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Abstract

The transportation of goods is essential for the economy, but it also contributes to air pollution which, in turn, affects human health. These negative impacts generate additional costs for society that are not necessarily taken into account in public transportation policies and in private transportation decisions of companies and individuals. This leads to inefficient transportation systems where the social equilibrium is not reached. Intermodal transport is promoted by the European Commission to reduce these negative externalities. The objective of this paper is to analyze at a strategic level the effect on modal split between road, intermodal rail and intermodal inland waterway transport of several economic or environmental policies. An intermodal allocation model is applied to the Belgian case in order to identify the modal split changes between the single minimization of costs (operational or health-related external) and the introduction of additional road taxes.

Keywords: intermodal transport, air pollution, human health, intermodal allocation model

1. Introduction

Transportation activities have been increasing in the last years. Between 1995 and 2010, an annual transportation growth rate of 1.5% for freight (road, rail, inland waterway (IWW), oil pipelines, intra-EU air, intra-EU sea) and 1.3% for passengers has been observed in the European Union's 27 countries (European Commission, 2012).

Transportation of goods and people brings several advantages to society, both from the personal and the economic side. Freight transportation in particular allows access to previously unreachable goods, but also enables cost reduction for products developed in further regions at a lower price. Unfortunately, these benefits are also counterbalanced by undesirable features. Ricardo AEA (2014) states that "when side effects of a certain activity impose a cost upon society, economists speak of such a cost as an external cost." The negative effects generated by transport but not directly supported by the related sector are therefore known as transport external costs. The latter can be of various types such as climate change, air pollution, water pollution, congestion, accidents or noise.

Among these externalities, air pollution is receiving increasing interest. This is observable through several policy measures applied at different levels of decision. Some examples of these measures to mitigate air pollution are the development of European air pollutant standards, the introduction of low emissions zones or alternate traffic circulation in European city centers, the introduction in some countries of stronger speed limitations on highways when pollutant thresholds are reached, or the development and encouragement to use alternative transportation modes like rail or IWW (European Commission, 2011).

The World Health Organization (WHO) estimates that air pollution is now "the world's largest single environmental risk." In 2012, one out of eight people who passed away died because of air pollution exposure (WHO, 2014). Indeed, the emissions generated during the movement of goods directly affect air quality. A higher level of exposure to these chemical components increases the percentage of disease development and aggravation. Heart attacks, cancers and respiratory system illnesses are some of the negative impacts on human health generated by transport.

Human health external costs are divided into two categories: mortality and morbidity costs. Mortality costs reflect the reduction in life expectancy due to acute and chronic effects and are often computed through values of statistical lives (Ricardo AEA, 2014). The monetization of mortality costs is important since they represent the most important part of human health external costs (Ricardo AEA, 2011). Morbidity costs refer to the other costs generated by air pollution, such as costs of curing, costs of hospitalization, and costs of restricted activity days (Ricardo AEA, 2014). These consequences of transportation are not supported by transportation companies and impose a cost on society. For this reason, the limitations and reduction of transport air pollution are encouraged by the European Commission in its White Paper on Transport (European Commission, 2011).

Road is currently the most used mode for freight transport in Europe. Europe is willing to decrease its modal share and to go for more environmentally friendly modes in order to restrict the negative impacts of transport on its environment (European Commission, 2011). This objective can be achieved by the use of rail and IWW in the framework of an intermodal transport. Intermodal transport is defined as the transportation of goods using two or more modes of transport, in the same loading unit, without handling the goods themselves (United Nations, 2001).

Intermodal transport is generally composed of five main stages. Goods are first transported by truck for the pre-haulage from the origin node to the first intermodal terminal. At this first terminal, goods are transferred from truck to train or to barge. The long-haul transport by the more environmentally friendly mode is then performed on rail or IWW. At the second terminal, freight is transferred from train or barge to truck. The post-haulage, i.e. the last part of the travel, is done by truck until the final destination node. The main benefits of intermodal transport lie in the reduced costs and externalities of the environmentally friendly long-haul transport (Mostert and Limbourg, 2016).

Analyses of the relation between transport, air pollution, and human health are often performed at the urban level (de Leeuw et al., 2001, Costabile and Allegrini, 2008, Bagienski, 2015, Lozhkina and Lozkhin, 2015, Tainio, 2015, Aggarwal and Jain, 2015). The focus is often, therefore, on a restricted mode and case study. However, a wider perspective of analysis at the strategic level is also needed to develop long-term transportation policies which account for human health impacts.

How do different modes of transport perform regarding human health external costs? Does the modal split between road and intermodal transport vary, when economic or human health objectives are followed? In an economic optimization strategy, can the intervention of states (for instance through the implementation of taxes) lead to the same modal split, as an environmental optimization strategy? Which modes of transport should be promoted in order to ensure reduced human health external costs? In which infrastructure projects should public authorities invest? What is the implication on modal split of external costs variations, resulting, for instance, from technological improvement or traction mix modifications?

This research aims to respond to these questions by filling the gap which exists in linking transport and human health external costs at a strategic level of decision making. This is done with tools of the operations research domain. For this purpose, an intermodal allocation model is used to compare the modal split between road, intermodal rail and intermodal IWW transport, under economic and environmental optimization strategies. An intermediate policy between economic and environmental optimization is also studied. This policy consists of public intervention through additional road taxes in a system which follows an economic optimization strategy.

The resulting flow distribution under operational costs or human health external costs minimization is analyzed. Sensitivity analysis of transportation external costs is also performed in order to evaluate how modifications of these costs influence the market shares of road and intermodal transport. The mathematical model is applied to the case of Belgium in order to practically emphasize which kinds of policy-related decisions can be provided.

The next section provides a literature review on the links between the modeling of freight transport and its impact on air pollution and human health, and a positioning of our research in this framework. Section 3 details the model formulation and elaborates on the used methodology. Section 4 concentrates on the used data for the case study. Section 5 focuses on the case study findings. Discussion of these results is provided in Section 6. Conclusions are drawn in the last part of the paper.

2. Freight transport, air pollution and human health impacts: what are the implications for business and stakeholders?

Transportation directly influences human health through the emission of chemical components which affect air quality. According to the Update of the Handbook on External Costs of Transport (Ricardo AEA, 2014), the most important emissions related to transport are sulfur dioxide (SO_2), nitrogen oxides (NO_x), Non-Methane Volatile Organic Compounds (NMVOCs) and particulate matters (PM). Particulate matters are divided into two categories: PM2.5 and PM10, representing the particles of a diameter size of less than 2.5 and 10 micrometers, respectively.

These gases emitted by transport are responsible for several harmful impacts such as asthma, inflammation of the respiratory system, headaches, anxiety, cardiovascular diseases, effects on the central nervous system, lung diseases, cancers and premature mortality (EEA, 2013a). The combination of some of these emissions also contributes to the generation of ground-level ozone (O_3), leading to breathing difficulties, especially for young, old or sensitive (for instance, asthmatic) people.

Since these emissions are generated by the transportation companies, but impose a cost on other economic actors of society, they are recognized as externalities or external costs. The non-consideration of externalities on the economic market leads to the production of a higher quantity of transport services than the optimal societal one. As transport externalities can be considered to be market failures, they might provide a rationale for government intervention (for instance through the introduction of additional taxes) in order to reach the societal optimal level of transport.

Several stakeholders like shippers, public authorities, private individuals and private companies may benefit from introducing external costs in transportation planning policies.

Shippers may take advantage of an improvement in their transportation mode attractiveness. This can increase the market share revenues of owners of more environmentally friendly modes.

Government and public authorities mainly support the costs of public health care and hospitals. By ensuring a restricted amount of transport externalities, public authorities could reduce the budget assigned to these services. In Europe, between 46% and 66% of total healthcare expenses were used for curative and rehabilitative care in the different states in 2012 (European Commission, 2015c). Limiting health-related externalities may thus help states better control healthcare expenditures. This is still a major problem in all types of healthcare systems (Wendt, 2009). Some public deficits may thus be recovered, or some money could be transferred to other areas of expenses. These savings are welcome in times of economic crisis when the European Union encourages the reduction of public debt of the member states (European Commission, 2016).

Private individuals also benefit from transport externalities being taken into account in transportation policies. The potential advantages happen at two levels. First, by explicitly making decisions related to the restriction of these external effects, people may enjoy a healthier way of life. Second, households need to invest less money in healthcare expenses, which alleviates their global budget.

Finally, private companies may also benefit from reduced externalities through transportation policies. Indeed, air pollution is responsible for the development of serious health problems such as cancers or heart attacks. The latter often imply sickness absences for employees who do not work anymore. This has a cost for companies which pay sick leave to their members (Gimeno et al., 2014). In addition, new employees might need to be hired and trained to replace the sick person, which also represents an indirect cost to support. Consequently, even if the effects of air pollution related to transport are not directly noticeable, their impact on society is not marginal and concerns a lot of economic actors.

The enhancement of human health preservation is currently done through the setting of global reduction targets for air pollutant emissions. At the world level, air pollution matters are consolidated in the United Nation Economic Commission for Europe (UNECE) Convention on Long-range Transboundary Air Pollution (LRTAP). Introduced in 1979, this convention is the first international legally binding tool developed to limit air pollution. It has been followed by a set of protocols aiming at enforcing the transboundary air pollution abatement (UNECE, 2015). At the European level, the National Emission Ceilings Directive sets national emission objective values for four pollutants, i.e. NOx, SO2, NMVOC and NH3 for the year 2010. These maximum ceilings are more restrictive than those of the LRTAP convention (European Commission, 2015a).

According to Ricardo AEA (2014), the best-known and recommended method for evaluating the impact of emissions of air pollutant is the Impact Pathway Approach developed in the context of the ExternE project (Bickel et al., 2005). This method follows a bottom-up approach, which evaluates the external effect from the lowest level, i.e. the micro level. The analysis is based on the definition of the external effects of a particular object and how it affects its direct environment. This approach focuses on determining the marginal external costs. The specific parameters related to externalities (e.g. the speed of a vehicle or the slope on which it evolves for emissions) can be taken into account precisely. Nevertheless, since this method focuses on very specific cases, it might be difficult to translate the obtained results into policy measures (Van Essen et al., 2007). The Impact Pathway Approach is constructed around five main steps: identification and quantification of the emissions, evaluation of the dispersion of the pollutants around its source, determination of the extent to which a population is exposed to the burdens, identification of the impact in terms of premature deaths and ill health, and finally monetary evaluation of the damage using the damage cost approach (EEA, 2014). The latter defines the real damages caused by the externalities to its surrounding environment.

As the Impact Pathway Approach suggests an evaluation of external costs at the micro-level, the evaluation of the impact of land transportation on air pollution is often considered in urban contexts. The particular attention to these zones mainly lies in the higher concentration of both gases and human beings in these areas. The intensity of exposition as well as the number of people exposed are increased, which generates a higher interest in these regions.

Road transport is the most concerning mode in urban zones. According to EEA (2013b), 10.8% of the PM10 and 16.1% of the PM2.5 emissions are attributed to road transport. As a comparison, only 1.7 and 2.9% of emissions can be attributed to non-road transport, for PM10 and PM2.5, respectively.

Air pollution deterioration in cities may be performed by evaluating *a posteriori* how pollutant values exceed the legal sanitary thresholds that are imposed by authorities (de Leeuw et al., 2001). A more proactive approach consists of better understanding the source-receptor relationship related to traffic air pollution (Costabile and Allegrini, 2008). The traffic density is not the only parameter influencing air quality. Indeed, the interaction between road transport emissions and street structures also plays an important role (Bagienski, 2015). The correct modeling of transport emissions and their effects on air pollution remains one of the most challenging and important issues (Sen et al., 2010, van Lier and Macharis (2014), Lozhkina and Lozkhin, 2015).

The relationship between transport, air pollution and its effect on human health is modeled through various statistical tools, for instance for determining the impact of transport pollution on breast cancers (Hystad et al., 2015), on non-elective hospitalizations for pneumonia (Devos et al., 2015) or on cardio-respiratory risk (Aggarwal and Jain, 2015). Expression of transport impact on human health can also be assessed through exposure-response functions, with a disease burden evaluated in terms of Disability Adjusted Life Years (Tainio, 2015).

Beyond the direct analysis between transportation emissions, air pollution, and human health, other studies focus on the impact of transportation policies on air pollution and human health. Policy recommendations for reducing the human health impact of transport in urban areas often concern passenger transport (Smith et al., 2013, Aggarwal and Jain, 2015, Perez et al., 2015, Xia et al., 2015).

In a complementary approach to research methodologies which concentrate on dose-response functions, GIS-based models (Macharis and Pekin, 2009, Macharis et al., 2010, Meers and Macharis, 2014) or tools of the operations research domain can be used to identify the effect of different freight transportation policies on the flow distribution between several modes of transport. For decision support tools relating to optimization, this analysis is performed through network design models which determine the flow distribution between road and intermodal transport, as well as the location of intermodal terminals. Most of the research concentrates on the minimization of the operational costs on the network (for instance Arnold et al. 2004, Racunica and Wynter, 2005, Limbourg and Jourquin, 2009, Limbourg and Jourquin, 2010, Ishfaq and Sox, 2011, Sörensen et al., 2012, Sörensen and Vanovermeire, 2013, Ghane-Ezabadi and Vergara, 2016); however, some models focus on CO_2 emissions (Mostert et al., 2017) or on generalized costs of transport, including transport externalities (Iannone, 2012, Zhang et al., 2013, Santos et al., 2015, Zhang et al., 2015).

The impact of transport on human health is an important topic of research in the framework of urban passenger transportation. However, freight transportation is also responsible for negative human health effects and even if pollution is generated at a local and operational level, it is not restricted to urban areas. Many other areas can be impacted by the transportation travels that happen with longer distances. It is, therefore, interesting to identify how air pollution can be dealt with at a more global and strategic level. As highlighted here above, not only are stakeholders who are related to the transport sector concerned with transport air pollution. Private individuals and companies are concerned as well, as they face an economic impact due to the non-integration of air pollution externalities in transport policies.

Some contributions in the literature define models that focus on all kinds of externalities (e.g. Macharis et al., 2010 and Santos et al., 2015), providing a global insight but making it impossible to assess the specific impact of each specific external cost (congestion, accident, air pollution, water pollution, noise, etc.). Others account mainly for CO_2 emissions (Zhang et al., 2013, Mostert et al., 2017, Zhang et al., 2015) in order to analyze how the integration of global warming influences the location of intermodal terminals, and the allocation of flows. However, no study was found that specifically focused on the trade-offs between economic and human health interests of freight transport at a strategic level of decision making, using an optimization approach. This paper therefore aims at closing this gap by proposing a model which allows assessing at the global level the effect on modal split of economic or human health transportation policies.

3. Intermodal allocation model formulation

The following formulation is based on the intermodal location-allocation model developed by Mostert et al. (2017). In this paper, we consider that intermodal terminals are already located on the studied geographical zone. This formulation is thus an intermodal allocation model, i.e. a simplification of the intermodal location-allocation model developed by Mostert et al. (2017).

The model minimizes the total operational or external costs (1) of air pollution of transport companies. These costs are divided into four main parts: door-to-door road operational/external costs, transshipment operational/external costs between sea and road, rail-road intermodal operational/external costs and IWW-road intermodal operational/external costs. Rail-road and IWW-road operational and external costs are subdivided into (a) pre-haulage operational/external costs by road, (b) transshipment operational/external costs at origin intermodal terminal, (c) long-haul travel operational/external costs by rail or IWW, (d) transshipment operational/external costs at the destination terminal and (e) post-haulage operational/external costs by road. The focus is on containerized flows of transport between several origin-destination pairs.

The main decisions that are made concern the choice of the mode for achieving the best objective value, subject to several constraints. The decision variables are the amount of flows transported directly by road, by intermodal rail transport, and by intermodal IWW transport. Classically, intermodal flows passing through two terminals are modelled using one variable with four indices (indicating origin, first terminal, second terminal, and destination). We use another approach (based on Ernst and Krishnamoorthy, 1998) which models intermodal flows using two variables with three indices each. The first variable indicates origin, first terminal, and second terminal of the origin-destination pair. The second variable indicates origin, second terminal, and destination of the origin-destination pair. The joint reading of these two variables describes the total travel of the flows, with origin, first terminal, second terminal, and destination. This formulation allows reducing the size of the problem to solve.

The mathematical formulation of the model is described hereafter.

Sets:

N	node set consisting of n demand nodes, indexed by i, $m \in \{1, \ldots, n\}$
H	existing terminal (hub) set, ($H \subseteq N$) consisting of h nodes, indexed by j, $k \in \{1, \ldots, h\}$

Subsets:

N_0	set of port nodes, existing rail and IWW terminals, inside the studied geographical area
N_1	set of demand nodes, with rail-road terminals inside the studied geographical area
N_2	set of demand nodes, with IWW-road terminals inside the studied geographical area,
N_3	set of demand nodes, with rail-road terminals located outside the studied geographical area
N_4	set of demand nodes, with IWW-road terminals located outside the studied geographical area
N_5	set of demand nodes inside the studied geographical area
N_6	set of demand nodes outside the studied geographical area

Thus $N = \cup_{i=0}^{6} N_i$; $H = \cup_{i=0}^{4} N_i$; $H_R = N_0 \cup N_1 \cup N_3$ and $H_W = N_0 \cup N_2 \cup N_4$

Parameters:

d_{im}	road distance between demand nodes i and m (in km)
s_{jk}	rail distance between terminals j and k (in km)
l_{jk}	IWW distance between terminals j and k (in km)
D_{im}	cargo demand from demand node i to demand node m (in t)
y_k	=1 if a terminal is located at k, $\forall\ k \in H$
	=0 otherwise

The value of the following parameters depends on the type of optimization that is performed. If the focus is on economic optimization, the following parameters take the value of operational costs. If the focus is on environmental optimization, the following parameters take the value of external costs.

C_{im}^{L}	long-haul road transportation operational or external costs for travelling from node i to node m (in €/t.km)
C_{ij}^{P}	collection/distribution road transportation operational or external costs for travelling from node i to terminal j (in €/t.km)

C_{jk}^{R}	long-haul rail transportation operational or external costs for travelling from terminal j to terminal k (in €/t.km)
C_{jk}^{W}	long-haul IWW transportation operational or external costs for travelling from terminal j to terminal k (in €/t.km)
C_{j}^{T}	handling operational or external costs at terminal j (in €/t)

Variables:

W_{im}	road flows from demand origin i and destination m (in tonnes), $\forall\, i, m \in N$
X_{jk}^{i}	flows from node i firstly routed through origin rail terminal j and then through destination rail terminal k (in tonnes), $\forall\, i \in N, \forall\, j, k \in\ H_R$
Q_{km}^{i}	flows from origin i to destination m that are routed through rail destination terminal in k (in tonnes), $\forall\, i, m \in N, \forall\, k \in H_R$
F_{jk}^{i}	flows from node i firstly routed through origin IWW terminal j and then through destination IWW terminal k (in tonnes), $\forall\, i \in N, \forall\, j, k \in\ H_W$
V_{km}^{i}	flows from origin i to destination m that are routed through IWW destination terminal in k (in tonnes), $\forall\, i, m \in N, \forall\, k \in H_W$

Mathematical formulation:

Minimize

$$
\begin{aligned}
f = {} & \\
& \sum_{i \in N} \sum_{m \in N} d_{im}.C_{im}^{L}.W_{im} \\
& + \sum_{i \in N_0} C_{i}^{T}.W_{im} + \sum_{m \in N_0} C_{m}^{T}.W_{im} \\
& + \sum_{i \in N} \sum_{j \in H_R} \sum_{k \neq j \in H_R} \left(d_{ij}.C_{ij}^{P} + C_{j}^{T}\right).X_{jk}^{i} \\
& + \sum_{i \in N} \sum_{j \in H_R} \sum_{k \neq j \in H_R} s_{jk}.C_{jk}^{R}.X_{jk}^{i} \\
& + \sum_{i \in N} \sum_{k \in H_R} \sum_{m \in N} (d_{km}.C_{km}^{P} + C_{k}^{T}).Q_{km}^{i} \\
& + \sum_{i \in N} \sum_{j \in H_W} \sum_{k \neq j \in H_W} \left(d_{ij}.C_{ij}^{P} + C_{j}^{T}\right).F_{jk}^{i} \\
& + \sum_{i \in N} \sum_{j \in H_W} \sum_{k \neq j \in H_W} l_{jk}.C_{jk}^{W}..F_{jk}^{i} \\
& + \sum_{i \in N} \sum_{k \in H_W} \sum_{m \in N} (d_{km}.C_{km}^{P} + C_{k}^{T}).V_{km}^{i}
\end{aligned}
\qquad (1)
$$

Subject to

$$y_k = 1 \qquad \forall\, k \in H_R \cup H_W \tag{2}$$

$$D_{im} = W_{im} + \sum_{k \in H_R} Q_{km}^i + \sum_{k \in H_W} V_{km}^i \qquad \forall\, i, m \in N \tag{3}$$

$$\sum_{m \in N} D_{im} = \sum_{m \in N} W_{im} + \sum_{j,k \in H_R} X_{jk}^i + \sum_{j,k \in H_W} F_{jk}^i \qquad \forall\, i \in N \tag{4}$$

$$\sum_{k \in H_R} X_{jk}^i \leq y_j \sum_{m \in N} D_{im} \qquad \forall\, i \in N, \forall\, j \in H_R \tag{5}$$

$$\sum_{j \in H_R} X_{jk}^i \leq y_k \sum_{m \in N} D_{im} \qquad \forall\, i \in N, \forall\, k \in H_R \tag{6}$$

$$\sum_{k \in H_W} F_{jk}^i \leq y_j \sum_{m \in N} D_{im} \qquad \forall\, i \in N, \forall\, j \in H_W \tag{7}$$

$$\sum_{j \in H_W} F_{jk}^i \leq y_k \sum_{m \in N} D_{im} \qquad \forall\, i \in N, \forall\, k \in H_W \tag{8}$$

$$\sum_{j \in H_R} X_{jk}^i = \sum_{m \in N} Q_{km}^i \qquad \forall\, i \in N, \forall\, k \in H_R \tag{9}$$

$$\sum_{j \in H_W} F_{jk}^i = \sum_{m \in N} V_{km}^i \qquad \forall\, i \in N, \forall\, k \in H_W \tag{10}$$

$$W_m^i \geq 0 \qquad \forall\, i, m \in N \tag{11}$$

$$X_{jk}^i \geq 0 \qquad \forall\, i \in N, \forall\, j, k \in H_R \tag{12}$$

$$Q_{km}^i \geq 0 \qquad \forall\, i, m \in N, \forall\, k \in H_R \tag{13}$$

$$F_{jk}^i \geq 0 \qquad \forall\, i \in N, \forall\, j, k \in H_W \tag{14}$$

$$V_{km}^i \geq 0 \qquad \forall\, i, m \in N, \forall\, k \in H_W \tag{15}$$

The model structure can be summarized as follows:

Minimize

Operational or air pollution external costs (1)

Subject to

The existing terminals should be open (2)
Demand should be satisfied for each origin-destination pair (3)
All the flows should leave their origin (4)
Flows cannot go through a closed terminal (5)-(8)
Flows should be conserved between the intermodal variables of a specific origin-destination pair (9)-(10)
Flow variables should be nonnegative (11)-(15)

The model is applied to the Belgian case and considers all flow exchanges at the third-level of Nomenclature of Territorial Units for Statistics (NUTS 3) represented in Fig. 1. Sea flows originating from or leaving the country at maritime ports are also taken into account. The problem is solved on a personal computer (Windows 10 Dual-Core 2.5 GHz, 8 GB of RAM) and with CPLEX 12.6.

4. Data of the Belgian case

The model presented above is applied to the Belgian case for analyzing how economic and health objectives impact the modal split between road and intermodal freight transport. Belgium is chosen for its very dense network of road, rail and IWW, as well as for its characteristic of being one of the least performant European countries in terms of air quality (European Commission, 2015b). The strategic location of Belgium at the heart of Europe also makes it an interesting case regarding flow volumes passing through it. A map of the Belgian terminals and NUTS 3 regions is presented in Fig. 1.

The Belgian case has already been analyzed several times in the literature. Besides other studies focusing on the Belgian flows from and to the port of Antwerp (Macharis and Pekin, 2009, Macharis et al., 2010, Meers and Macharis, 2014), this research evaluates the flow distribution between NUTS 3 regions in Belgium. Flow exchanges between Belgian NUTS 3 regions and some NUTS 3 regions of neighboring countries (the Netherlands, Germany, France and Luxembourg) are also taken into account. Our study differs from the analysis of Santos et al. (2015) since it allows the intermodal IWW option, whereas Santos et al. (2015) focus on road and intermodal rail transport.

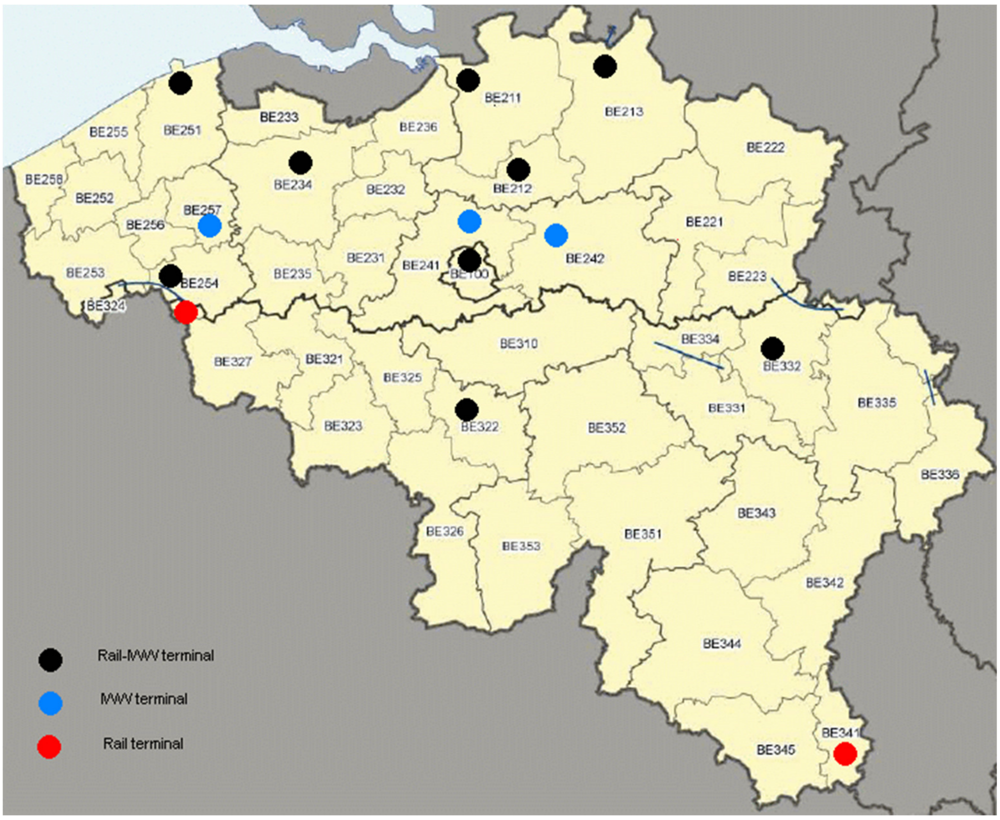

Fig. 1. Map of the rail-IWW, IWW and rail terminals in Belgium.

The analysis of this application should provide insights on the relationship between economic or human health goals and the allocation of containerized flows between the different modes of transport. The study identifies the distribution of the total containerized flows sent to and from the considered NUTS 3 regions by road, rail and IWW. The demand of each region is concentrated on a single generation node, i.e. a city of this region which is chosen for its economic and population importance, and for the existence of a rail/IWW platform nearby. References and additional comments related to the parameters used in this case study are listed in Table 1.

Table 1. References and comments related to the used parameters

Data	Source	Comment
Demand for containerized road, rail and IWW flows	Mostert et al. (2017)	The original 2005 database has been extrapolated to 2010, based on aggregated flow values available from Eurostat and from

		Belgian ports' annual outlooks. Data at the NUTS 2 level have been disaggregated to a NUTS 3 level within Belgium and the neighboring regions, using the number of companies of productive sectors in these regions as the proxy indicator. An origin-destination pair is constituted by any combination of two nodes in Belgium or in its surrounding NUTS 3 regions.
Road and rail network	Carreira et al. (2012)	
IWW network	Promotie Binnenvaart Vlaanderen (2015)	
Road, rail, IWW and transshipment operational costs	BRAIN-TRAINS study (Troch et al., 2015)	Road, rail and transshipment operational costs originate from Janic (2007, 2008). IWW costs are based on PWC (2003). Road and rail operational costs are nonlinear with the distance traveled, assuming economies of distance.
Road, rail and IWW external costs of air pollution	Ricardo-AEA (2014)	Damage cost values of air pollutants for road and rail are based on the European New Energy Externalities Development for Sustainability (NEEDS) study (Preiss and Klotz, 2007). IWW values originate from CE Delft (2011) and Brons and Christidis (2013).
Transshipment external costs of air pollution	Baccelli et al., 2001	Marginal external costs related to the transshipment of goods from one mode to another are small and negligible compared to other externalities of intermodal transport. They are equal to zero both for intermodal rail and IWW transport.

One particularity of this research is to account for human health external costs related to air pollution. Air pollution external cost values of this case study are computed based on a tank-to-wheel approach. More detailed information regarding road, rail and IWW external costs calculations is provided in the following paragraphs.

Road external costs related to air pollution are differentiated according to the size of the truck, the Euro norms of the diesel technology, and the region in which pollutants are emitted (urban, suburban, interurban or highways). Urban external costs are considered for short-haul travels whereas highway external costs are used for long-haul travels by trucks. Pre- and post-haulage travels of intermodal transport are considered to be short-haul travels. It is assumed that most of these travels happen in urban zones, leaving companies/intermodal terminals or arriving at customers/intermodal terminals that are located in cities. This assumption is supported by the fact that an important part of economic activities happens in cities. Moreover, since the model aims at minimizing costs, it tries to reduce as much as possible the road pre-and post-haulage travels. It is, therefore, common to observe flows sent through terminals located in the same city as its origin or destination, implying urban travels.

In order to avoid underestimating intermodal pre- and post-haulage costs, all short-haul travels are considered with urban external cost values. Average road external costs are computed as air pollution costs of the different EURO standard categories, weighted by the proportion of vehicles in each category for 2014 (Emisia, 2015). These costs are presented in Table 2. Road costs provided in Ricardo AEA (2014) are expressed in vehicle-kilometer. The translation into t.km is based on load factors of 0.85 for long-haul and 0.6 for short-haul travels (Janic, 2007) for a truck transporting two TEU of 12 tonnes each.

Table 2. EURO standards shares (Emisia, 2015) and costs (Ricardo AEA, 2014) for the truck fleet in Belgium in 2014

EURO Standard	Share of the fleet (%)	Short-haul air pollution external costs (€cents/vehicle.km)	Long-haul air pollution external costs (€cents/vehicle.km)
HD Euro I - 91/542/EEC Stage I	4.53	11.06	26.66
HD Euro II - 91/542/EEC Stage II	17.43	11.10	22.07
HD Euro III - 2000 Standards	25.49	8.82	18.41
HD Euro IV - 2005 Standards	20.63	5.97	10.43
HD Euro V - 2008 Standards	26.67	2.40	7.98
HD Euro VI	5.26	0.49	1.75

Rail external costs related to air pollution are given for different categories of technology (diesel versus electricity traction). Air pollution external costs for diesel traction contain exhaust and non-exhaust emission costs. Since electric traction does not generate exhaust emissions during the transportation of goods, only non-exhaust costs of wear and tear PM emissions are taken into account. Air pollution external costs are 0.7 €cents/t.km for diesel traction and 0.1 €cents/t.km for electric traction, considering trains loaded with 500 tonnes of goods. The diesel-electric traction ratio is 17%-83% (Eurostat, 2016a).

IWW external costs related to air pollution are expressed for motor vessels and barges of freight capacity between 1,000 and 3,000 tonnes.

The already existing terminals in Belgium and in its neighboring countries are considered to be open in the model. Based on the references described in Table 1, the values given to each operational and external unit cost are provided in Table 3.

Table 3. Operational and external costs of transportation modes

Mode	Operational costs (*€/t.km*)	Air pollution external costs (*€/t.km*)
Road – short-haul	From 0.04 to 0.1	0.00692
Road – long-haul	From 0.02 to 0.07	0.00323
Rail	From 0.019 to 0.025	0.00202
IWW	0.02285	0.00229

5. Findings of the Belgian case

This section details the findings of the application of the model to the Belgian case study. It focuses on the analysis of the resulting flow distribution of goods between road and intermodal transport when different policies are followed. The economic optimization of transport operational costs is first analyzed. The environmental optimization of transport human health external costs related to air pollution is then evaluated. An intermediate policy consisting of the economic optimization of transport operational costs with the introduction of additional road taxes is then assessed. Finally, sensitivity analysis of the main hypotheses of the Belgian case study is also performed.

5.1. Economic optimization

When operational costs are minimized, one notices that most of the flows are transported by road (Fig. 2), which is what currently happens in Belgium and in Europe. The intermodal modal share provided by the model is around 27%. This is 5% lower than the observed rail and IWW market share in 2013 for Belgium and its surrounding countries (Eurostat, 2016b). Within the intermodal market, and compared to reality, the model underestimates the IWW share in relation to the rail component. This might be explained in several ways. First, regarding flows, we only took containerized transport into account. However, a lot of travels performed by IWW are bulk transport. Moreover, the initial model does not account for the different policies introduced by public authorities. Nevertheless, the attribution of taxes or subsidies for specific transportation modes impacts the modal choice and thus influences the general flow distribution (Santos et al., 2015).

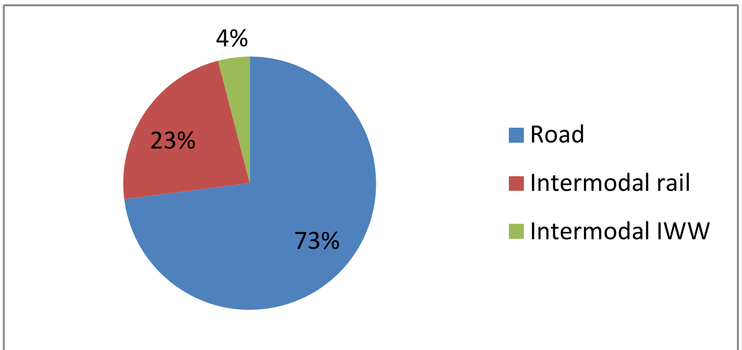

Fig. 2. Flow distribution for operational costs minimization.

5.2. Air pollution optimization

When external costs related to the impact of air pollution on human health are considered to be the objective to minimize, the optimal solution suggests a more intensive use of intermodal transport, to the detriment of road (Fig. 3). Market shares of both rail and IWW increase. The predominance of rail is explained by its lower external costs compared to IWW. Nevertheless, this predominance should be balanced, since this model considers a tank-to-wheel approach, and therefore does not reflect the externalities related to the production of electricity for running trains. In practice, this high modal share for rail could be limited by technical issues, such as capacity restrictions of rail lines and terminals. Capacity restrictions on the network may in particular be encountered because of the priority rule of passenger over freight trains. Road transport becomes the second mode of transport. According to the cost data used in the model, a minimization of the human health external costs of transport would, therefore, be achieved with a higher proportion of intermodal than road transport. Similar to the results of Macharis et al. (2010), this shows that taking into account externalities in transportation policies increases the use of intermodal transport.

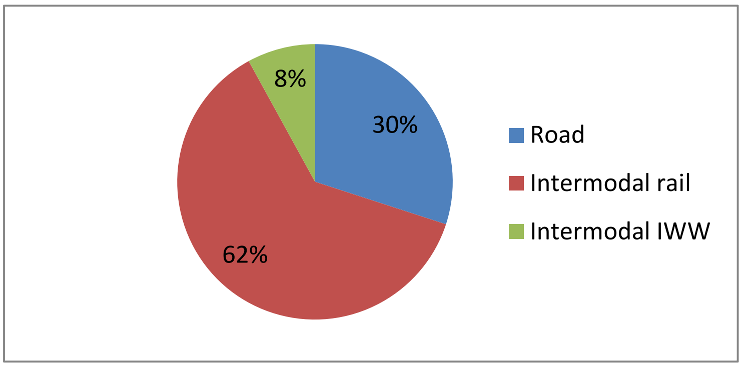

Fig. 3. Flow distribution for air pollution external costs minimization.

5.3. Economic optimization with taxation system

This section analyzes the impact on flows of the introduction of an additional tax on the road network, when operational costs are optimized. This analysis takes its sources from the recent introduction of the “Viapass” tax on highways and denser roads by the Belgian public authorities (April 2016). The objective of this tax is to allocate fairly the different damages provoked by trucks to the infrastructure and to the environment (Viapass, 2015). The Viapass tax replaces the Eurovignette system, which was previously in place in Belgium. It is a kilometer-based charge for trucks only. The paid tax thus reflects the intensity of use of the vehicles. Different kilometric tax rates are applied based on the weight and EURO norm of the vehicle.

The tax per kilometer is applied to each truck with a permissible weight greater than 3.5 tonnes. A Viapass tariff of 0.14€/km is assumed, which corresponds to the average existing rates, weighted by the number of vehicles in each category for 2014 (Emisia, 2015). The Walloon/Flemish fees are considered in this case, since their respective highways represent the major part of the Belgian network. Supposing that an average truck carries 20.4 t (2 TEU*12 tons/TEU*0.85 of load factor), this leads to a tax of 0.007€/t.km. The flow distribution when operational costs are minimized under the introduction of the Viapass tax for the long-haul travels by road is given by Fig. 4.

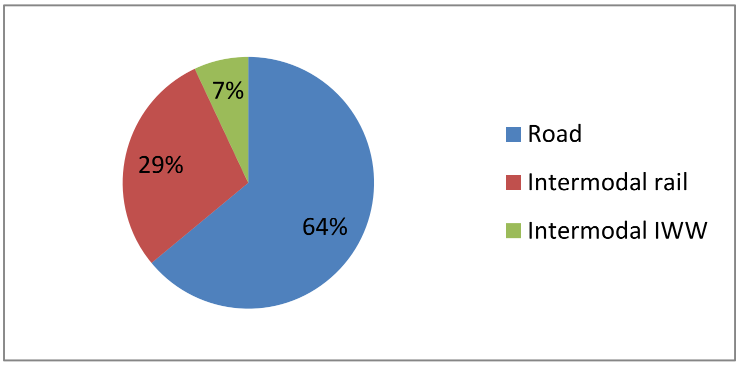

Fig. 4. Flow distribution for operational costs minimization with Viapass on the long-haul travels.

Compared to the operational costs minimization policy, an increase of intermodal flows is noticed. By charging an additional cost to the direct road transport, more flows are transported using the rail and IWW infrastructure. The amount of t.km transported by IWW is almost doubled while a relative increase of around 25% is observed for intermodal rail transport. With this additional tax, road transport still remains the most used mode.

If the Viapass tax is also included for short-haul travels of the intermodal transport, the flow distribution is as given in Fig. 5. Applying the Viapass fees on the short-haul travel corresponds to the assumption that all urban travels are affected by the tax, whereas this is presently only the case for the urban area of Brussels. This situation does not correspond to the current reality but the results of this analysis are interesting since they show that, even if this short part of the trip is impacted by the Viapass tax, more intermodal transport would nevertheless be used when compared to the single operational cost minimization problem. Indeed, the kilometers performed by road inside the intermodal travel are much fewer than the kilometers for door-to-door transport by truck. Intermodal transport is, therefore, less impacted by the Viapass fee per kilometer than road-only transport.

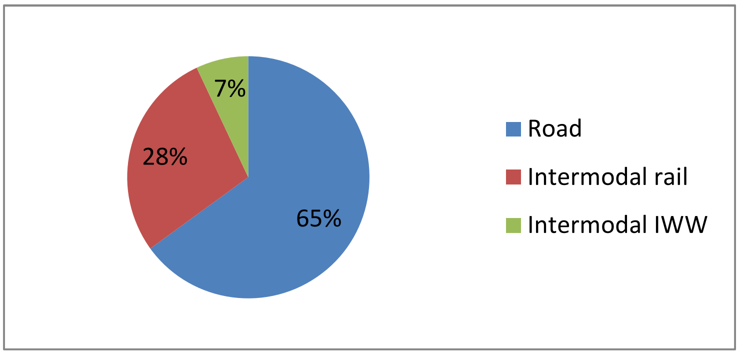

Fig. 5. Flow distribution for operational costs minimization with Viapass on both long-haul and short-haul travels.

5.4. Sensitivity analysis

This section identifies the impact on the modal split of variations of some of the main hypotheses related to the Belgian case study. The effects of road, rail and IWW external costs changes are evaluated. A comparison between the effects of operational and external costs variation is also provided.

5.4.1. Road external costs

This section analyzes the effects on modal split of a variation of road air pollution external cost parameters. In particular, the effect of truck fleet structure on flow distribution is evaluated.

The fleet constitution influences the average air pollution external cost value. Fleets are evolving with technological improvement. Progressively, old and more polluting trucks are replaced with cleaner vehicles. This sensitivity analysis evaluates the change of modal split when cleaner vehicles of EURO VI type are progressively replacing the oldest trucks in the Belgian territory. The reference case is compared to three scenarios: EURO VI proportion of 10%, 15% and 20% of the fleet. These scenarios reflect potential increases of the EURO VI vehicle share in the fleet. This progressive replacement of old vehicles with new vehicles is indeed expected in the future. The fleet structure of these scenarios as well as their resulted modal split are given in Table 4.

Results show that fleet structure affects modal split in terms of environmental perspective. The road market share increases with a greater proportion of EURO VI vehicles in the fleet. The introduction of cleaner road vehicles thus leads to solutions in which road transport is more and more included. Both rail and IWW lose market share when the road fleet becomes cleaner. A replacement of older trucks for reaching a 25%-share of EURO VI vehicles (starting from a 5%-share in the reference scenario) leads to an increase of 8% of the road market share. Therefore, improving the technology of trucks makes road transport more competitive on certain connections, from the perspective of air pollution external costs minimization. If the technology of trains and barges remains constant, intermodal rail and IWW attractiveness can subsequently be limited by an environmental improvement in truck technology. This scenario is plausible since renewal rates for barges and trains are much slower than for trucks. Truck technology is therefore more quickly adapted on the market than rail and IWW technological improvements.

Table 4. Sensitivity of flow distribution to truck fleet structure

Scenario	EURO Standard	Share of the fleet (%)	Modal split of air pollution external cost min. (road - intermodal rail - intermodal IWW in %)
EURO VI = 5% - Reference scenario	HD Euro I	4.53	30-62-8
	HD Euro II	17.43	
	HD Euro III	25.49	
	HD Euro IV	20.63	
	HD Euro V	26.67	
	HD Euro VI	5.26	
EURO VI = 10%	HD Euro I	0.00	31-62-7
	HD Euro II	17.21	
	HD Euro III	25.49	
	HD Euro IV	20.63	
	HD Euro V	26.67	
	HD Euro VI	10.00	
EURO VI = 15%	HD Euro I	0.00	33-59-8
	HD Euro II	12.21	
	HD Euro III	25.49	
	HD Euro IV	20.63	
	HD Euro V	26.67	
	HD Euro VI	15.00	
EURO VI = 20%	HD Euro I	0.00	35-59-7
	HD Euro II	7.21	
	HD Euro III	25.49	
	HD Euro IV	20.63	
	HD Euro V	26.67	
	HD Euro VI	20.00	
EURO VI = 25%	HD Euro I	0.00	38-57-5
	HD Euro II	2.21	
	HD Euro III	25.49	
	HD Euro IV	20.63	
	HD Euro V	26.67	
	HD Euro VI	25.00	

5.4.2. Rail external costs

This section presents the effects on modal split of a variation of rail air pollution external cost parameters. In particular, the impact on modal split of a modification of the electric-diesel traction ratio is studied.

Two scenarios are compared to the reference scenario. These scenarios show the potential evolution of the traction mix in Belgium, where most diesel traction is used for shunting activities at the intermodal terminals. The choice for electric or diesel traction may be driven by various criteria such as physical (some slopes on the network imply the use of electric locomotives) or financial (diesel locomotives are cheaper than electric locomotives) constraints. The modal split of the scenarios is presented in Table 5.

Table 5. Sensitivity of flow distribution to rail traction mix

Scenario	Modal split of air pollution external cost min. (road - intermodal rail - intermodal IWW in %)
17% diesel – 83% electric - Reference scenario	30-62-8
15% diesel – 85% electric	29-64-7
10% diesel – 90% electric	26-69-5

The train traction mix between diesel and electricity influences the flow distribution. As expected, an increase of electricity use implies a bigger rail market share, since rail air pollution external costs decrease. The rail market share increase happens with a reduction of both IWW and road market shares. However, the road is a little bit more impacted than intermodal IWW transport. Consequently, reductions in the average unit external costs, through a higher use of electric traction, may be a solution to achieving part of the flow transfer from road to more environmentally friendly modes, as expected by the European Commission in its White Paper on Transport (European Commission, 2011).

5.4.3. IWW operational and external costs

This section develops the effects on modal split of a variation of IWW operational and air pollution external cost parameters.

In the literature, usually only the road and intermodal rail transport are compared. This is not surprising since a lot of regions are connected through road and rail, but are not necessarily equipped with waterways. This paper includes the intermodal IWW option. Belgium is well-connected through IWW, with around 1,500 km of waterways for a total surface of 31,000 km² (Eurostat, 2016c).

In order to identify how the flow distribution is impacted by the specific costs of IWW in this region, we perform a sensitivity analysis by increasing and decreasing successively the operational and external IWW costs by 10%, 20% and 30%. These theoretical variations aim at estimating the flow distribution when the IWW input parameter varies. This helps assess the robustness of the model and also provides information on how results could evolve with other IWW cost values. The flow distribution for these different scenarios is given in Table 6. The first column provides the results of the operational/external cost minimization, whereas the second column shows the results of the external cost minimization when the operational/external IWW costs are modified.

Results show that variations of the operational and external costs of IWW play a role in modal split. Road market share seems more sensitive to IWW operational than external costs variations. Focusing on air pollution's external costs would lead to a higher proportion of intermodal transport than focusing on operational costs. However, reductions in IWW external costs, resulting from, for instance, technological improvement, would lead to flow transfers from rail to IWW, inside the intermodal market share, rather than from road to intermodal transport. This risk of flow transfer within the intermodal market share has also been highlighted by Macharis and Pekin (2009) and Mostert et al. (2017).

In terms of operational costs, intermodal IWW transport never exceeds 18% of the market share, remaining the least used mode in most of the scenarios. However, intermodal IWW transport may reach 41% of the market share when external costs are optimized. In this case, intermodal IWW transport is the most used mode in only one out of the seven analyzed scenarios. These results are explained by the lower values of rail air pollution external costs.

Table 6. Sensitivity of flow distribution to IWW external and operational costs

IWW cost value	Modal split of operational cost min. (*road-intermodal rail-intermodal IWW in* %)	Modal split of air pollution external cost min. (*road-intermodal rail-intermodal IWW in* %)
0.7* IWW cost	67-15-18	28-31-41
0.8* IWW cost	68-18-14	29-40-31
0.9* IWW cost	72-19-9	30-50-20
1.0* IWW cost - Reference scenario	73-23-4	30-62-8
1.1* IWW cost	74-23-3	30-65-5
1.2* IWW cost	74-24-2	30-66-4
1.3* IWW cost	75-24-1	30-67-3

6. Discussion of the Belgian case

The analysis of the Belgian case study shows that the optimal flow distribution differs according to the objective that is pursued and according to the policies that are implemented. Following an economic optimization strategy by considering only operational costs leads to a high proportion of direct door-to-door road transport. On the contrary, optimizing human health external costs of transport related to air pollution provides a system where intermodal transport has the largest market share. Economic and health objectives thus lead to different trends in terms of flow allocation.

Introducing an additional road tax per kilometer allows a slight reduction in the road market share. Even when the additional tax is introduced for both short-haul and long-haul travels, an increase in the intermodal market share is noticed. Of course, this increase is greater when no tax is applied for the pre- and post-haulage travels by truck in the framework of an intermodal trip. Nevertheless, the introduction of a tax on roads never allows reaching the intermodal market share of the external costs minimization strategy.

The introduction of cleaner vehicles in the truck fleet increases the road market share under the air pollution external cost minimization strategy. The development of improved environmental technologies for trucks therefore makes road transport competitive regarding air pollution optimization. This trend tends to reduce the rail and IWW market shares and the transfer from road to intermodal solutions.

Variations in rail external costs imply changes in the modal split. Some road flows are transferred to rail, which increases the intermodal market share. Reducing rail external costs also slightly reduces the market share of intermodal IWW transport. Decreasing rail pollution external costs by increasing the electricity share in rail traction mix is, therefore, a potential solution for transferring goods from road to intermodal transport.

This case shows that road market share seems more sensitive to IWW operational than external costs variations. If policies were focusing on air pollution external costs, rather than on operational costs, decreases of IWW external costs (for instance, resulting from technological improvement) would have a low impact on flow distribution between road and intermodal transport. On the contrary, changes in unit IWW external costs would lead to flow transfers between rail and IWW, within the intermodal market share, rather than between road and intermodal transport. This switch between two intermodal modes is not aligned with the willingness of the European Commission to transfer freight flows from road to other environmentally-friendly transportation means by 2030 et 2050 (European Commission, 2011). If an air pollution costs minimization strategy is followed, policy makers should be aware that reducing unit IWW external costs will not contribute to major flow transfers from road to intermodal transport.

More generally, results of the sensitivity analysis show that modal split depends on the value of the respective operational and external costs of transportation modes. Consequently, the precise valuation of these costs is necessary for ensuring good results of the model. The valuation of operational costs is easier than the valuation of external costs since operational costs are more tangible. Mortality external costs related to air pollution are based on statistical tools such as value of statistical life or value of a life year (Ricardo AEA, 2014). The current recommended studies evaluate morbidity external costs related to air pollution through stated preference surveys (Ricardo AEA, 2014). The continuous development of such valuation methods is necessary for ensuring accurate decision support systems for long-term transportation planning policies.

Several intermodal stakeholders can gain insight from the results of this case. First, intermodal operators are able to identify the effect on their market share of a potential improvement of their technology, reflected in a decrease of their operational or external costs. Public leaders can assess the impact of their transportation policies on the flow distribution, and thus identify how a taxation system would, for instance, support the development and extension of intermodal transport. Terminals managers are also concerned with the results. Indeed, they can evaluate the evolution of the flows passing through their terminals, and therefore determine the potential investments for matching the terminal capacity with its future demand. Finally, infrastructure managers are also able to determine the modal split and thus, for instance, to forecast which further railway or IWW connections should be developed or removed, according to the decided policy for transport planning.

7. Conclusions

In a complementary approach to studies focusing on the effects of transport in urban contexts, this paper develops an analysis of the flow distribution between road and intermodal transport at the strategic level. This research contributes to the development of decision-support tools for long-term transportation policies, by allowing the identification of the effects of current (economic) and expected future (human-health) objectives. The performance of road and intermodal transport regarding operational costs and human health external costs related to air pollution can be identified. This study improves the understanding of the impact that public authorities can have on modal split using taxation systems. The trends in the evolution of flow distribution under technological improvement or modifications of traction mix can also be deduced.

An intermodal allocation model is applied to the Belgian case in order to highlight which kinds of policy measures can be evaluated. The outcome is interesting for public authorities, terminal operators, intermodal carriers, and shippers, as well as for infrastructure managers.

Results show that rail and IWW transport perform better than road regarding human health external costs. The modal split between road and intermodal transport is affected by the followed economic or environmental policy. Indeed, the external costs' minimization strategy leads to a configuration where intermodal transport has the most important market share. On the contrary, the operational costs minimization strategy defines road transportation as the most competitive mode.

The introduction of road taxes under economic optimization decreases the road market share in relation to intermodal transport. Nevertheless, this decrease leads to an underuse of intermodal transport, compared to the environmental optimization strategy.

Under an environmental optimization strategy, sensitivity analyses demonstrate that modifications of external cost values of the three modes imply variations of the modal split.

An improvement in the environmental friendliness of road transport through the introduction of cleaner vehicles in the truck fleet makes road competitive regarding human health external costs. The environmental improvement in truck technology, therefore, restricts the potential for flow transfer from road to rail or IWW. A reduction in rail air pollution external costs, through an increased use of electricity in the traction mix, increases the intermodal market share.

Sensitivity analysis of IWW external costs underlines the possibility of flow transfers within the intermodal market share between rail and IWW rather than between road and intermodal transport. This effect is in contradiction to the willingness of the European Commission to transfer freight flows from road to more environmentally friendly modes. Therefore, this topic should be carefully analyzed when implementing measures aimed at reducing road freight flows.

The chosen transport policy definitely influences the modal split. This implies that, according to the environmental or economic strategy that is followed, different kinds of investments might need to be performed. If the focus is on environmental optimization, money should be spent on rail or IWW infrastructure, to support intermodal development. If the focus remains on economic optimization, or if cleaner trucks progressively replace older technology vehicles, road investments should be reinforced.

This research compares the economic and air pollution external costs minimization strategies. Further research work should be performed regarding the analysis of other intermediate policies such as the introduction of subsidies or the economic optimization with an internalization of external costs. This study only analyzes the effects of human health external costs related to air pollution. However, other external costs like noise could also be integrated in policy analysis. Results of the model are influenced by the value given to external costs and other studies focusing on the precise valuation of these costs are, therefore, necessary. This paper does not account for intermodal terminal capacity. This helps intermodal stakeholders determine the most important connections in terms of flows. However, further research work should also be done to identify the match between flows and terminal capacity.

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