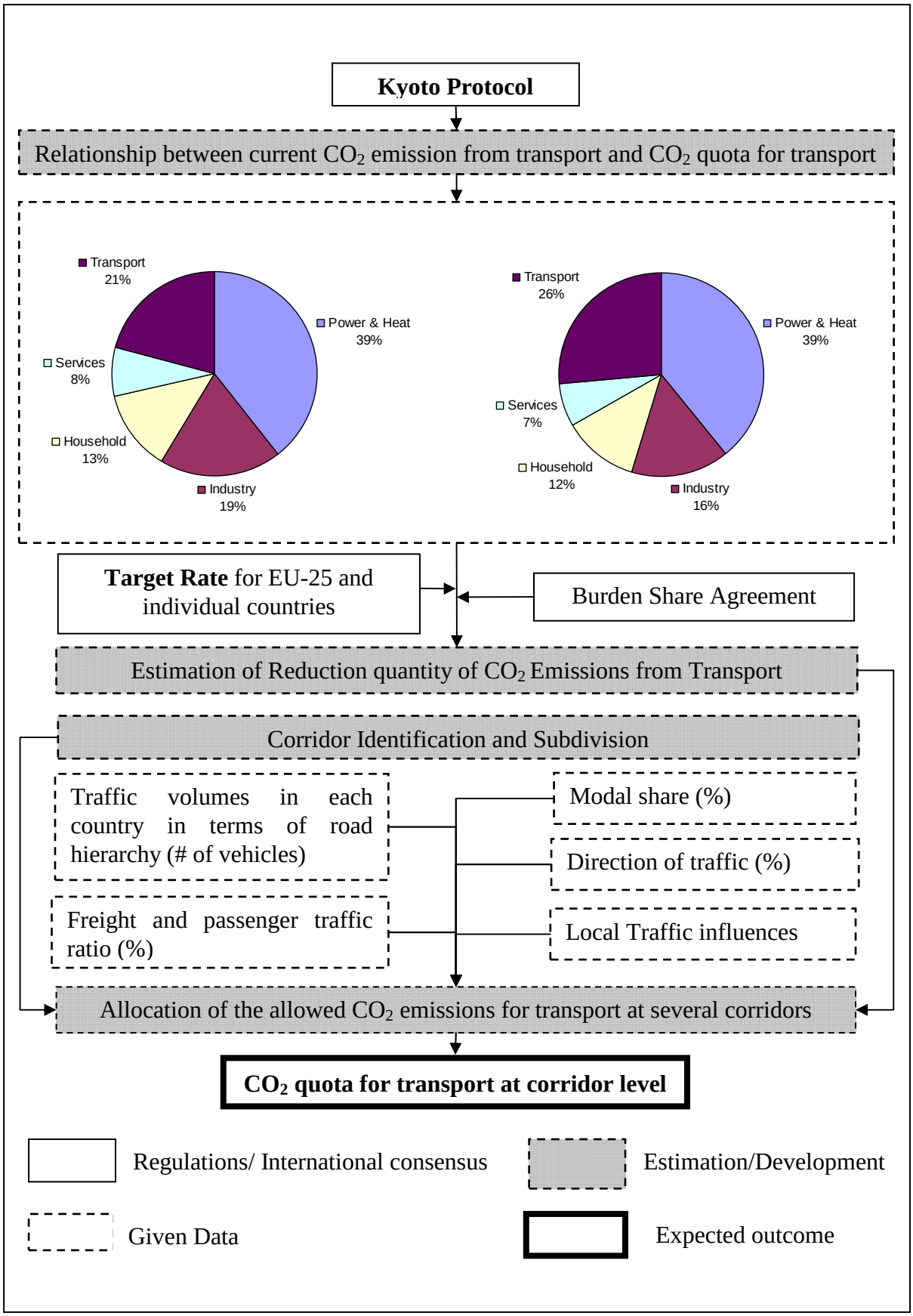

Figure B.3 Methodology for initial distribution of allowed CO2 emissions to quota at corridors

Analysis and Result

Mathematical formulation

All the noted data and expected outcomes below will be used later in this paper.

Notations:

k	is a country
n	is a corridor number (the positive integer from 1 is assigned to the selected corridors; the last number of *n* indicates the summation of all other arcs including collective/local roads in country *k*)
l	is a traffic class (*l*=1 for international flows; *l*=2 for domestic flows entering and leaving the defined corridors; *l*=3 for domestic flows on the other lower level of roads such as local traffics)
f	is an indicator for freight/passenger (*f*=1 for freight, *f*=2 for passenger)
m	is a mode (*m*=1 for road (car or truck); *m*=2 for rail; *m*=3 for inland waterway; *m*=4 for short-see shipping; *m*=5 for deep sea shipping)

Given Data:

M^{n}_{kfm} is the CO_2 mass for *f* type and *m* mode of transport in country *k* in a corridor *n* in a given year, for *f*, *m*, *k*, and *n*

$\sum_{f,m,n} M^{n}_{kfm}$ is the CO_2 mass for the transport sector in each country in a given year, for *k*;

$\sum_{m,n} M^{n}_{k1m}$ is the CO_2 mass for the freight transport sector in each country in a given year, for *k*;

$\sum_{k,f,m,n} M^{n}_{kfm}$ is the CO_2 mass for the transport sector in all EU-25 countries in a given year

X^{n}_{kfml} is the annual average traffic volume of traffic class *l* for *f* type and *m* mode of transport in country *k* in a corridor *n*, for *f*, *m*, *k*, and *n*;

Accordingly, $\sum_{f,m,n,l} X^{n}_{kfml}$ is the total traffic flows from country *k*

Parameters

R^{n}_{kfm} is the freight ratio for *m* mode of transport in country *k* in a corridor *n* in a given year, for *m*, *k*, and *n*;

Accordingly, $\sum_{f} R^{n}_{kfm} = 1$, for *m*, *k*, and *n*

$$\sum_{m,n} M^{n}_{k1m} = \sum_{f,m,n} M^{n}_{kfm} * R^{n}_{kfm} \text{ ; for only freight}$$

$$\sum_{m,n,l} X^{n}_{k1ml} = \sum_{f,m,n,l} X^{n}_{kfml} * R^{n}_{kfm} \text{ ; for only freight}$$

S^n_{kfm} is the mode share ratio for *f* type of transport in country *k* in a corridor *n* in a given year, for *f*, *k*, and *n*;

Accordingly, $\sum_m S^n_{kfm} = 1$, for *f*, *k*, and *n*

$$\sum_{f,n} M^n_{kfm} = \sum_{f,m,n} M^n_{kfm} * S^n_{kfm}; \text{ for } m$$

$$\sum_{f,m,n,l} X^n_{kfml} = \sum_{m,n,l} X^n_{kfml} * S^n_{kfm}; \text{ for only freight}$$

The expected outcomes:

Q^n_{kf} is the CO_2 quota for *f* type of transport in country *k* on corridor *n* during a given period of time, for *f*, *k*, and *n*

$\sum_{f,n} Q^n_{kf}$ is the CO_2 quota for the entire transport sector during a given period of time, for *k*

$\sum_n Q^n_{k1}$ is the CO_2 quota for the freight transport sector during a given period of time, for *k*

$\sum_{k,f,n} Q^n_{kf}$ is the CO_2 quota for the transport sector in all EU-25 countries during a given period of time

It is notable that Q^n_{kf} is the summation value for all transport modes.

The relationship between current CO_2 mass and the CO_2 quota at European level

A relationship between current CO_2 mass generated from transport ($\sum_{f,m,n} M^n_{kfm}$) and the future CO_2 quota for transport sector ($\sum_{k,f,n} Q^n_{kf}$) can be deduced from the agreement of the Kyoto protocol. Since the protocol only suggests the target mass of CO_2 emissions in all sectors by country, the CO_2 mass that should be reduced in the transport sector in a country or in a certain corridor depends on the reduction strategy of the country. However, in Europe, the EU Burden Share Agreement tied all EU countries as one country when considering CO_2 emissions. As a result, the target reduction of the CO_2 mass is 92% of the total mass of CO_2 in 1999 (5429.4Mt) among 25 EU countries. Then, the total target (4995 Mt) is estimated as the target for all sectors. It is simple to calculate the difference between the target amount (4995.0Mt) and the current amount (5240.5 Mt): - 245.5 Mt. Now, a detailed strategic question is asked: *What percentage would be reduced in the transport sector?* Three simple target scenarios related to the reduction mass by transport sector are specified as followed:

If the transport sector is the only sector to reduce emissions whereas the other sectors together should stabilize their emissions, the amount of the reduction of CO_2 is 245.5Mt.
If the transport sector reduces half, the quantity is 122.72Mt.

If the transport sector does not reduce any, the quantity is 0 Mt.

Only the first scenario is considered in this study. Then, $\sum_{k,f,n} Q_{kf}^{n}$, CO_2 quota for both freight and passenger, in all EU-25 countries, on all corridors for the given period of time (e.g. between 2008 to 2012), is estimated (i.e. **1,010.8** Mt per annum), which is $\sum_{k,f,m,n} M_{kfm}^{n}$ (1256.3 Mt) subtracted by 245.5 Mt. Finally, the relationship can be derived as followed:

$$\sum_{k,f,n} Q_{kf}^{n} = [T_{1990} - T_{1990} * \Phi_{europe}] - T_{2005} + \sum_{k,f,m,n} M_{kfm}^{n} \qquad [\textit{Equation 1}]$$

Where,
T_{1990} is the total CO_2 emissions in 1990, the base year
T_{2005} is the total CO_2 emissions in 2005, the current year
Φ_{europe} is the European target rate for reduction of CO_2 emissions

CO_2 quota for transport sector at country level under EU burden share agreement

The next question is "*how does each country shares the total* $\sum_{k,f,n} Q_{kf}^{n}$ ***(1,010.5)*** *Mt of* CO_2*?*" According to the EU BSA, the target rate for reduction of CO_2 emissions is adjusted reflecting the countries situation. Thus, *Equation 1* can be applied to each individual country as follows:

$$\sum_{f,n} Q_{kf}^{n} = [T_{1990} - T_{1990} * \Phi_{k}] - T_{2005} + \sum_{f,m,n} M_{kfm}^{n} \qquad ; \text{for } k$$

Where,
Φ_k is the target rate for reduction of CO_2 emissions for country *k*.

Table B.1 shows the estimated $\sum_{f,n} Q_{kf}^{n}$ by country (i.e. CO_2 quota for both freight and passenger (*f*), by all transport modes (*m*), on the all corridors (*n*) in between 2008 to 2012 for all EU-25 countries)

Table B.1 CO_2 quota for transport sector at country level EU-25 (unit: Mt)

	1990 Total	*2005 Total*	*2005 Transport*	*Target rate(%)*	*Total Target*	*The CO_2 difference between 2005 and 1990*	*CO_2 quota for transport sector at country level*
	T_{1990}	T_{2005}	$\sum_{f,m,n} M^n_{kfm}$	Φ_k	T_{1990}-T_{1990}*Φ_k	[T_{1990}-T_{1990}*Φ]-T_{2005}	$\sum_{f,n} Q^n_{kf}$
EU25	5429.4	5240.5	1256.3	-8.0	4995.0	-245.5	1010.8
BE	162.9	171.2	53.7	-7.5	150.7	-20.5	33.2
CZ	196.8	146.6	18.5	-8.0	181.1	34.5	53.0
DK	73.9	69.2	18.9	-21.0	58.4	-10.8	8.1
DE	1247.6	1030.7	195.0	-21.0	985.6	-45.1	149.9
EE	43.6	21.2	2.6	-8.0	40.1	18.9	21.5
IE	56.5	72.8	16.3	13.0	63.8	-9.0	7.3
EL	119.3	150.8	34.7	25.0	149.1	-1.7	33.0
ES	302.5	475.6	140.3	15.0	347.9	-127.7	12.6
FR	580.7	578.0	169.0	0.0	580.7	2.7	171.7
IT	528.0	597.1	146.4	-6.5	493.7	-103.4	43.0
CY	7.0	11.4	3.7	-8.0	6.4	-5.0	-1.3
LV	28.2	11.9	4.0	-8.0	25.9	14.0	18.0
LT	48.8	23.2	4.8	-8.0	44.9	21.7	26.5
LU	13.1	14.0	8.8	-28.0	9.4	-4.6	4.2
HU	99.2	81.2	12.9	-6.0	93.2	12.0	24.9
MT	2.7	6.5	3.6	-8.0	2.5	-4.0	-0.4
NL	252.0	277.3	100.4	-6.0	236.9	-40.4	60.0
AT	79.9	95.0	26.1	-13.0	69.5	-25.5	0.6
PL	487.4	400.7	38.4	-6.0	458.2	57.5	95.9
PT	63.1	90.2	24.6	27.0	80.1	-10.1	14.5
SI	18.5	20.3	4.6	-8.0	17.0	-3.3	1.3
SK	73.0	48.9	6.8	-8.0	67.2	18.3	25.1
FI	74.0	72.2	17.1	0.0	74.0	1.8	18.9
SE	75.8	75.7	29.0	4.0	78.8	3.1	32.1
UK	794.0	698.7	176.1	-12.5	694.8	-4.0	172.2

CO_2 quota for transport sector at the corridor level

After estimating $\sum_{f,m,n} Q^n_{kfm}$ for each country, the results are allocated to several corridors indicated as *n*. The objective is to estimate the CO_2 quota for the transport sector at the corridor level ($\sum_{f,m} Q^n_{kfm}$) for each country and, furthermore, the CO_2 quota for *f* type and *m* mode of transport in country *k* on corridor *n* (**(**Q^n_{kfm}). In order to estimate those, the relationship between the CO_2 quota at the corridor level and the existing traffic volumes in the corridor should be examined.

By taking into account the traffic classification into three types in terms of the destination (international/domestic) and in relation to the selected corridors, those traffic volumes can be estimated using R^n_{kfm} and S^n_{kfm}. The main reason to consider traffic data is to reflect the current condition at the corridor level. From this point of view, [*Equation 2*] is presented.

$$\sum_{m,n,l} X^n_{kfml} : \sum_n Q^n_{kf} = \sum_m \sum_{l=1}^{2} X^n_{kfm} : Q^n_{kf} \qquad \text{if } l=1, \text{ for } k, f, n, \qquad [\textit{Equation 2}]$$

$$Q_{kf}^{n} = \frac{\left(\sum_{n} Q_{kf}^{n} \times \sum_{m} \sum_{l=1}^{2} X_{kfml}^{n} \right)}{\sum_{m,n,l} X_{kfml}^{n}}$$

$\sum_{m,n,l} X_{kfml}^{n}$ is the total *f* type of traffic in country *k* (given)

$\sum_{m} \sum_{l=1}^{2} X_{kfm}^{n}$ is the corridor traffic from *f* transport by *m* mode in country *k* on the *n* corridor (given)

$\sum_{f,n} Q_{kf}^{n}$ is the total CO_2 quota from transport in country *k* (given)

Q_{kf}^{n} is the CO_2 quota for corridor *n*, for *k*

It is notable that $\sum_{m} \sum_{l=1}^{2} X_{kfm}^{n}$ is the summation of international (*l*=1) and domestic (*l*=2) traffic on corridor *n* by all modes. Furthermore, we can get the following inequality;

$$\sum_{m} M_{kfm}^{n} X_{kfm}^{n} \leq Q_{kf}^{n} \times (\sum_{m} X_{kfm}^{n}), \qquad \text{for } k, f, n \qquad [\textit{Equation 3}]$$

This inequality implies that certain traffics on a corridor *n*, whose CO_2 emissions are over the given CO_2 quota, should be shifted to the less CO_2 emitting transport modes. Note, this inequality can be used as a constraint in several Operational Research (OR) problems. For example, the CO_2 quota can be used in a network design problem (finding optimal route/mode) with the minimization of CO_2 emission in a given network. It can be applied furthermore for a multi-objective optimization problem in order to ensure the allowed CO_2 emissions both at the corridor level and accordingly at the country level.

Discussions

No matter what policy option is realized, some expected and unexpected side effects in general may happen. On the side of tax or subsidy, the Centre for Environmental Assessment of Product and Material Systems (2006) stated, "*New stricter requirements on the environmental performance of vehicles will mean some increased costs for goods transports*"(Dickinsson, 2006). It is necessary to answer "who will take the responsibility of the increased cost? Shippers? Transport operators? Government? Or the final customer?" Basically, transport operators and other actors in the logistics chain may tend to impute it to shippers. Shippers may transfer the burden to the final customers if the shippers are manufactures or producers. It is expected that the final customers who will buy the items with the extra increased costs will take the responsibility. Certainly, the existing freight modal share (%) will be shifted. However, the shifting quantity may not be sufficient to achieve the assigned target, although it depends on countries strategies. Therefore we ask: "*What percent of reduction should be reduced from the freight transport sector?"*

In favor of Cap-and-Trade, there have been some concerns pointing out that the Kyoto protocol itself is too strict (Hartley, 1997). In addition to the concerns of the general Cap-and-

Trade approach, the proposed concept of a CO_2 quota could come under certain criticism. One may argue that it might be too early to launch the quota system since there are still several options potentially able to reduce CO_2 emissions in a logistics chain. For example, inventory management and production scheduling would be better options for reducing CO_2 emissions (Mckinnon, 2003). Furthermore, through some network optimizing techniques such as reallocation, location optimization, and minimization of empty running, the travel distance can be reduced and accordingly CO_2 emissions can be reduced.

In addition to the general and specific concerns, despite the analytical soundness, this study also has two main caveats that should be carefully considered for the future research and policy. The first issue is the uncertainty in setting up the target amount of CO_2 emissions by country and the differences across different countries. In addition, according to the relationship with other sectors, it is not possible to judge "*what percentage of CO_2 should be reduced in the transport sector*." However, this study does assume that "the *transport sector must be the only sector to reduce CO_2 emissions*" (i.e. 100% responsibility of the target reduction: 245.5 Mt of CO_2 in Europe). The second caveat is that the quota system may lead to perverse market reactions. For example, some logistic companies may intend to use *more generous CO_2 emissions quota* (i.e. non-severe CO_2 concentrating corridor) in order to avoid the strict CO_2 quota even if the corridors are not the shortest paths but rather are considerable long-distance detours.

In order to avoid those inefficient side effect (e.g. detouring and taking local/regional road without CO_2 emissions restriction), some necessary provisions and enforcement may both be required. First, the so-called "*corridor-usage reservation system*" may be provided. Since most of the logistics demand is reserved at least a month before the date of the trip; "*First buyers have the right to claim the whole quota*" can be an appropriate option. The other trucking demand over the CO_2 quota limits would choose the other alternatives so that CO_2 emissions are ensured at the corridor. The second provision is that the quality of alternatives (i.e. intermodal freight systems) should be improved in parallel. Actually, some researchers and policy makers doubt that the rail and inland waterway system is enough to absorb the shifted demand even if significant road freights are shifted to the intermodal freight system (Dickinsson, 2006, NERA et al., 1997). Thus, the capacity of the railway and inland waterway should be increased in order to implement the CO_2 quota at the corridor level. It is also notable that the provision/enforcement resources consumed for maintaining a quota system should be taken into account in the long term.

Nevertheless, ironically, those arguments which seem to be pessimistic toward implementing a "strict" CO_2 quota as a real policy instrument can actually be the rationale for implementing it. Despite of the deterioration of CO_2 emissions in freight transport, the timely and appropriate policies to reduce it has not been enforced. The "strict CO_2 quota" is true if the first priority is to ensure the "sustainable" level of CO_2 emissions rather than the others. With this as the primary objective tone can even expect the indirect desirable CO_2 emissions reduction. The above-mentioned criticism might dim the objective of reducing CO_2 emissions from transport or even promotes freight transport. Therefore, despite some of the expected criticisms, the authors still believe that allocating the CO_2 emission quota to a given freight transport corridor is one of best options for reducing CO_2 emissions.

Conclusions

This paper presents a methodology to regulate CO_2 emissions from freight transport at the corridor level and eventually induce the reduction of CO_2 emissions through the modal shift in Europe. The concept of a quota seems to be impracticable and over-controlled. However, according to the relationship between CO_2 emissions and global warming, the concept of a quota might be very practicable and timely. Referring to a target reduction of CO_2 based on the Kyoto protocol, current country's situation, and other practical conditions (e.g. traffic volumes, mode share, and percentage of freights on road), three main relationships are modeled as followed:
The relationship between current CO_2 mass and the CO_2 quota at European level:
CO_2 quota for the transport sector at a country level under EU Burden Share Agreement:
CO_2 quota for the transport sector at the corridor level for type *f* and mode *m* of transport in country *k* on corridor *n*.

The last outcome is the eventual objective of this study. However, the first and second outcomes might be useful as a reference, particularly when examining some scenarios (e.g. downgrading/upgrading the reduction target rate and changing the portion of responsible reduction quantity of the transport sector).

This study may be meaningful since it shows the possibility of overcoming or at least compensating the limitations of the current control system for transport CO_2 emissions. Essentially, the corridor is the most basic geographical level of commodity flows at which multi-modal freight transport can be controlled, which may ensure the target amount of CO_2. Once the CO_2 quota per each corridor is determined, each corridor will have a *directly* limited mass of CO_2 and each country will finally achieve the target amount of CO_2 emission in transport sector. The concept introduced in this study was based on Europe. However, it is applicable for the other bordering countries (e.g. in North America: Canada, the United States, and Mexico) if the inputs and parameters are adjusted.

Some feasible means to realize the concept of a CO_2 quota at the corridor level is to create a central organization or an on-line optimization system (similar to an airline reservation system) in order to optimize the total CO_2 mass generated by corridors. The system should be able to reassign, consolidate, or shift flows to other freight transport modes. Specifically, if CO_2 is over-emitted in a corridor, the CO_2 network optimization model can suggest a choice of another transport modes with a less CO_2 emissions intensive such as rail or inland waterway or an enhancement of engines of old vehicles. The other advantage of the control of CO_2 emissions at the corridor level is the opportunity to eventually control both air-pollutants and noise along corridors as well as at the intensive emitting nodes such as ports and terminals.

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About the author

Nam Seok Kim was born on the 2nd of June 1976 in Seoul, the Republic of Korea. He began his study in transport at the Hanyang University in Republic of Korea in 1995. After discharged from military service for Korean Army in 1998, he obtained a BSc. in Transportation Engineering and Planning from the Hanyang Universty in 2002. His first official job is a research coordinator in Urban Action Network, a NGO (Non-Government Organization) in Korea writing reports about bicycle, pedestrian, and public transports. In 2003, he went cross the *Pacific* from Asia to the North America pursuing MSc. at University of Maryland, College Park in the United States. After finalizing MSc. in 2005 with the thesis entitled "Trip Generation for Pedestrians based on NHTS 2001", he went cross the *Atlantic* from the United States to Europe pursuing Ph.D at Delft University of Technology, the Netherlands. Since 2006, he published two scientific journal articles, five magazine/news paper articles, and more than ten conference proceedings and submitted four scientific journal articles that were either (conditionally) accepted or under review at the time of finalizing this thesis. In June 2010, he left for Korea and began to work for the Korea Transport Research Institute (KOTI) in the Republic of Korea. In December 2010, he came back to Delft for completion of his Ph.D study with the dissertation entitled "Intermodal Freight Transport on the Right Track? Environmental and Economic Performances and their Trade-off".

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