

Road and intermodal transport performance: the impact of operational costs and air pollution external costs

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3 **Abstract**

4 The transportation of goods is essential for the economy, but it also contributes to air pollution which, in turn, affects human
5 health. These negative impacts generate additional costs for society that are not necessarily taken into account in public
6 transportation policies and in private transportation decisions of companies and individuals. This leads to inefficient
7 transportation systems where the social equilibrium is not reached. Intermodal transport is promoted by the European
8 Commission to reduce these negative externalities. The objective of this paper is to analyze at a strategic level the effect on
9 modal split between road, intermodal rail and intermodal inland waterway transport of several economic or environmental
10 policies. An intermodal allocation model is applied to the Belgian case in order to identify the modal split changes between the
11 single minimization of costs (operational or health-related external) and the introduction of additional road taxes.
12

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

14 **1. Introduction**

15 Transportation activities have been increasing in the last years. Between 1995 and 2010, an annual transportation
16 growth rate of 1.5% for freight (road, rail, inland waterway (IWW), oil pipelines, intra-EU air, intra-EU sea) and
17 1.3% for passengers has been observed in the European Union's 27 countries (European Commission, 2012).

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

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

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

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

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

50 Intermodal transport is generally composed of five main stages. Goods are first transported by truck for the pre-
51 haulage from the origin node to the first intermodal terminal. At this first terminal, goods are transferred from truck
52 to train or to barge. The long-haul transport by the more environmentally friendly mode is then performed on rail
53 or IWW. At the second terminal, freight is transferred from train or barge to truck. The post-haulage, i.e. the last
54 part of the travel, is done by truck until the final destination node. The main benefits of intermodal transport lie in
55 the reduced costs and externalities of the environmentally friendly long-haul transport (Mostert and Limbourg,
56 2016).

57 Analyses of the relation between transport, air pollution, and human health are often performed at the urban
58 level (de Leeuw et al., 2001, Costabile and Allegrini, 2008, Bagienski, 2015, Lozhkina and Lozhkin, 2015, Tainio,
59 2015, Aggarwal and Jain, 2015). The focus is often, therefore, on a restricted mode and case study. However, a
60 wider perspective of analysis at the strategic level is also needed to develop long-term transportation policies which
61 account for human health impacts.

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

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

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

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

84 **2. Freight transport, air pollution and human health impacts: what are the implications for business and** 85 **stakeholders?**

86 Transportation directly influences human health through the emission of chemical components which affect air
87 quality. According to the Update of the Handbook on External Costs of Transport (Ricardo AEA, 2014), the most
88 important emissions related to transport are sulfur dioxide (SO₂), nitrogen oxides (NO_x), Non-Methane Volatile
89 Organic Compounds (NMVOCs) and particulate matters (PM). Particulate matters are divided into two categories:
90 PM_{2.5} and PM₁₀, representing the particles of a diameter size of less than 2.5 and 10 micrometers, respectively.

91 These gases emitted by transport are responsible for several harmful impacts such as asthma, inflammation of
92 the respiratory system, headaches, anxiety, cardiovascular diseases, effects on the central nervous system, lung
93 diseases, cancers and premature mortality (EEA, 2013a). The combination of some of these emissions also
94 contributes to the generation of ground-level ozone (O₃), leading to breathing difficulties, especially for young, old
95 or sensitive (for instance, asthmatic) people.

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

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

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

106 Government and public authorities mainly support the costs of public health care and hospitals. By ensuring a
107 restricted amount of transport externalities, public authorities could reduce the budget assigned to these services.
108 In Europe, between 46% and 66% of total healthcare expenses were used for curative and rehabilitative care in the
109 different states in 2012 (European Commission, 2015c). Limiting health-related externalities may thus help states
110 better control healthcare expenditures. This is still a major problem in all types of healthcare systems (Wendt,
111 2009). Some public deficits may thus be recovered, or some money could be transferred to other areas of expenses.
112 These savings are welcome in times of economic crisis when the European Union encourages the reduction of
113 public debt of the member states (European Commission, 2016).

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

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

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

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

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

150 Road transport is the most concerning mode in urban zones. According to EEA (2013b), 10.8% of the PM₁₀
151 and 16.1% of the PM_{2.5} emissions are attributed to road transport. As a comparison, only 1.7 and 2.9% of emissions
152 can be attributed to non-road transport, for PM₁₀ and PM_{2.5}, respectively.

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

160 The relationship between transport, air pollution and its effect on human health is modeled through various
161 statistical tools, for instance for determining the impact of transport pollution on breast cancers (Hystad et al.,
162 2015), on non-elective hospitalizations for pneumonia (Devos et al., 2015) or on cardio-respiratory risk (Aggarwal
163 and Jain, 2015). Expression of transport impact on human health can also be assessed through exposure-response
164 functions, with a disease burden evaluated in terms of Disability Adjusted Life Years (Tainio, 2015).

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

169 In a complementary approach to research methodologies which concentrate on dose-response functions, GIS-
170 based models (Macharis and Pekin, 2009, Macharis et al., 2010, Meers and Macharis, 2014) or tools of the
171 operations research domain can be used to identify the effect of different freight transportation policies on the flow
172 distribution between several modes of transport. For decision support tools relating to optimization, this analysis
173 is performed through network design models which determine the flow distribution between road and intermodal
174 transport, as well as the location of intermodal terminals. Most of the research concentrates on the minimization of
175 the operational costs on the network (for instance Arnold et al. 2004, Racunica and Wynter, 2005, Limbourg and
176 Jourquin, 2009, Limbourg and Jourquin, 2010, Ishfaq and Sox, 2011, Sørensen et al., 2012, Sørensen and
177 Vanovermeire, 2013, Ghane-Ezabadi and Vergara, 2016); however, some models focus on CO₂ emissions (Mostert
178 et al., 2017) or on generalized costs of transport, including transport externalities (Iannone, 2012, Zhang et al.,
179 2013, Santos et al., 2015, Zhang et al., 2015).

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

188 Some contributions in the literature define models that focus on all kinds of externalities (e.g. Macharis et al.,
189 2010 and Santos et al., 2015), providing a global insight but making it impossible to assess the specific impact of
190 each specific external cost (congestion, accident, air pollution, water pollution, noise, etc.). Others account mainly
191 for CO₂ emissions (Zhang et al., 2013, Mostert et al., 2017, Zhang et al., 2015) in order to analyze how the
192 integration of global warming influences the location of intermodal terminals, and the allocation of flows.
193 However, no study was found that specifically focused on the trade-offs between economic and human health
194 interests of freight transport at a strategic level of decision making, using an optimization approach. This paper
195 therefore aims at closing this gap by proposing a model which allows assessing at the global level the effect on
196 modal split of economic or human health transportation policies.

197 **3. Intermodal allocation model formulation**

198 The following formulation is based on the intermodal location-allocation model developed by Mostert et al.
199 (2017). In this paper, we consider that intermodal terminals are already located on the studied geographical zone.
200 This formulation is thus an intermodal allocation model, i.e. a simplification of the intermodal location-allocation
201 model developed by Mostert et al. (2017).

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

210 The main decisions that are made concern the choice of the mode for achieving the best objective value, subject
211 to several constraints. The decision variables are the amount of flows transported directly by road, by intermodal
212 rail transport, and by intermodal IWW transport. Classically, intermodal flows passing through two terminals are
213 modelled using one variable with four indices (indicating origin, first terminal, second terminal, and destination).
214 We use another approach (based on Ernst and Krishnamoorthy, 1998) which models intermodal flows using two

215 variables with three indices each. The first variable indicates origin, first terminal, and second terminal of the
 216 origin-destination pair. The second variable indicates origin, second terminal, and destination of the origin-
 217 destination pair. The joint reading of these two variables describes the total travel of the flows, with origin, first
 218 terminal, second terminal, and destination. This formulation allows reducing the size of the problem to solve.

219 The mathematical formulation of the model is described hereafter.

220

221 Sets:

222

223 N node set consisting of n demand nodes, indexed by $i, m \in \{1, \dots, n\}$

224 H existing terminal (hub) set, ($H \subseteq N$) consisting of h nodes, indexed by $j, k \in \{1, \dots, h\}$

225 Subsets:

226

227 N_0 set of port nodes, existing rail and IWW terminals, inside the studied geographical area

228 N_1 set of demand nodes, with rail-road terminals inside the studied geographical area

229 N_2 set of demand nodes, with IWW-road terminals inside the studied geographical area,

230 N_3 set of demand nodes, with rail-road terminals located outside the studied geographical area

231 N_4 set of demand nodes, with IWW-road terminals located outside the studied geographical area

232 N_5 set of demand nodes inside the studied geographical area

233 N_6 set of demand nodes outside the studied geographical area

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

235

236 Parameters:

237

238 d_{im} road distance between demand nodes i and m (in km)

239 s_{jk} rail distance between terminals j and k (in km)

240 l_{jk} IWW distance between terminals j and k (in km)

241 D_{im} cargo demand from demand node i to demand node m (in t)

242 $y_k = 1$ if a terminal is located at k , $\forall k \in H$

243 $= 0$ otherwise

244

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

248

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

250 C_{ij}^P collection/distribution road transportation operational or external costs for travelling from node i to
 251 terminal j (in €/t.km)

252 C_{jk}^R long-haul rail transportation operational or external costs for travelling from terminal j to terminal k (in
 253 €/t.km)

254 C_{jk}^W long-haul IWW transportation operational or external costs for travelling from terminal j to terminal k (in
 255 €/t.km)

256 C_j^T handling operational or external costs at terminal j (in €/t)

257

258 Variables:

259

260 W_{im} road flows from demand origin i and destination m (in tonnes), $\forall i, m \in N$

261 X_{jk}^i flows from node i firstly routed through origin rail terminal j and then through destination rail terminal k
 262 (in tonnes), $\forall i \in N, \forall j, k \in H_R$

263 Q_{km}^i flows from origin i to destination m that are routed through rail destination terminal in k (in tonnes),
 264 $\forall i, m \in N, \forall k \in H_R$

265 F_{jk}^i flows from node i firstly routed through origin IWW terminal j and then through destination IWW
 266 terminal k (in tonnes), $\forall i \in N, \forall j, k \in H_W$

267 V_{km}^i flows from origin i to destination m that are routed through IWW destination terminal in k (in tonnes),
 268 $\forall i, m \in N, \forall k \in H_W$

269

270 Mathematical formulation:

271

272 *Minimize*

273

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

Subject to

$$y_k = 1 \quad \forall k \in H_R \cup H_W \quad (2)$$

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

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

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

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

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

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

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

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

$$W_m^i \geq 0 \quad \forall i, m \in N \quad (11)$$

$$X_{jk}^i \geq 0 \quad \forall i \in N, \forall j, k \in H_R \quad (12)$$

$$Q_{km}^i \geq 0 \quad \forall i, m \in N, \forall k \in H_R \quad (13)$$

$$F_{jk}^i \geq 0 \quad \forall i \in N, \forall j, k \in H_W \quad (14)$$

$$V_{km}^i \geq 0 \quad \forall i, m \in N, \forall k \in H_W \quad (15)$$

274

275 The model structure can be summarized as follows:

276

277 *Minimize*

278

279 Operational or air pollution external costs (1)

280

281 *Subject to*

282

283 The existing terminals should be open (2)

284 Demand should be satisfied for each origin-destination pair (3)

285 All the flows should leave their origin (4)

286 Flows cannot go through a closed terminal (5)-(8)

287 Flows should be conserved between the intermodal variables of a specific origin-destination pair (9)-(10)

288 Flow variables should be nonnegative (11)-(15)

289 The model is applied to the Belgian case and considers all flow exchanges at the third-level of Nomenclature of

290 Territorial Units for Statistics (NUTS 3) represented in Fig. 1. Sea flows originating from or leaving the country at

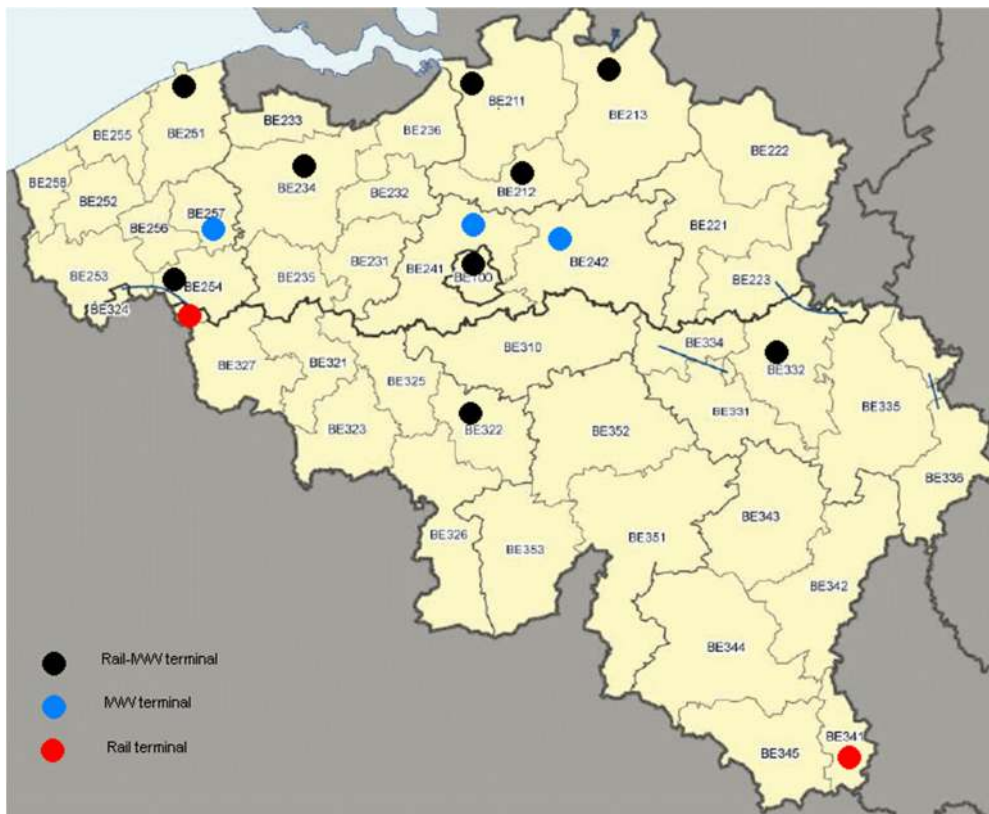
291 maritime ports are also taken into account. The problem is solved on a personal computer (Windows 10 Dual-Core

292 2.5 GHz, 8 GB of RAM) and with CPLEX 12.6.

293 **4. Data of the Belgian case**

294 The model presented above is applied to the Belgian case for analyzing how economic and health objectives
 295 impact the modal split between road and intermodal freight transport. Belgium is chosen for its very dense network
 296 of road, rail and IWW, as well as for its characteristic of being one of the least performant European countries in
 297 terms of air quality (European Commission, 2015b). The strategic location of Belgium at the heart of Europe also
 298 makes it an interesting case regarding flow volumes passing through it. A map of the Belgian terminals and NUTS
 299 3 regions is presented in Fig. 1.

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



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

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

340
 341

342 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

Road and rail network IWW network	Carreira et al. (2012) Promotie Binnenvaart Vlaanderen (2015)	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, 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.

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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

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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

372 diesel traction and 0.1 €cents/t.km for electric traction, considering trains loaded with 500 tonnes of goods. The
 373 diesel-electric traction ratio is 17%-83% (Eurostat, 2016a).

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

376 The already existing terminals in Belgium and in its neighboring countries are considered to be open in the
 377 model. Based on the references described in Table 1, the values given to each operational and external unit cost
 378 are provided in Table 3.
 379

380 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

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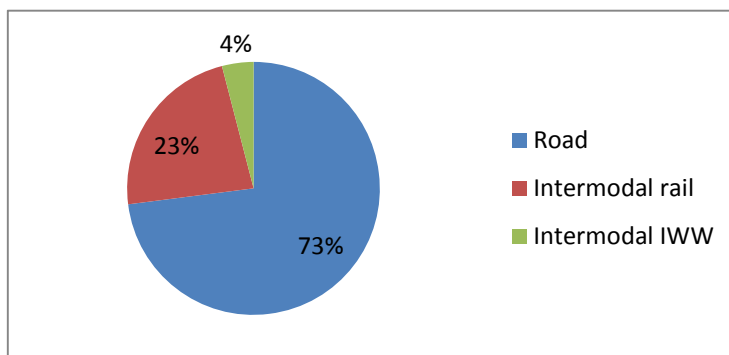
383 5. Findings of the Belgian case

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

391 5.1. Economic optimization

392 When operational costs are minimized, one notices that most of the flows are transported by road (Fig. 2), which
 393 is what currently happens in Belgium and in Europe. The intermodal modal share provided by the model is around
 394 27%. This is 5% lower than the observed rail and IWW market share in 2013 for Belgium and its surrounding
 395 countries (Eurostat, 2016b). Within the intermodal market, and compared to reality, the model underestimates the
 396 IWW share in relation to the rail component. This might be explained in several ways. First, regarding flows, we
 397 only took containerized transport into account. However, a lot of travels performed by IWW are bulk transport.
 398 Moreover, the initial model does not account for the different policies introduced by public authorities.
 399 Nevertheless, the attribution of taxes or subsidies for specific transportation modes impacts the modal choice and
 400 thus influences the general flow distribution (Santos et al., 2015).

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Fig. 2. Flow distribution for operational costs minimization.

425 *5.2. Air pollution optimization*

426 When external costs related to the impact of air pollution on human health are considered to be the objective to
427 minimize, the optimal solution suggests a more intensive use of intermodal transport, to the detriment of road (Fig.
428 3). Market shares of both rail and IWW increase. The predominance of rail is explained by its lower external costs
429 compared to IWW. Nevertheless, this predominance should be balanced, since this model considers a tank-to-
430 wheel approach, and therefore does not reflect the externalities related to the production of electricity for running
431 trains. In practice, this high modal share for rail could be limited by technical issues, such as capacity restrictions
432 of rail lines and terminals. Capacity restrictions on the network may in particular be encountered because of the
433 priority rule of passenger over freight trains. Road transport becomes the second mode of transport. According to
434 the cost data used in the model, a minimization of the human health external costs of transport would, therefore,
435 be achieved with a higher proportion of intermodal than road transport. Similar to the results of Macharis et al.
436 (2010), this shows that taking into account externalities in transportation policies increases the use of intermodal
437 transport.

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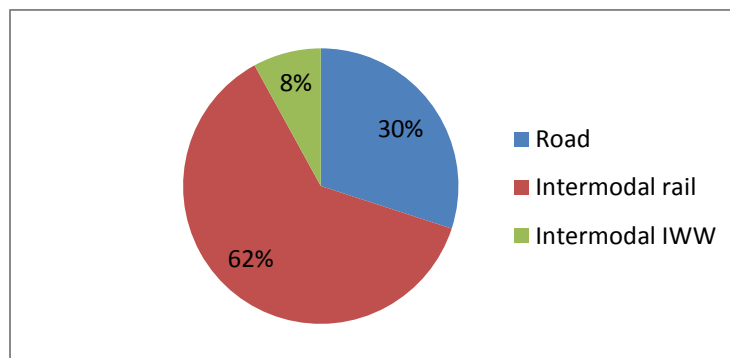


Fig. 3. Flow distribution for air pollution external costs minimization.

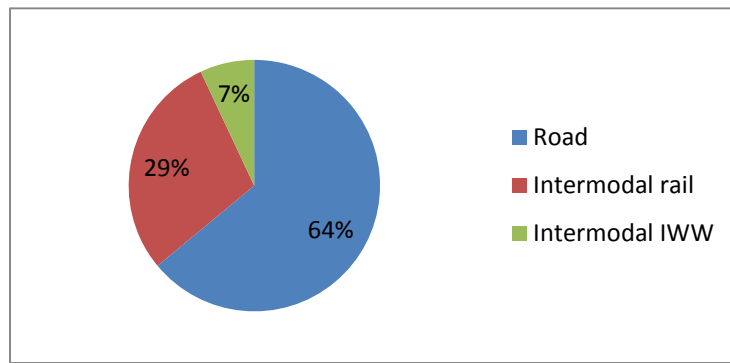
450 *5.3. Economic optimization with taxation system*

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

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

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

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

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

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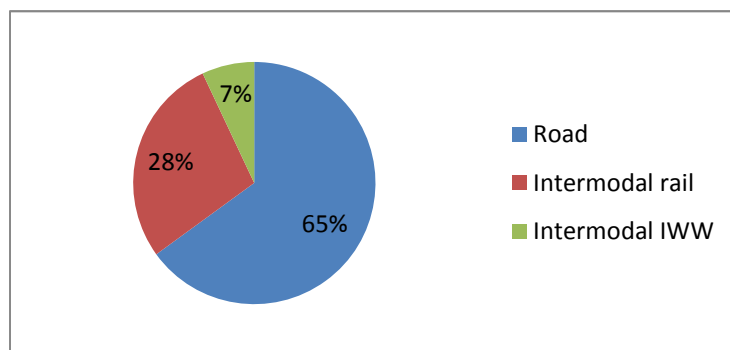
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Fig. 5. Flow distribution for operational costs minimization with Viapass on both long-haul and short-haul travels.

497 5.4. Sensitivity analysis

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

501 5.4.1. Road external costs

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

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

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

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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	

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524 5.4.2. Rail external costs

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

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

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

542 *5.4.3. IWW operational and external costs*

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

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

549 In order to identify how the flow distribution is impacted by the specific costs of IWW in this region, we perform
550 a sensitivity analysis by increasing and decreasing successively the operational and external IWW costs by 10%,
551 20% and 30%. These theoretical variations aim at estimating the flow distribution when the IWW input parameter
552 varies. This helps assess the robustness of the model and also provides information on how results could evolve
553 with other IWW cost values. The flow distribution for these different scenarios is given in Table 6. The first column
554 provides the results of the operational/external cost minimization, whereas the second column shows the results of
555 the external cost minimization when the operational/external IWW costs are modified.

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

563 In terms of operational costs, intermodal IWW transport never exceeds 18% of the market share, remaining the
564 least used mode in most of the scenarios. However, intermodal IWW transport may reach 41% of the market share
565 when external costs are optimized. In this case, intermodal IWW transport is the most used mode in only one out
566 of the seven analyzed scenarios. These results are explained by the lower values of rail air pollution external costs.
567

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

IWW cost value	Modal split of operational cost min. (<i>road-intermodal rail-intermodal IWW in %</i>)	Modal split of air pollution external cost min. (<i>road-intermodal rail-intermodal IWW in %</i>)
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

570 6. Discussion of the Belgian case

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

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

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

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

590 This case shows that road market share seems more sensitive to IWW operational than external costs variations.
591 If policies were focusing on air pollution external costs, rather than on operational costs, decreases of IWW external
592 costs (for instance, resulting from technological improvement) would have a low impact on flow distribution
593 between road and intermodal transport. On the contrary, changes in unit IWW external costs would lead to flow
594 transfers between rail and IWW, within the intermodal market share, rather than between road and intermodal
595 transport. This switch between two intermodal modes is not aligned with the willingness of the European
596 Commission to transfer freight flows from road to other environmentally-friendly transportation means by 2030 et
597 2050 (European Commission, 2011). If an air pollution costs minimization strategy is followed, policy makers
598 should be aware that reducing unit IWW external costs will not contribute to major flow transfers from road to
599 intermodal transport.

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

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

617 **7. Conclusions**

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

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

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

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

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

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

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

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

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

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667 of the authors.
668

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