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Master's Thesis

Assess The Performance of Nation's Freight Transport System Sustainability Using Open-source Data

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22/07/2022

Place, Date

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Abbreviation

EAP	Environment Action Programme
EBD	Environmental burden of disease
EBD	Environmental burden of disease
EC	European Commission
GDP	Gross domestic product
GHG	Greenhouse gases
GWP	Global Warming Potential
HGVs	Heavy goods vehicles
IPCC	Intergovernmental Panel on Climate Change
IWT	Inland waterway transport
JRC	Joint Research Center
LCVs	Light commercial vehicles
MAIS	Maximum Abbreviated Injury Scale
mTKM	Million ton km
RP	Revealed preference
SDGs	Sustainable Development Goals
SP	Stated preference
VSL	Value of statistical life
WCED	The World Commission on Environment and Development
WTA	Willingness to accept
WTP	Willingness to pay
WTT	Well-To-Tank

Abstract

Interest in environmental issues has significantly increased over the past thirty years, positioning sustainability at the top the political agendas of most nations. In parallel, an increase understanding of the weight of transportation on sustainability led more expert to focus on strategies for the monetarization and internalization of external transport costs. While the current literature provides frameworks to estimate the external costs of transport, they require intensive data collection campaigns and analysis, which limit their usage in terms of timing and geographical scope. Through a multilinear regression model, this research proposes six models to exploit open source indicators to estimate each category of external costs. Through the use of the nine independent variables, and the external costs models, the research democratize accessibility to to external costs of transport in a time efficient manner.

Contents

Chapter 1

Introduction

Sustainable development has become the goal that shapes strategies and policies adopted at the international, national, and local levels.

In 1986 the concept of sustainable development was first introduced and defined as "the ability to meet the present needs without compromising the needs of the future generations while considering the environmental limitations" (WCED, 1986). As a response to the UN General Assembly's request to set long-term environmental strategies to face the global environmental challenges (global warming and desertification), the WCED (the World Commission on Environment and Development) publishes the report "Our common future" (Hall et al., 2014) providing the sustainable development definition and framework.

With an increase of interest in the topic, the year 1992 represented another milestone for sustainable development, with the Rio UN Conference on Environmental and Development. The Rio Conference highlighted the three dimensions of sustainable development: economic, environmental, and social (Hall et al., 2014). As an outcome of the Rio conference, the Declaration on Environment and Development (a list of principles to guide governments in sustainable development) was published, and Agenda 21 (a non-binding action plan for UN Organizations and Countries) was created. Although this documents are often considered to be the blueprint of sustainable development, they did not clearly acknowledged the impact of transportation on sustainable development. It was only 20 years later, that transportation was finally considered as an essential element of sustainable development, in Rio+20 (Hall et al., 2014) .

The association between transport and sustainability was further acknowlegded in 2016, when the United Nations Secretary-General's High-level Advisory Group defined sustainable transport as *"the provision of services and infrastructure for people and goods mobility—advancing economic and social development for the benefit of current and future generations—in a safe, affordable, accessible, efficient, and resilient manner, while minimizing carbon and other emissions and environmental impacts"* (United Nations, 2016). Thus sustainable transportation is not perceived as a goal in itself, but rather a means to achieve sustainability.

Even in literature, the concept of transportation sustainability is seen as a paradigm rather than a straightforward application. Two approaches are used in addressing transportation sustainability; the sustainability-centered approach and the transportation-centered approach. The first approach tends to be more holistic, seeing transportation as one of many sectors contributing to sustainable development. This perspective is essential in developing a national framework for sustainable development (Hall et al., 2014). However, the transportation-centered approach is the most commonly observed in the literature. This approach analyses the dynamics of transportation systems and assesses their impact on the three pillars: economic, environmental, and social sustainability (Hall et al., 2014).

Transport is a prerequisite for the proper operation of the modern society, the well-being of people and the economy. At the same time, transportation leads to various external influences, such as air pollution, noise and congestion. Moreover, the construction, maintenance and management of transportation infrastructure results in significant costs. In contrast to the benefits of transportation, these external costs and infrastructure costs are generally not borne by transportation users, without political interference, and therefore are not taken into account when making a transportation decision. By internalizing external and infrastructure costs (i.e. making these costs part of the decision-making process), the efficiency of the transportation system can be increased (Schroten & Scholten, 2019).

This research will focus on freight transport, a critical factor in the economy of any nation, in particular on its economical, environmental and social external costs. In fact, while freight transport is crucial for the growth on national economies, providing connection between customers and producers, determining trade competitiveness and supporting global supply chain integration, it generates external costs that significantly impact the sustainability objectives (UNCTAD, 2017). Freight transport contributes to eight (2, 3, 6, 7, 9, 11, 12, 13) out of the seventeen UN goals for sustainable development for 2030 (UN-Habitat, 2015). Despite freight transport threat on sustainability, freight demand continues to grow putting in question the UN 2030 agenda for sustainable development. Thus, it is crucial for national and international interests that countries shift to more sustainable freight transport (SFT) (UNCTAD, 2017).

In recent years, a political will to internalize external costs have also increased, becoming one of the leading principles of EU transport policy. In fact, the European Parliament called for renewed efforts in the area of internalization and emphasized the need to take steps forward in implementing "polluter pays" and "user pays" principles (Schroten & Scholten, 2019), an approach to restruction the application of transport duties and taxes, presented in the 2011 White Paper on Transport (EEA, 2011).

The increased political interest on assessing transport externalities, have brought the Commission of the European Union (EC) to develop the first Handbook on External Costs of Transport in 2008 and update it in 2014 and 2020. Through a state-of-the-art methodology, the latest Handbook estimates external transport costs for seven categories in 33 countries (EU28, Norway, Switzerland, Canada, US, and Japan). In particular, the total external freight transport costs in EU28 were estimated to be € 203.4 billion in 2016.

The aim of this research is to investigates the possibility of using open-source data to assess a nation sustainable freight transport system. This research will follow a transportation-centered approach, and build on the state-of-the-art methodology of the Handbook on External Costs of Transport (European Commission et al., 2020) to assess the external costs of freight considering each external transport cost category as dependent variable. In particular, analyze the relationship between accidents, air pollution, noise, habitat damage, congestion and climate change (dependent variables) and multiple independent variables. The goal is to define and understand which costs factors (independent variable) that affect more significantly external costs categories.

Chapter 2

Background

2.1. External costs

The external transport costs, as defined by (European Commission et al., 2020), consist of the difference between social and private costs. In other words, external transport costs are all the costs linked to transport that are not borne by the transport users (private costs).

The estimation of external costs of transport is quite challenging due to the absence of their value in the actual market. There are three main approaches highlighted in the literature to estimate external costs: the damage cost approach, the avoidance cost approach and the replacement cost approach. The damage cost approach measures the willingness to accept (WTA) or willingness to pay (WTP) for damages, using stated preference surveys or revealed preference surveys. The avoidance cost approach estimates the costs to achieve a particular policy. Despite being a good approach to measure the uncertain external costs, its target policy orientation makes it less accurate in reflecting individual preferences (European Commission et al., 2020). The replacement cost, as for his name, focuses on the costs of replacement or repair of damages, however its limitation stands on the impossibility to repair or replace certain damages.

External costs of transport can be classified into seven main categories (European Commission et al., 2020):

I. Accident costs
II. Air pollution costs
III. Climate change costs
IV. Noise costs
V. Congestion costs
VI. Habitat damage costs
VII. Well-to-tank emissions costs

This research will deep dive into the literature of each one of the seven categories above, to better understand their definition and the methodology used to monetarize their costs.

Looking at real world data, the overall external freight transport expenditures in the EU28 are estimated to be € 203.4 billion in 2016 (Table1) (European Commission et al., 2020). Congestion costs are the most significant cost category, accounting for 35 percent of overall expenditures, followed by accident cost (21 percent). The remaining 44 percent of total expenditures are accounted for by environmental costs (climate change, air pollution, noise, well-to-tank and habitat damage). However, it is important to notice that the distribution of costs through categories differs significantly across modes of transport (road, rail, IWT).

Table 1: Total external costs 2016 for EU28 freight transport by cost category and transport mode (European Commission et al., 2020)

	Freight Transport						
	Road				Rail		IWT
	LCV-petrol	LCV-diesel	LCV-total	HGV - total	Electric freight	Diesel freight	Inland vessel
Cost category	bn €/a	bn €/a	bn €/a	bn €/a	bn €/a	bn €/a	bn €/a
Accidents	19.8			23.0	0.3		0.1
Air Pollution	0.3	15.2	**15.5**	13.9	0.01	0.7	1.9
Climate	0.7	12.5	**13.2**	9.6	0.00	0.2	0.4
Noise	5.4			9.1	2.1	0.4	-
Congestion	55.5			14.6	-	-	-
Well-to-Tank	0.2	3.6	**3.8**	3.7	0.5	0.1	0.2
Habitat damage	0.2	4.2	**4.4**	3.6	0.8	0.2	0.3
Total	-	-	**117.6**	**77.5**	**5.4**		**2.9**
Total per mode	**195.1**				**5.4**		**2.9**
Total as % of EU28 GDP	**1.31%**				**0.04%**		**0.02%**
Total freight transport	**203.4**						

2.1.1 Accident costs

The definition of the accident external costs is the social costs linked to transport accidents, that are not covered by individuals (e.g., Insurance coverage) (European Commission et al., 2020). The accident costs can be classified into five main categories: 1) human costs; 2) material damages; 3) medical costs; 4) administrative costs; 5) production losses. Human costs (e.g., victim's pain and suffering) are fully included in the external accident costs, instead material damages are fully excluded in external accident costs as internalized through individuals' insurance (European Commission et al. 2020). Moreover, the share of external costs (not covered by individuals) for medical costs, administrative costs, and production losses are 50%, 30%, and 55% respectively.

Furthermore, accidents are also classified by severity: fatality, serious injury, and slight injury. As defined by UNECE, fatality is considered for any immediate death or accident injury led to a death that occurred within 30 days of the accident. On the other hand, serious injury is considered if the injured person needs to be hospitalized for more than 24hrs (UNECE, 2020). It is worth noting that the MAIS3+ scale (Maximum Abbreviated Injury Scale) has been adopted by the EU members since 2014 (European Transport Safety Council et al., 2020), as this scale has more classifications for both severe and slight injuries. Unfortunately, not all the EU countries have the exact definition (European Transport Safety Council et al., 2020). Therefore, it is better to use the old scale in this research.

The number of reported road accidents is underreported, especially for the number of injuries. Therefore correction factors are used in many studies to overcome these unreported cases, based on the finding of a large EU study (HEATCO, 2006), which are 1.25 and 2.0 for serious injury and slight injury, respectively (for LCV and HGV). Despite these data being collected more than 15 years ago, its relevancy is still accurate (European Commission et al., 2020).

In regard to the fatalities, no correction factor is applied to the data, based on a recent Swiss study (ECOPLAN & INFRAS, 2014) highlighting that accident fatalities are no longer unreported in Switzerland. It is also worth noting that reported accidents for other transport modes than road do not need a correction factor (European Commission et al., 2020).

Monitoring each external cost category per casualty type was done in the Handbook (European Commission et al., 2020), as shown in Table 2, based mainly on SafeCube studies. Nonetheless, the human costs were calculated based on the OECD value of statistical life (VSL) for each country in the EU. The VSL calculations consider both the human costs and the future consumption of the person. Thus, to avoid the redundancy of future consumption costs (in both production loss and human costs), the value of future consumption is subtracted from the VSL.

Table 2: External accident cost components per casualty for the EU28 (€2016) (European Commission et al., 2020)

	Human costs (€)	Production loss (€)	Medical costs (€)	Administrative costs (€)	Total external cost per casualty (€)
Fatalities	2,907,921	361,358	2,722	1,909	**3,273,909**
Serious injuries	464,844	24,055	8,380	1,312	**498,591**
Slight injuries	35,757	1,472	721	564	**38,514**

As for the accident cost allocation, each vehicle participating in an accident assigns the opposite vehicle cost of damage. For example: if a car and truck hit each other, and the car driver passed away while the truck driver was injured, the fatality cost is assigned to the truck, while the injury costs are allocated to the car (European Commission et al., 2020).

In 2016, the total freight transport external accident costs reached € 43.1 billion (Table 3). These costs were calculated by multiplying the adjusted number of casualties per vehicle category by the costs per casualties, then allocate the costs to vehicle categories using the accident cost allocation method. The results show that road freight has the dominant share of external accident costs, as rail freight and inland vessel contribute only 1% of the freight accident costs.

Table 3: Total and average external accident costs for land-based modes for the EU28(2016) (European Commission et al., 2020)

Transport mode	Total costs EU28 (Billion €)	Average costs (€-cent per tkm)	Average costs (€-cent per vkm)
LCV	19.8	6.0	4.1
HGV	23.0	1.3	15.5
Total freight road	**42.8**		
Freight train	0.3	0.1	34.1
Inland Vessel	0.1	0.1	86.3
Total freight (road, rail, inland waterway)	**43.1**		

2.1.2 Air pollution costs

Since the 1990s, a wide range of international studies and research initiatives on air pollution costs have been carried out, notably at the European level. In recent years, there have not been many major international studies that include the whole effect route from emission to impact and costs (European Commission et al., 2020). However, epidemiological research has continued investigating the relationship between air pollution exposure and health hazards.

Many different types of damage occur due to transport emissions. The most significant damages identified are the following: (1) Health effects; (2) Crop losses; (3) Material and building damage and (4)

Biodiversity loss (Friedrich & Quinet, 2013). Thus monetizing these monetizing these damages is critical to assess air pollution costs, and consequently the sustainability of the freight sector.

The Priority impact pathway is an approach used to identify which pollutant is causing more damages. This approach focuses on the primary pollutant in each category, and is commonly given the existing complexity in modeling the impact of every (Friedrich & Quinet, 2013). The primary air pollutants impact health are $PM_{2.5}$, PM_{10}, and NO_x, where those pollutants directly correlate with cardiovascular and respiratory diseases. Regarding crop losses, O3 and SO2 lead to lowering crop yields. As for material and building damage, acidic substances (NOx or SO2) cause building corrosion. Also, acidic substances damage the ecosystems (e.g. soil acidification), leading to a biodiversity decrease (European Commission et al., 2020).

To calculate the total emission costs, a bottom-up approach is used (European Commission et al., 2020) which incorporates for each country three input values:

I. Emissions factors (t/veh-km): the COPERT database is used to collect the emissions factors per vehicle type
II. Transport performance (veh-km): the database of Eurostat is used to collect the number of vehicle km per EU country.
III. Cost factors for both health and non-health (€/t)

Road freight is the primary source of freight transport pollution costs, similarly to accident costs, reaching € 29.42 billion (Table 4). On the other hand, inland vessel contributes much more than rail freight, compared to accident costs. The total cost per country calculated by multiplying the emission factors by the transport performance, and then multiply the outcome by the cost factor for both health and non-health.

Table 4: Total and average air pollution costs for land-based modes for the EU28 (2016) (European Commission et al., 2020)

Transport mode	Total costs EU28 (Billion €)	Average costs (€-cent per tkm)	Average costs (€-cent per vkm)
LCV	15.49	4.68	3.24
HGV	13.93	0.76	9.38
Total freight road	**29.42**		
Freight train electric	0.01	0.004	2.14
Freight train diesel	0.66	0.68	305.39
Total freight rail	**0.67**		
Inland Vessel	1.93	1.29	1,869
Total freight (road, rail, inland waterway)	**32.02**		

2.1.3 Climate change costs

All transport modes emit greenhouse gases (GHG) (e.g., CO_2, N_2O, and CH_4), which contribute significantly to climate change. Thus it is essential to estimate the costs of climate change (Friedrich & Quinet, 2013). Climate change costs arise from the effects of global warming, such as crop failure, issues in water management, biodiversity loss, and sea-level rise (European Commission et al., 2020). Hence estimating the costs of such long-term impacts on the ecosystem, human health, and society is extremely complex.

Due to the complexity of estimating climate change costs, the assumption that the three primary GHGs (CO_2, N_2O, and CH_4) emitted by transport modes significantly impact global warming is commonly used (European Commission et al., 2020). Furthermore, Global Warming Potentials (GWP) approach can be used to convert the two non-CO_2 emissions to total CO_2 emissions due to the difference in the lifetime and potency of each gas (European Commission et al., 2020). The GWP compares over a specific period (100 years) the heat trapped by a certain mass of N_2O and CH_4 to its equivalent of heat trapped by CO2.

The inputs used to calculate the climate change costs are the following (European Commission et al. 2020):

I. GHG emissions (CO_2, N_2O, and CH_4) per vehicle type (t/veh-km): the data sources are COPERT database v5 for Road freight, TREMOD for rail, and EcoTransit World database for Inland waterways.
II. GWP of GHG emissions: the equivalent measures of N2O and CH4 are 34 and 298, respectively, over 100 years. Based on the IPCC report (IPCC, 2013).
III. Climate change costs per tonne of CO2 equivalent: short-medium term cost (2030) is 100 €/tCO2, and the long-term cost (2060) is 269 €/tCO2.

The EC Handbook (European Commission et al., 2020) also proposes the avoidance cost approach instead of the damage cost approach. The difference between the two approaches is that the first one is centralized around the costs of achieving a specific policy; however, the damage approach sums up the values of each individual affected by climate change. The major criticism against the damage cost approach is the uncertainty in estimating the actual cost of climate change, especially in extreme events (as all the climate damages need to be acknowledged and quantified). A meta-analysis done by Tol (Tol, 2008) on 211 studies highlighted the enormous variance in estimating the climate damage costs from 1 €/tCO2 to 500 €/tCO2. On the other hand, the avoidance cost approach has less variance in the literature (European Commission et al., 2020). It is important to note that the avoidance cost approach is highly sensitive to the target. Thus EC Handbook (European Commission et al., 2020) used the 2016 Paris agreement target. The target is less than a 2 degrees Celsius increase in the world temperature by 2050, equivalent to 450 ppm (parts per million) CO2 in the atmosphere.

The total EU28 climate change freight costs in 2016 reached € 23.43 billion (Table 5). Total cost of climate change in each country is calculated by firstly, converting greenhouse gas emissions (carbon dioxide, nitrous oxide and methane) for each type of vehicle (tons/km) into GWP, then multiplying the result by the vehicle's performance for each type of vehicle. Further, multiply the output by the cost factor of 100 euros per ton of CO2 equivalent.

Table 5: Total and average climate change costs for land-based modes for the EU28 (2016) (European Commission et al., 2020)

Transport mode	Total costs EU28 (Billion €)	Average costs (€-cent per tkm)	Average costs (€-cent per vkm)
LCV	13.17	3.98	2.75
HGV	9.63	0.53	6.48
Total freight road	**22.79**		
Freight train electric	0	0	0
Freight train diesel	0.24	0.25	112.4
Total freight rail	**0.24**		
Inland Vessel	0.40	0.27	383.1
Total freight (road, rail, inland waterway)	**23.43**		

2.1.4 Noise costs

Noise emission is a growing environmental problem due to the growth in traffic volumes and urbanization. According to the WHO, traffic noise is the second most important cause of illness in west Europe; it is an underestimated threat to human health (WHO and JRC 2011). EEA estimated that around 12,000 premature death occurs as well as 48,000 new cases of ischemic heart disease (EEA 2020) are caused every year in Europe, by noise pollution.

A prominent characteristic of noise pollution is the nonlinearity in sound perception from different sources and during different times. The noises that occur during the evening or night are considered more nuisance than day noise (Friedrich & Quinet, 2013). Thus many studies used L_{den} to normalize the noise level by penalizing both evening and nighttime noise by adding an additional 5 and 10 dB(A), respectively(L_{den} — European Environment Agency n.d.).

Regarding the different perceptions of the same noise level from different sources (e.g., rail and road), it is quite debatable in the literature. Some studies use rail bouns, which is a discount of 5dB(A) for the rail noise compared to road noise, assuming that the rail noise has less nuisance than road noise(International Union of Railways, 2010). On the other hand, many studies are not including the rial bouns anymore, including the EC Handbook. New studies show that rail noise annoyance is higher than the road (Guski et al., 2017) (Elmenhorst et al., 2014).

Noise threshold identification substantially influences its marginal costs. Three thresholds are used in literature to identify the sound as a nuisance (50, 55, 60 dB(A)). The 7th EAP (Environment Action Programme) identified the noise level at 55 dB L_{den} (European Commission & Directorate-General for Environment, 2014). However, the EC Handbook (European Commission et al., 2020) used a 50 dB(A) threshold, as it is the least likely threshold to underestimate the noise cost.

Health and annoyance are the two main impacts considered in assessing the noise costs. There are three main approaches used in the literature to estimate the annoyance costs (€/dB/person). First revealed preference (RP) mainly uses hedonic price (Friedrich & Quinet, 2013). Secondly, stated preference (SP) uses two techniques stated choice and the contingent valuation method (Bristow et al., 2015). The third is the environmental burden of disease (EBD). The EC Handbook followed the SP approach in calculating the annoyance costs of noise.

According to the WHO, transport noises could lead to ischaemic heart disease, stroke, diabetes, obesity, hypertension, hearing impairment, and sleep disturbance (WHO, 2018). Unfortunately, there is an absence of a study that fully addresses all the noise health effects listed by the WHO (European Commission et al., 2020). Thus EC Handbook used the noise health costs values from a study conducted by the British Department for Environment, Food and Rural Affairs (Defra, 2014). Even though the Defra study did not consider the costs of diabetes and obesity, it is by far the most aligned study with the WHO recommendations. Table 6 shows the annual noise costs per person for each dB level.

Table 6: Environmental price of traffic noise for the EU28 (€2016/dB/person/year) (European Commission et al., 2020)

Lden (db(A))	Road transport			Rail transport		
	Annoyance	**Health**	**Total**	**Annoyance**	**Health**	**Total**
50-54	14	3	17	14	3	17
55–59	28	3	31	28	4	32
60–64	28	6	34	28	6	34
65–69	54	9	63	54	9	63
70–74	54	13	67	54	13	67
≥ 75	54	18	72	54	18	72

The inputs used by the EC Handbook (European Commission et al. 2020) to calculate the noise costs are the following:

I. Yearly affected people by noise per transport mode per country: as mentioned above, the noise threshold used was 50 dB(A).
II. The weighted factor for each vehicle type: HGV has more nuisance noise than LCV.
III. Noise costs per person exposed: as shown in Table 6, the costs are classified to cost of health and cost of annoyance.

The total EU28 noise freight costs in 2016 reached €17.1 - billion (Table 7). The methodology used in calculating the noise external cost is: multiplying the number of people exposed to a certain noise level by the price of both health and annoyance. Then applying the weighted factor for each vehicle type.

Table 7: Total and average noise costs for land-based modes for the EU28 (2016) (European Commission et al., 2020)

Transport mode	Total costs EU28 (Billion €)	Average costs (€-cent per tkm)	Average costs (€-cent per vkm)
LCV	5.4	1.6	1.1
HGV	9.1	0.7	5.85
Total freight road	**14.5**		
Freight train electric	2.1	0.6	359
Freight train diesel	0.4	0.4	201
Total freight rail	**2.5**		
Inland Vessel	-	-	-
Total freight (road, rail)	**17.1**		

2.1.5 Congestion costs

Road congestion is defined as the impedance vehicles impose on one another as traffic flow approaches the network's maximum capacity. Congestion costs arise when an additional vehicle slows other vehicles in the flow, causing an increase in travel time. The cost of road congestion is estimated using the speed-to-flow relationship and the value of travel time. The average travel time is not the only component affected by congestion; travel time reliability is also affected. However, it is not considered in many studies due to the lack of information (Friedrich & Quinet, 2013).

Other modes of transportation, such as rail, increase in travel time are not considered an indicator of congestion. Because they mainly provide scheduled services and are planned based on the allocative capacity of networks and nodes. Instead, three other indicators are more significant—first, timetable changes; second, increases in the unreliability of timetable scheduling (which occurs during high congestion); third, the lack of infrastructure may preclude the provision of some profitable services (Friedrich & Quinet, 2013). Due to the complexity of assessing the cost of rail congestion, EC Handbook did not consider it. As for the congestion cost on the inland waterway, a study by the Joint Research Center (JRC) of the EC (Christidis & Brons, 2016) indicates that this cost can be assumed to be negligible. Based on this finding, the EC handbook did not consider the congestion cost on the inland vessels.

There are four main approaches to estimate road congestion costs (as shown in Figure 1); 1) delay costs; 2) the sum of marginal costs; 3) the sum of marginal costs above the optimum point; 4) deadweight loss costs (Cambridge Econometrics et al., 2020). The total delay cost is the total increased travel time above the free-flow state. The sum of marginal costs, also known as the gross external congestion costs, is the summation of all costs generated by all marginal vehicles entering the traffic. The third approach is a variation of the second one, where only the marginal costs above the optimal marginal cost point are considered. The last approach (deadweight loss) is a societal cost caused by market inefficiencies, which arises when supply and demand are not balanced. Methods 3 and 4 consider the notion that even when there is congestion, there is an optimal flow that is greater than the free-flow scenario (Cambridge Econometrics et al., 2020). Thus the deadweight loss costs is significantly lower than delay cost.

Figure 1: Road congestion depending on network conditions (Cambridge Econometrics et al., 2020)

In Figure 1, the SMC(q) is the social marginal cost function. The SMC(q) is calculated by adding the average travel cost incurred by road users AC(q) and the cost of the increased travel time caused by the marginal vehicle, which decreases the speed of all other vehicles. As for D(q), it is an inverse function representing the demand for a road link. Method 1 represents delay costs; method 2 represents the sum of marginal costs; method 3 represents the sum of marginal costs above the optimum point; method 4 represents the deadweight loss costs.

The approach used by the EC handbook was the delay cost approach. In order to calculate the congestion costs, the following inputs were used by the EC handbook:

I. Speed-flow functions
II. Demand curve $D(q)$
III. Value of time
IV. Vehicle load factor
V. The population of EU cities
VI. TomTom traffic index as a source for the level of congestion of roads

The total EU28 congestion freight costs in 2016 reached €62.3 - billion (Table 8).

Table 8: Total congestion costs borne by road freight in the EU28 (European Commission et al., 2020)

Transport mode	Total costs EU28 (Billion €)	Average costs (€-cent per tkm)	Average costs (€-cent per vkm)
LCV	38.5	11.63	8.05
HGV	23.8	1.30	17.72
Total freight road	**62.3**		

2.1.6 Habitat damage costs

Transport has different negative effects on nature, landscape and natural habitats, which can be summarized in three categories of habitat damages: loss, fragmentation or degradation (European Commission et al. 2020).

Habitat loss occurs typically at the time of transport infrastructure creation, as the latter requires the use of land or natural surfaces, which are natural habitats for animals, insects and plants. Although habitat loss damages happen at one time, their harmful consequences on biodiversity continue to last with the existence of the infrastructure (European Commission et al. 2020).

Habitat fragmentation refers to the disruption and separation of species (animals or insects) from their habitat. Similarly, to habitat loss it occurs at the time of infrastructure creation, but in addition it also continues with usage of transport over time. An example of fragmentation could be the creation of a railway and its consequences overtime on wildlife animals such as rabbits, wolves, etc. on their natural life environment (European Commission et al. 2020).

Habitat degradation refers to the negative effects of air pollutants caused by transport emissions. Pollutants and toxic substances can be harmful on the natural ecosystem and cause losses of biodiversity (European Commission et al. 2020).

Table 9: Cost factors for costs of habitat damage EU28 (European Commission et al., 2020)

	Road €/(km *a)		Rail €/(km*a)		Inland waterways €/(km*a)
	Motorways	Other roads	High-speed	Other railways	
Habitat loss	78,900	1,900	57,500	8,200	6,600
Habitat fragmentation	14,600	2,200	27,000	5,900	0
Total habitat damage	93,500	4,100	84,500	14,100	6,600

In the above table, costs factors for habitat loss and habitat fragmentation were estimated for the EU28. The study computed habitat loss and fragmentation costs for Switzerland (Bieler et al., 2019), and then applied it to the whole EU transport infrastructure. The approach used raises questions about the representativeness of the data and the validity of scaling up to European level, since local and natural habitat characteristics are likely to be very different depending on country and region. (Cambridge Econometrics et al., 2020)

The total EU28 noise freight costs in 2016 reached €9.3 - billion (Table 10). The road freight has the dormancy with share rate 86%. However, the average cost/tkm of HGV is the least across all the modes.

Table 10: Total and average habitat damage costs for land-based modes for the EU28 (2016) (European Commission et al., 2020)

Transport mode	Total costs EU28 (Billion €)	Average costs (€-cent per tkm)	Average costs (€-cent per vkm)
LCV	4.4	1.35	0.9
HGV	3.6	0.19	2.4
Total freight road	**8.0**		
Freight train electric	0.8	0.24	134
Freight train diesel	0.2	0.25	111
Total freight rail	**1**		
Inland Vessel	0.3	0.2	2.9
Total freight (road, rail, inland waterway)	**9.3**		

2.1.7 Well-to-tank emissions costss

The Well-To-Tank (WTT) emission cost encompass all emission costs (diffusion of air pollutants, greenhouse gases and other toxic substances) that derives from the production of energy sources (European Commission et al. 2020).

Energy production processes leading to emission:

- Extraction of energy sources,
- Processing of the energy
- Transport and transmission,
- Built of energy plants (or other infrastructure needed)

Well-To-Tank emission costs are an important part of the total external costs. These costs are specifically non-negligible for electricity driven transport modes, since the energy use for transportation is virtually emission-free (European Commission et al. 2020).

2.2. Infrastructure costs

The costs of road, rail and inland waterway infrastructure in the EU28 in 2016 amounted to €267 billion (European Commission, Directorate-General for Mobility and Transport, Wijngaarden, et al., 2019), including the financial and direct expenses. Road infrastructure has the highest share with 69% (184 billion euros), then railways with 30% (81 billion euros) and IWT with 1% share (3 billion euros) (European Commission, Directorate-General for Mobility and Transport, Wijngaarden, et al., 2019). However, the share of heavy goods vehicles (HGVs) does not exceed 23% (42 billion euros) of total road infrastructure costs. Similarly, rail freight (electricity and diesel) contributes only 7% (€6 billion) to rail infrastructure costs.

Across inland freight modes, rail freight has the highest average infrastructure cost of 3.1 €/tkm (Table 11). This higher cost is mainly derived from higher fixed costs for railways. On the other hand, there is a significantly lower difference between the marginal infrastructure costs of railways and roads compared to the difference in the average infrastructure cost. The reason behind this is that the impact of a high fixed cost of railways is relatively low on marginal railway infrastructure costs, in contrast to the average cost (European Commission, Directorate-General for Mobility and Transport, Wijngaarden, et al., 2019).

Table 11: Infrastructure costs in the EU28 in 2016 (European Commission, Directorate-General for Mobility and Transport, Wijngaarden, et al., 2019)

Vehicle category	Total infrastructure costs (Billion €)	Average infrastructure costs (€-cent/tkm)	Marginal infrastructure costs (€-cent/tkm)
Light commercial Vehicle	20	4.1*	0.3*
Heavy Goods Vehicle	42	2.3	0.7
Electric freight train	9	3	0.6
Diesel freight train	3	3.2	0.6
IWT vessel	3	1.9	0.1

2.3. Transport taxes and charges

The European Commission has estimated total revenue from transport taxes and fees (in the EU 28) for 2016 at approximately €370 billion (European Commission, Directorate-General for Mobility and Transport, Wijngaarden, et al., 2019). This value includes all directly related taxes/fees (toll, registration, purchasing, and energy taxes). The share HGVs, electric freight trains, diesel freight trains, and IWT vessels are 9%, 0.5%, 0.3%, and 0.1%, respectively, of the total transport tax revenue, with passenger cars contributing the largest share (81%).

The sector's revenues from taxes and fees partially cover the infrastructure cost (direct and indirect). The cost-revenue ratio for all modes did not exceed 26%, except for small-volume vehicles, which amounted to 43% (Table 12). These lower ratios reveal the burden of each mode due to its restrictions on taxes and fees, especially for IWT vessels, which is 6% (European Commission, Directorate-General for Mobility and Transport, Wijngaarden, et al., 2019). Although the diesel freight train has a significantly low revenue tax (Table 12), it has a relatively high average tax revenue (1.5 €-cent/tkm) due to its higher energy (diesel) taxes.

Table 12: Tax/charge revenues in the EU28 in 2016 (European Commission, Directorate-General for Mobility and Transport, Wijngaarden, et al., 2019)

Vehicle category	Total tax/charge revenues (Billion €)	Average tax/charge revenues (€-cent/tkm)	Overall cost coverage
Light commercial Vehicle	35	7.3*	43%
Heavy Goods Vehicle	33	1.5	26%
Electric freight train	2	0.5	12%
Diesel freight train	1	1.3	26%

* Unit: €-cent/vkm

IWT vessel	0.4	0.3	6%

* Unit: €-cent/vkm

2.4. Sustainable freight transport VS UN sustainable development goals

World leaders met in New York in 2015 to approve the 2030 Agenda for Sustainable Development, which includes 17 SDGs that call for bold, ambitious action for the well-being of people and the planet and outline the path to a sustainable future. While there is no particular SDG for transportation, it is represented in multiple SDG objectives and is considered an enabler and a necessary condition for many SDGs to be met. The SDGs thus provide critical building blocks, such as resilient infrastructure development, energy efficiency, global access to safe, cheap, and sustainable transportation systems, health promotion, road safety, and climate change mitigation (United Nations, 2021).

Freight transport contributes directly and indirectly to eight of the seventeen SDGs (UNCTAD, 2017). Goals 3, 7, 9, 11, and 12 are directly influenced by freight transport. The third goal, which strives to ensure healthy lives and promote well-being for all people of all ages, is directly impacted by freight improvement on safety and reducing air pollution. Every year, a road accident kills an estimated 1.24 million people worldwide. For every fatality, ten individuals are severely injured (UN-Habitat, 2015). In order to achieve the seventh goal (Ensure affordable, reliable, sustainable, and modern energy for all), economic development must be decoupled from energy use and emissions. Different actions could be done to enhance transport energy efficiency, such as improving road conditions, supplying high-quality fuels, encouraging eco-driving, improving vehicle technology, and promoting electric cars (UN-Habitat, 2015).

The SDG's ninth target is to construct resilient infrastructure. Resilient transportation improves social and economic resilience while addressing security and emergency response requirements. Severe disruptions in transportation infrastructure can have disastrous consequences for the community, businesses, and economic capacity to plan for and recover from a disaster (UN-Habitat, 2015). In order to achieve a sustainable consumption and production pattern (goal 12), apply more green technologies, remove fuel subsidies and enhance rural transport infrastructure. The lack of dependable rural transportation services has been frequently blamed for food harvests not reaching the market and farmers' inability to boost food production for the market (UN-Habitat, 2015).

Freight transport indirectly impacts Goals 2, 6, and 13. The second SDG objective (eradicate hunger and ensure food security). Logistics improvements can help control food price risks, shocks, and instabilities. Also, efficient transport infrastructure, especially in rural areas, could improve access to water and sanitation facilities (goal 6). The SDGs thirteen goal is to take immediate action to address climate change and its consequences. Sustainable transportation alternatives, such as electric vehicles and cleaner and more efficient internal combustion engine vehicles, must be considered to meet this goal. Furthermore, greening vehicle manufacturing and infrastructure building can aid in lowering GHG emissions from the transportation industry (UN-Habitat, 2015).

Chapter 3

Methodology

3.1. Geographical scope

This analysis includes 27 countries: Norway, the United Kingdom, Switzerland, and the 27 European Union countries (excluding Belgium, Malta, and Cyprus). The diversity among the countries included in the analysis (e.g., country size, population, GDP, quality of infrastructure) overcomes the small sample size problem. The reasons behind the exclusion of Malta and Cyprus are the lack of data. For Belgium, many independent variables reported in the databases were outdated (until 2010).

3.2. Data Preparation

Two sets of data are used in this analysis: the cost of external freight (Appendix) and the indicators that affect the transportation of goods, whether economic, social, or environmental. The total number of indicators gathered from multiple sources was 187. Eurostat database was the primary source (108 indicators) in the data gathering process, using a library in R-software called 'eurostat'. The world bank database was used to gather the logistics performance index (LPI). For infrastructure costs for each mode of transport, the EC study (European Commission, Directorate-General for Mobility and Transport, Monden, et al., 2019) was used. Other sources, such as OCED, IFT(International Transport Forum), and UNstats databases, were also used.

The first set of data (freight external costs) was extracted from the annex of the EC handbook (European Commission et al., 2020). Thus, the base year of this analysis is 2016, as this year was the base year of the EC handbook. Consequently, all the indicators used were for the year 2016.

All the data, including the dependent variables, were normalized by the country's area (1000km^2) as this research seeks to assess the relationship between independent and dependent variables. Norm values allow the corresponding norm values to be compared for different data sets in a way that eliminates the effects of some aggregate effects. It is worth noting that the scalable indicators (e.g., mode share %, Infrastructure scoring, GDP/capita) were not normalized by the area.

3.3. Modeling

This research attempted to identify the independent variables that contribute the most to each freight external cost by applying a multiple linear regression for each external cost category. The process of selecting the independent variable was iteratively carried out by evaluating the outcome model by four main criteria as described below:

I. Assess the model significance
II. Evaluate the impact of each independent variable on the dependent variable while accounting for the impact of all other independent variables
III. Evaluate the normal distribution of the model
IV. Evaluate the correlation between all the independent variables used in each model as well as the dependent variable too

Three main aspects assess the significance of the model: first, the model adjusted R^2; second, the significance of each independent variable (less than 0.05); third, the coefficient sign of each independent variable. The literature cited in Chapter Two was used to validate each parameter coefficient sign.

The add-variable plot (also known as a partial regression plot) was used to evaluate each independent variable's impact while accounting for other independent variables. The plot shows whether the candidate predictor decreases the residual variability of the model. By plotting the residuals of two regression models, the first one is the complete model omitting the candidate predictor. For the second model, the candidate predictor acts as the dependent variable for the other dependent variables (Gallup, 2019).

QQ-plot was used to address the normal distribution assumptions of the regression model. The QQ-Plot sorts the z-scores from low to high and depicts the z-score of each value on the y-axis; the x-axis represents the equivalent quantile of a normal distribution for that value's rank. The sample distribution tends to be more normally distributed if the points lie closely on the diagonal line (Bruce & Gedeck, 2020). The Pearson correlation coefficient is used to calculate the correlation matrix between all variables (including depending and independent).

Chapter 4

Results

The results will be presented in six sections, each one highlighting a model for a specific external cost category. The reader will find four figures in each section, presenting the four assessment criteria (explained in chapter three).

Table 13 shows the nine independent variables used to estimate the freight external cost models. The arrows in the table indicate which variables were used in calculating each freight external cost model and the sign of influence. The red arrow indicates a positive correlation. On the other hand, the green one indicates a negative correlation. The model outcome clarifies that the most significant indicators (used in estimating the external costs) are goods transport/mode/km and the infrastructure cost/mode (including investment, operation, and maintenance costs). It is worth noting that all independent and dependent variables were normalized by the country area except the GDP per capita indicator.

The results show that road freight is the major cause of increasing external freight costs. In contrast, rail freight has a negative correlation with external costs. This relation emphasizes that a shift in rail freight from the road will decrease the external cost, not eliminate it (as the rail has external cost too)—likewise, the inland water transport.

Table 13: Independent variables used in each freight external costs model

	Freight External Costs	Road mTkm	Road Infrastructure Costs	Road freight Infrastructure Costs	Rail mTkm	Rail Freight Infrastructure Costs	In land water mTkm	Motorway Operation & Maintenance Costs	GDP per capita	In land water Infrastructure Costs
1	Accidents	⬆	⬆			⬇				
2	Air Pollution	⬆	⬆		⬇		⬇			
3	Climate Change	⬆	⬆		⬇					
4	Noise	⬆						⬆	⬆	
5	Congestion	⬆			⬇				⬆	
6	Habitat			⬆		⬇				⬇

4.1. Accident costs

Multiple linear regression was developed to analyze the main independent variables impacting external accident costs of freight (Figure 2). A significant regression equation was found with an R^2 of 0.87, where three independent variables significantly influence the accident cost. Those independent variables are 1) annual million-ton km of goods transported by road per 1000km^2 (Road_mTKM); 2) Total infrastructure cost of the road (Million €) per 1000km^2; 3) Total infrastructure cost of the rail (Million €) per 1000km2.

The model shows a positive correlation between the accident costs and both road ton-km and road infrastructure costs; this result is aligned with Table 3, which shows road freight as the dominancy of the accident cost. On the other side, the more investment in rail, the less accident cost occurs. This is reflected in the model's negative correlation between the rail infrastructure cost and the dependent variable.

The added-variable plot (Figure 3) shows that the three independent variables contribute to decreasing residual variability of the model. As for the model distribution, Figure 4 (QQ-plot) shows a sort of normality in the sample distribution. Nevertheless, the correlation matrix (Figure 5) shows a slight high correlation between independent variables.

```
lm(formula = TotalFreight_Accident_Externalcosts ~ Road_mTKM +
    `Infra_Cost_Total_Road_(m)` + `Infra_Cost_Total_Rail-Freight_(m)`,
    data = Acc_cost_1)

Residuals:
       Min         1Q     Median         3Q        Max
-0.0041630 -0.0021386 -0.0006848  0.0011394  0.0111746

Coefficients:
                                      Estimate Std. Error t value Pr(>|t|)
(Intercept)                          7.155e-04  1.038e-03   0.689  0.49770
Road_mTKM                            4.606e-06  1.582e-06   2.911  0.00787 **
`Infra_Cost_Total_Road_(m)`          1.811e-04  2.023e-05   8.953  5.9e-09 ***
`Infra_Cost_Total_Rail-Freight_(m)` -6.253e-04  2.261e-04  -2.766  0.01101 *
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 0.003501 on 23 degrees of freedom
Multiple R-squared:  0.8859,    Adjusted R-squared:  0.8711
F-statistic: 59.55 on 3 and 23 DF,  p-value: 5.364e-11
```

Figure 2: External freight accident costs model results

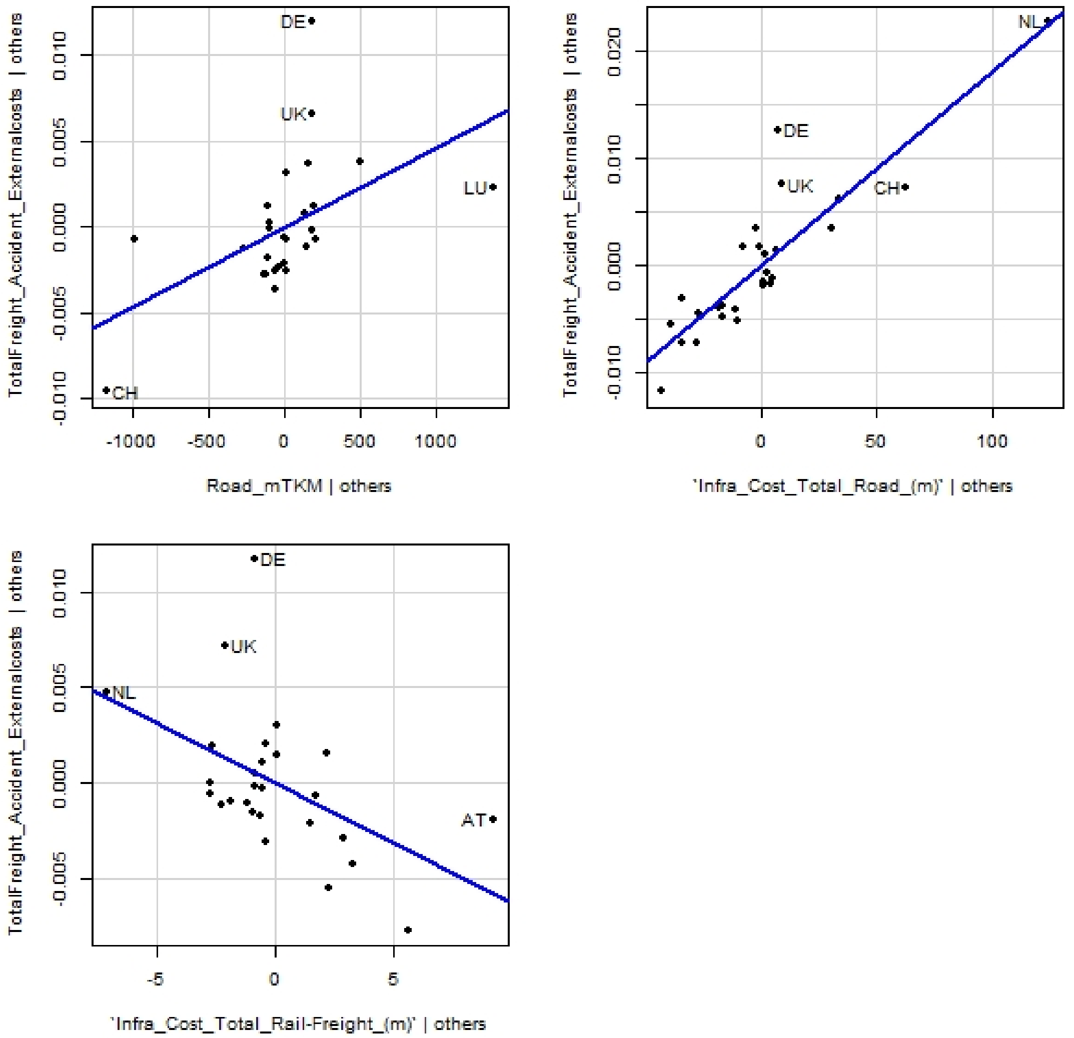

Figure 3: External freight accident costs added-variable residual plot

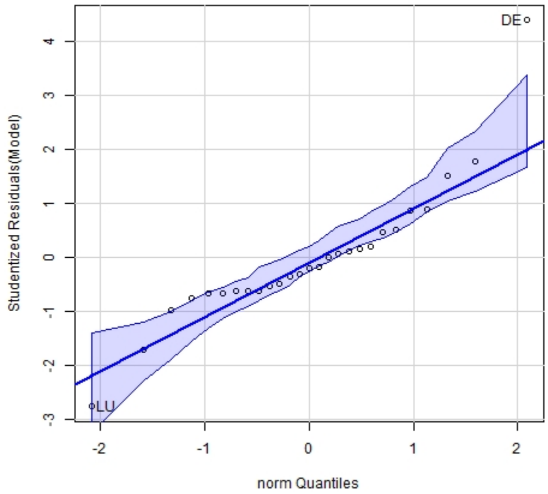

Figure 4: Accident model QQ-plot

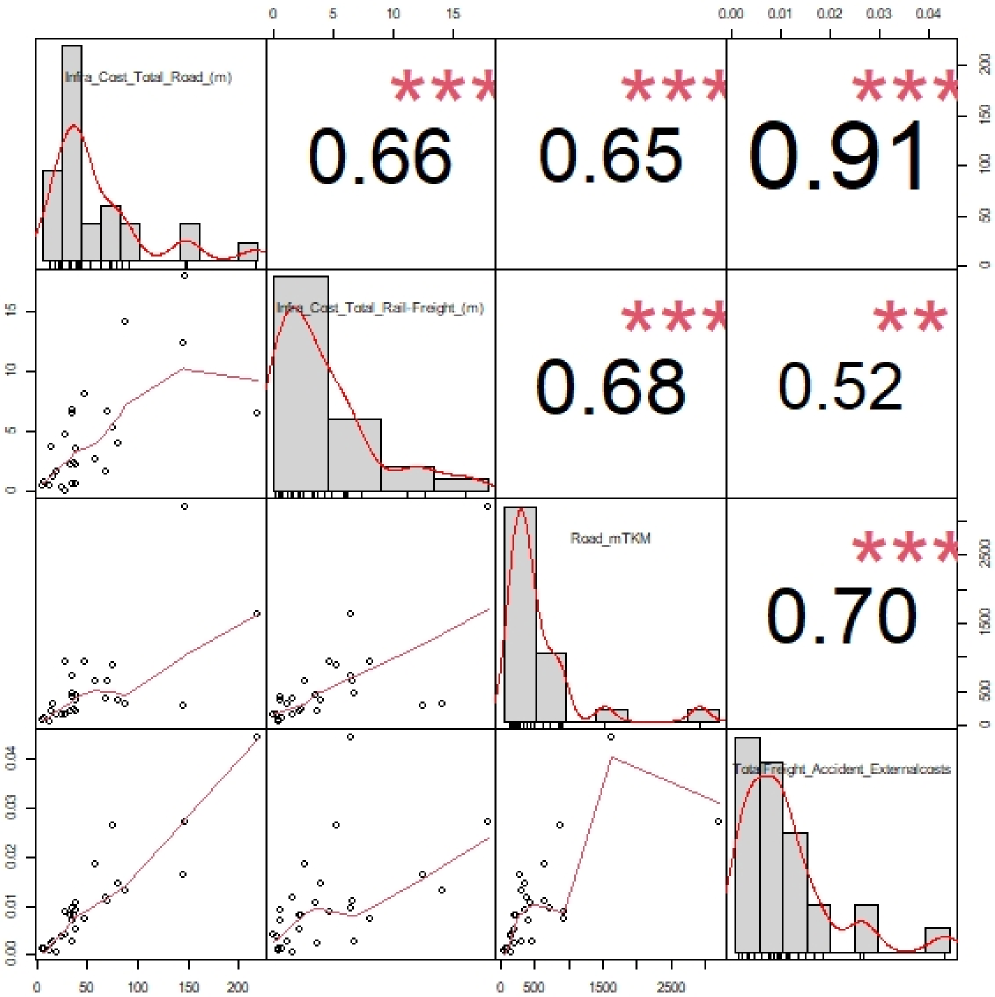

Figure 5: Correlation matrix of accident costs and independent variables

4.2. Air pollution costs

Multiple linear regression was developed to analyze the main independent variables impacting external air pollution costs of freight (Figure 6). A significant regression equation was found with an adjusted R^2 of 0.87, where four independent variables significantly influence the air pollution cost. Those independent variables are 1) annual million-ton km of goods transported by road per 1000km^2 (Road_mTKM); 2) annual million-ton km of goods transported by rail per 1000km^2 (Rail_mTKM); 3) annual million-ton km of goods transported by IWT per 1000km^2 (Inlandwater_mTKM); 4) Total infrastructure cost of the road (Million €) per 1000km^2.

The model shows a positive correlation between air pollution costs and both ton-km road transport and road infrastructure costs. This result is consistent with Table 4, which indicates that the share of air pollution among the three modes of inland transport is 92%, 2% and 6% for road freight, rail freight and IWT. In addition, Table 4 shows that the average air pollution cost/tkm of IWT is higher than diesel freight rail, which is reflected in this model as IWT has a higher coefficient than rail tkm.

The added-variable plot (Figure 7) shows that the four independent variables contribute to decreasing residual variability of the model. As for the model distribution, Figure 8 (QQ-plot) shows normality in the sample distribution (except for Luxembourg and Austria). Nevertheless, the correlation matrix (Figure 9) shows a slight high correlation between IWT tkm and road infrastructure costs.

```
lm(formula = TotalFreight_AirPollution_Externalcosts ~ Road_mTKM +
    Rail_mTKM + InlandWater_mTKM + `Infra_Cost_Total_Road_(m)`,
    data = Poll_cost_1)

Residuals:
       Min         1Q     Median         3Q        Max 
-0.0212850 -0.0067833 -0.0001454  0.0058762  0.0287514 

Coefficients:
                              Estimate Std. Error t value Pr(>|t|)    
(Intercept)                 -1.059e-02  4.048e-03  -2.616  0.01577 *  
Road_mTKM                    4.466e-05  4.791e-06   9.321 4.27e-09 ***
Rail_mTKM                   -6.066e-05  2.697e-05  -2.249  0.03486 *  
InlandWater_mTKM            -5.150e-05  1.450e-05  -3.553  0.00178 ** 
`Infra_Cost_Total_Road_(m)`  2.103e-04  8.623e-05   2.439  0.02325 *  
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 0.01162 on 22 degrees of freedom
Multiple R-squared:  0.8909,	Adjusted R-squared:  0.8711 
F-statistic: 44.91 on 4 and 22 DF,  p-value: 2.818e-10
```

Figure 6: External freight air pollution costs model results

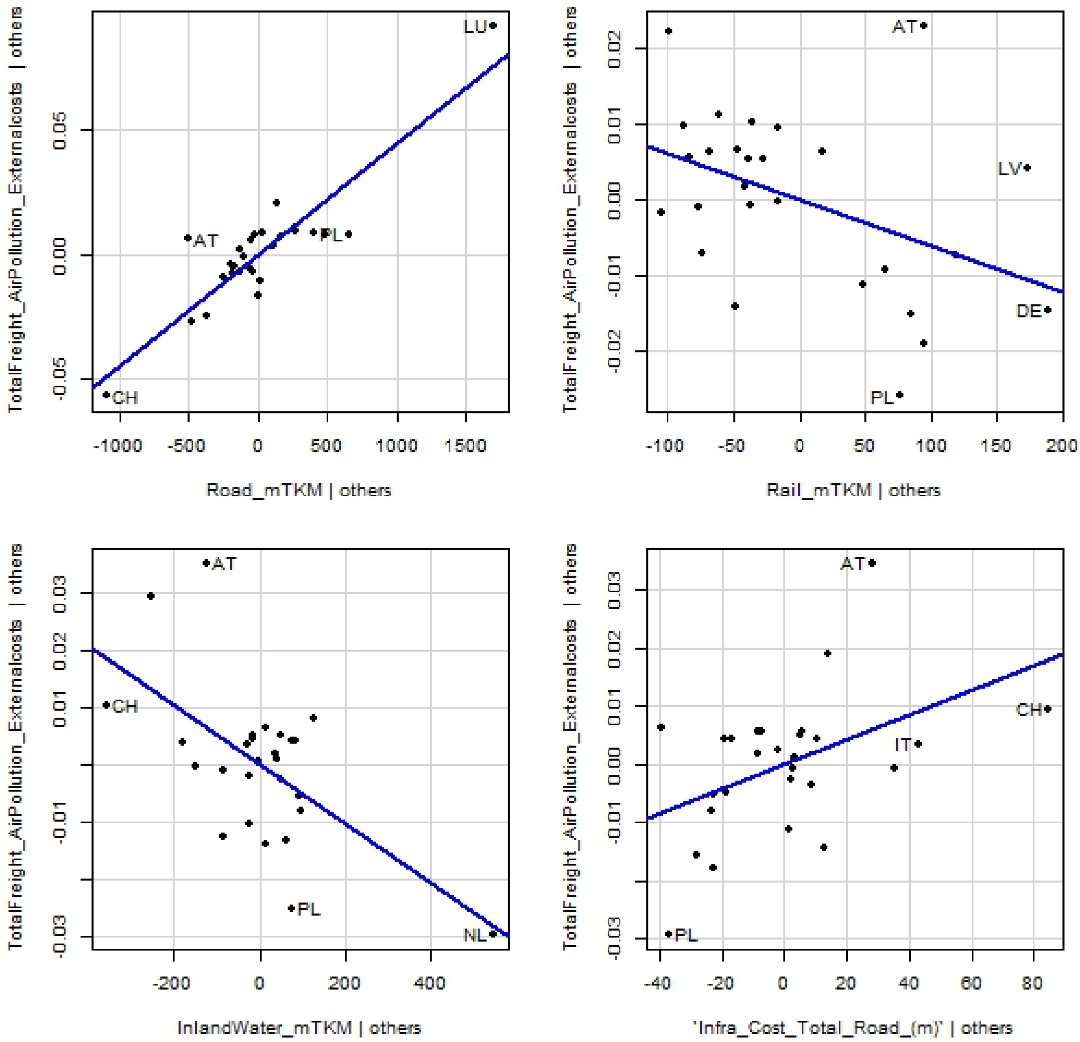

Figure 7: External freight air pollution costs added-variable residual plot

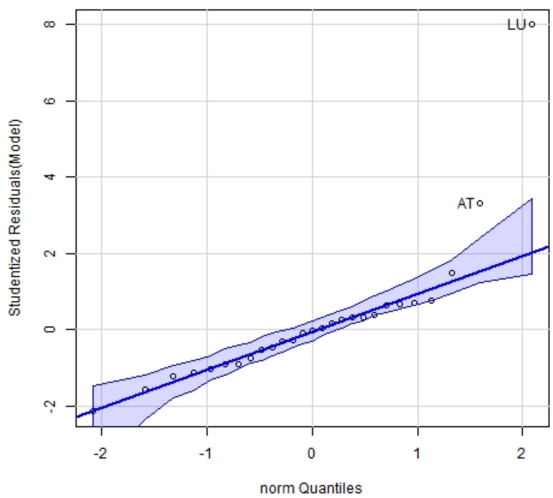

Figure 8: Air pollution model QQ-plot

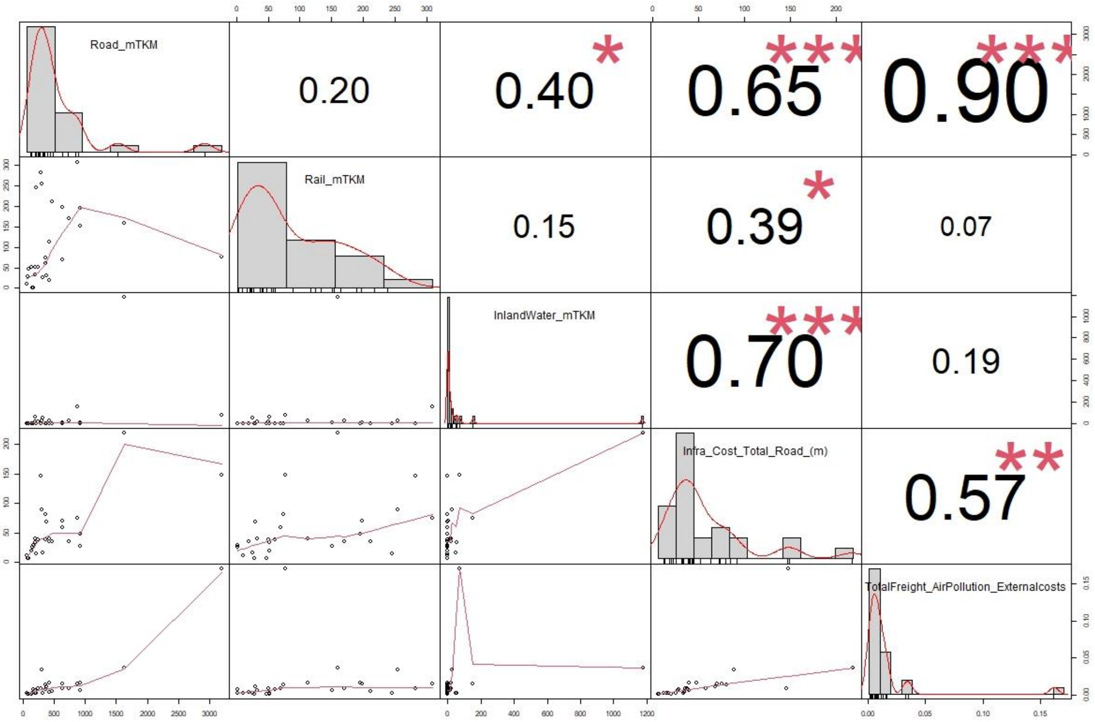

Figure 9: Correlation matrix of air pollution costs and independent variables

4.3. Climate change costs

Multiple linear regression was developed to analyze the main independent variables impacting external climate change costs of freight (Figure 10). A significant regression equation was found with an adjusted R^2 of 0.94, where three independent variables significantly influence the climate change cost. Those independent variables are 1) annual million-ton km of goods transported by road per 1000km^2 (Road_mTKM); 2) annual million-ton km of goods transported by rail per 1000km^2 (Rail_mTKM); 3) Total infrastructure cost of the road (Million €) per 1000km^2.

The model shows a positive correlation between the climate change costs and both road ton-km and road infrastructure costs. This result is aligned with Table 5, which indicates that road freight contributes to 97.3% of the overall climate change costs in EU28. In addition, Table 5 shows that diesel freight trains have the lowest average climate change cost/tkm across all inland transport modes. This is reflected in the negative coefficient of rail tkm in the model.

The added-variable plot (Figure 11) shows that the three independent variables contribute to decreasing residual variability of the model. As for the model distribution, Figure 12 (QQ-plot) shows normality in the sample distribution. The correlation matrix (Figure 13) shows low correlation between independent variables except road cost and road tkm.

```
lm(formula = TotalFreight_ClimateChange_Externalcosts ~ Road_mTKM +
    Rail_mTKM + `Infra_Cost_Total_Road_(m)`, data = Climate_cost_1)

Residuals:
       Min         1Q     Median         3Q        Max
-0.0055588 -0.0012802 -0.0000592  0.0010187  0.0044608

Coefficients:
                              Estimate Std. Error t value Pr(>|t|)
(Intercept)                 -1.911e-04  8.498e-04  -0.225 0.824095
Road_mTKM                    1.427e-05  1.051e-06  13.571 1.83e-12 ***
Rail_mTKM                   -2.370e-05  5.847e-06  -4.053 0.000493 ***
`Infra_Cost_Total_Road_(m)`  4.991e-05  1.455e-05   3.431 0.002281 **
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 0.002569 on 23 degrees of freedom
Multiple R-squared:  0.9493,    Adjusted R-squared:  0.9426
F-statistic: 143.4 on 3 and 23 DF,  p-value: 4.996e-15
```

Figure 10: External freight climate change costs model results

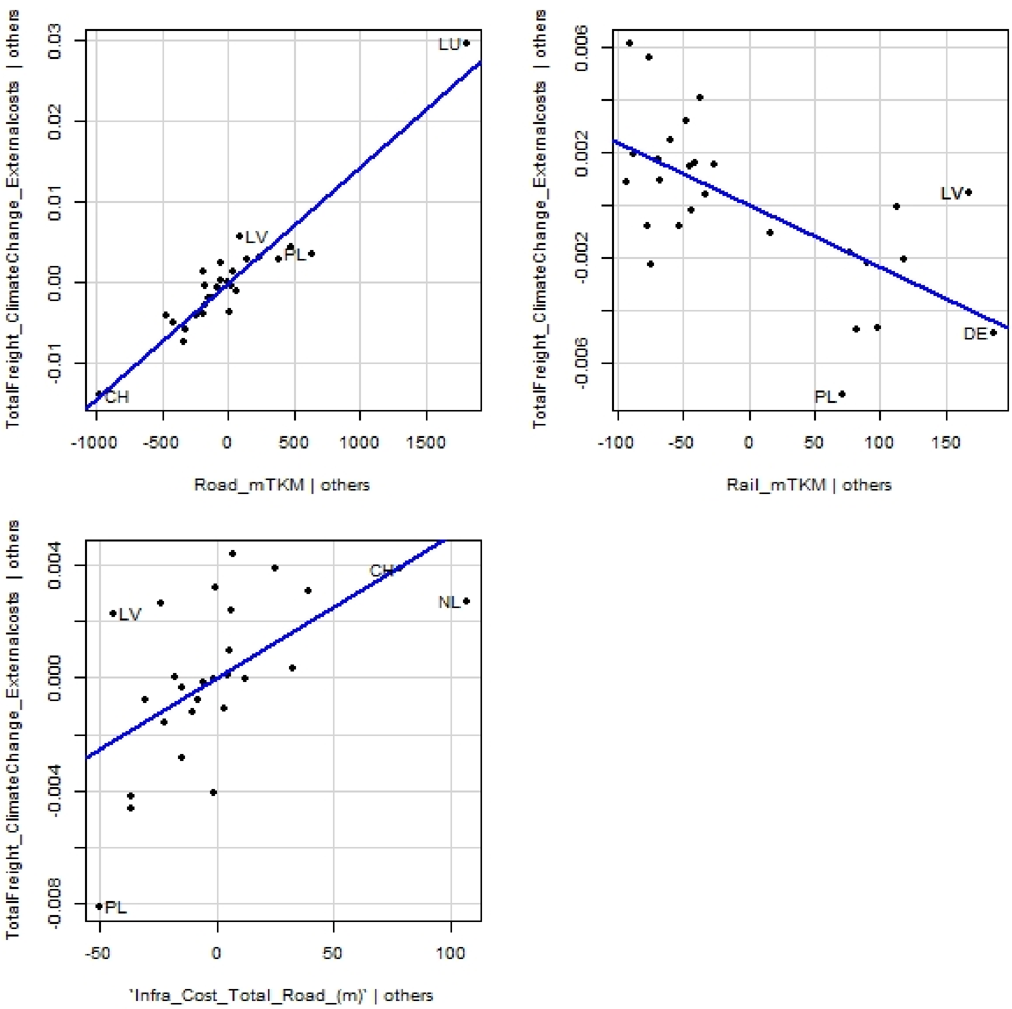

Figure 11: External freight climate change costs added-variable residual plot

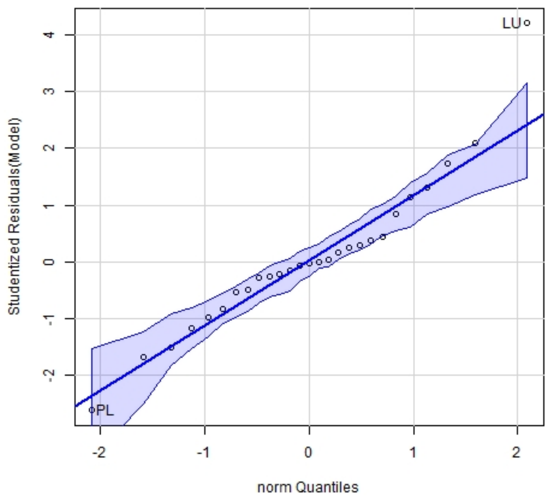

Figure 12: climate change model QQ-plot

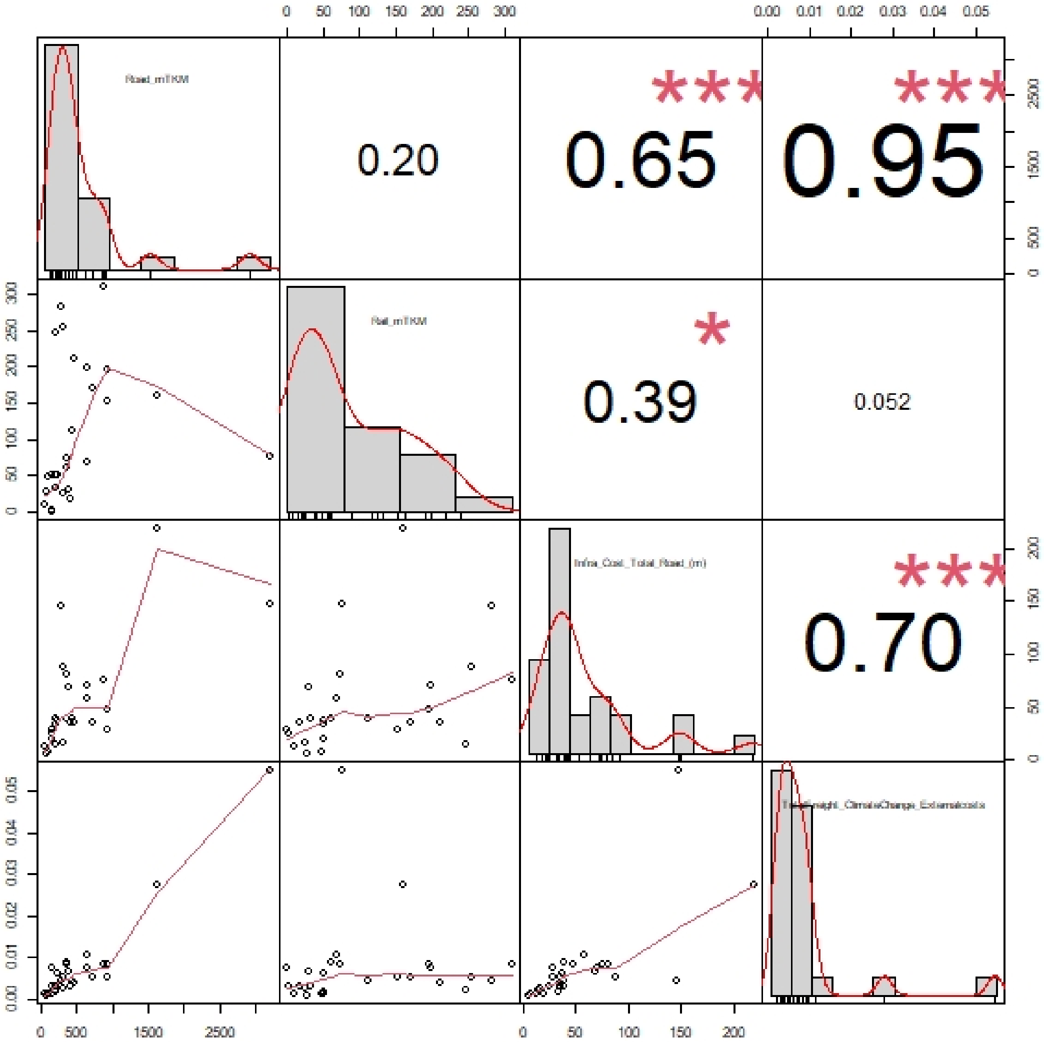

Figure 13: Correlation matrix of climate change costs and independent variables

4.4. Noise costs

Multiple linear regression was developed to analyze the main independent variables impacting external noise costs of freight (Figure 14). A significant regression equation was found with an adjusted R^2 of 0.85, where four independent variables significantly influence the noise cost. Those independent variables are 1) annual million-ton km of goods transported by road per 1000km^2 (Road_mTKM); 2) Total operation and maintenance cost for motorways (Million €) per 1000km2; 3) growth domestic product per capita.

The model shows a positive correlation through all the independent variables. This result is aligned with Table 7, which indicates that the road freight contribute to 85.2% of the total freight noise cost. The HGV has the highest influence of the cost, thus it is shown in the positive correlation of the motorway cost.

The added-variable plot (Figure 15) shows that the three independent variables contribute to decreasing residual variability of the model. As for the model distribution, Figure 16 (QQ-plot) shows slight normality in the sample distribution. The correlation matrix (Figure 17) shows a slightly low correlation between independent variables used in this model.

```
lm(formula = TotalFreight_Noise_Externalcosts ~ Road_mTKM + `Total O&M costs_MotorWay(m)` +
    `GDP/Capita`, data = Noise_cost_1)

Residuals:
       Min         1Q     Median         3Q        Max 
-0.0034067 -0.0015964  0.0001014  0.0010857  0.0059892 

Coefficients:
                                Estimate Std. Error t value Pr(>|t|)    
(Intercept)                   -1.626e-03  8.060e-04  -2.018  0.05542 .  
Road_mTKM                      5.614e-06  8.598e-07   6.530 1.16e-06 ***
`Total O&M costs_MotorWay(m)`  5.970e-04  1.859e-04   3.212  0.00387 ** 
`GDP/Capita`                   7.816e-08  2.518e-08   3.104  0.00500 ** 
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 0.002285 on 23 degrees of freedom
Multiple R-squared:  0.8705,	Adjusted R-squared:  0.8536 
F-statistic: 51.52 on 3 and 23 DF,  p-value: 2.299e-10
```

Figure 14: External freight noise costs model results

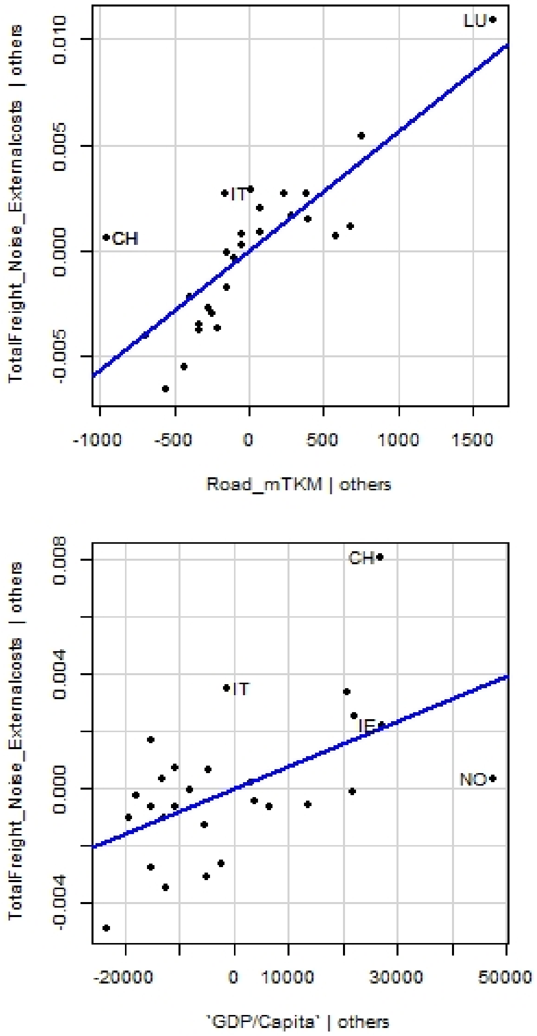

Figure 15: External freight noise costs added-variable residual plot

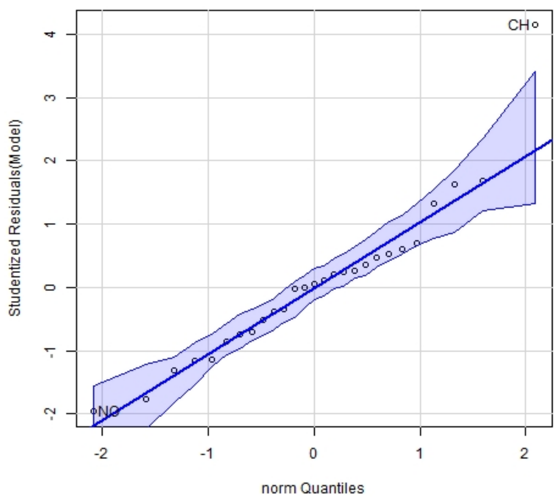

Figure 16: Noise model QQ-plot

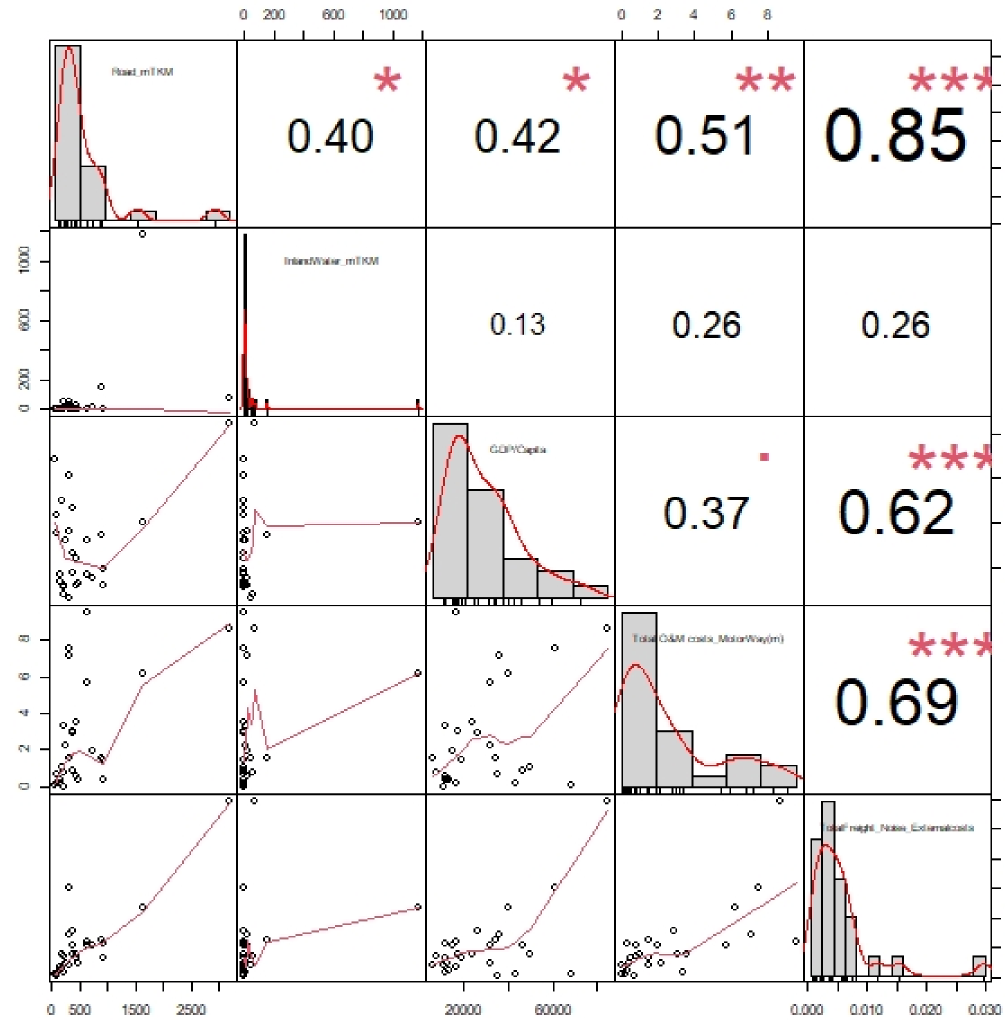

Figure 17: Correlation matrix of noise costs and independent variables

4.5. Congestion costs

Multiple linear regression was developed to analyze the main independent variables impacting external congestion costs of freight (Figure 18). A significant regression equation was found with an adjusted R^2 of 0.9, where three independent variables significantly influence the congestion cost. Those independent variables are 1) annual million-ton km of goods transported by road per $1000km^2$ (Road_mTKM); 2) annual million-ton km of goods transported by rail per $1000km^2$ (Rail_mTKM); 3) growth domestic product per capita.

The model demonstrates a positive relationship between congestion costs and both road ton-km and GDP/capita. This finding is consistent with the premise that only road traffic congestion costs are included. As a result, the rail tkm has a negative value since the shift to rail will reduce the road share. Regarding the positive correlation of GDP/capita, there is a positive correlation between the level of income and the value of time.

The added-variable plot (Figure 19) shows that the three independent variables contribute to decreasing residual variability of the model. As for the model distribution, Figure 20 (QQ-plot) shows slight normality in the sample distribution. The correlation matrix (Figure 21) shows a low correlation between independent varabiles used in this model.

```
lm(formula = TotalFreight_Congestion_Externalcosts ~ Road_mTKM +
    Rail_mTKM + `GDP/Capita`, data = Cong_cost_1)

Residuals:
      Min        1Q    Median        3Q       Max
-0.030171 -0.009092  0.001487  0.007753  0.033164

Coefficients:
               Estimate Std. Error t value Pr(>|t|)
(Intercept)  -1.664e-02  6.879e-03  -2.419  0.02390 *
Road_mTKM     6.914e-05  5.794e-06  11.933 2.47e-11 ***
Rail_mTKM    -1.247e-04  3.551e-05  -3.513  0.00187 **
`GDP/Capita`  6.671e-07  1.800e-07   3.707  0.00116 **
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 0.01651 on 23 degrees of freedom
Multiple R-squared:  0.9132,    Adjusted R-squared:  0.9018
F-statistic: 80.63 on 3 and 23 DF,  p-value: 2.361e-12
```

Figure 18: External freight congestion costs model results

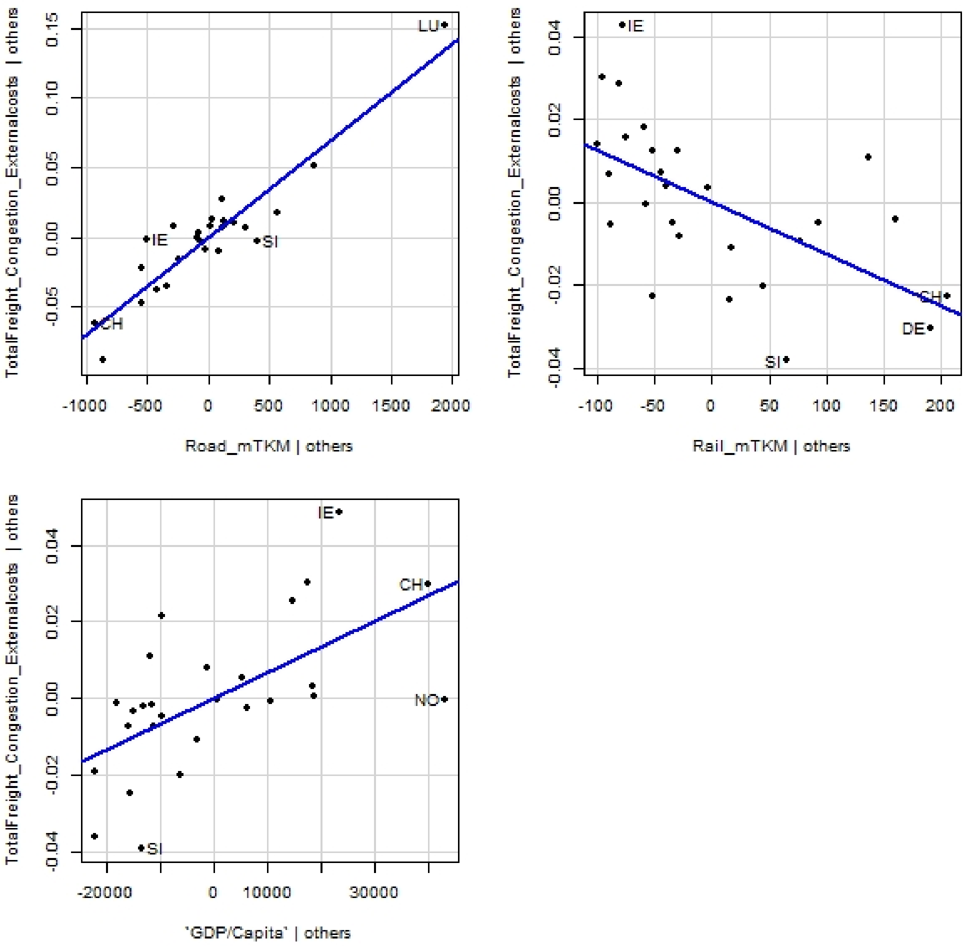

Figure 19: External freight congestion costs added-variable residual plot

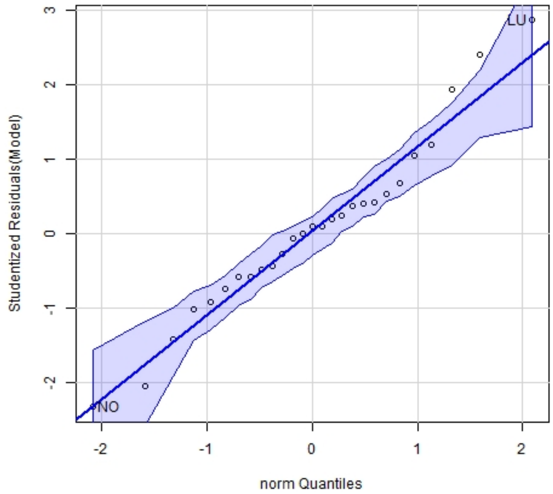

Figure 20: Congestion model QQ-plot

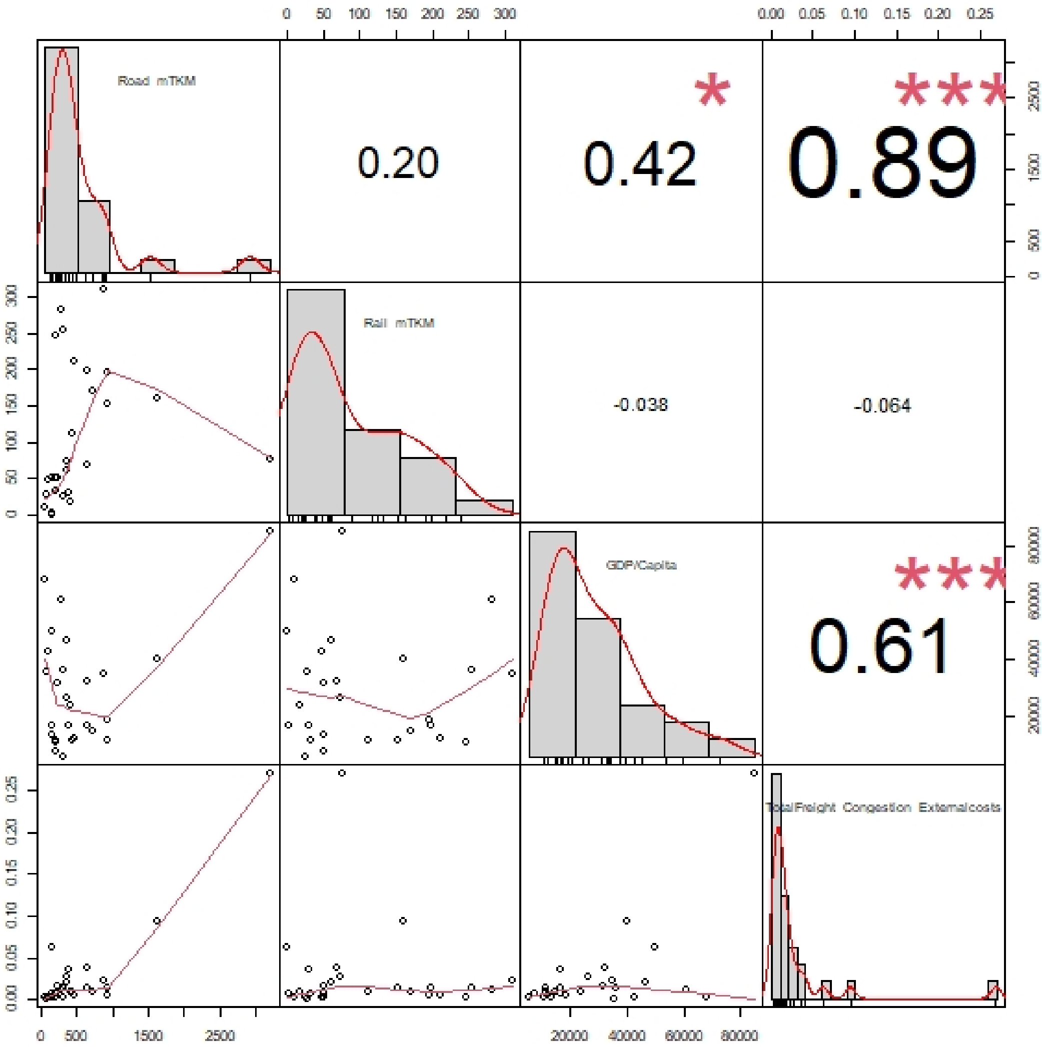

Figure 21: Correlation matrix of congestion costs and independent variables

4.6. Habitat damage costs

Multiple linear regression was developed to analyze the main independent variables impacting external habitat damage costs of freight (Figure 22). A significant regression equation was found with an R^2 of 0.87, where three independent variables significantly influence the habitat damage cost. Those independent variables are 1) Total infrastructure cost of the rail freight (Million €) per 1000km²; 2) Total infrastructure cost of road freight (Million €) per 1000km²; 3) Total infrastructure cost of inland waterway transport (Million €) per 1000km².

The positive coefficient of the road freight infrastructure cost is aligned with its share (86%) from the total habitat damages costs in the EU28 (as shown in Table 10). While the negative coefficient of both rail and IWT reflects the less contribution to the habitat damage (which is aligned with their share of the total habitat damage cost 14%).

The added-variable plot (Figure 23) shows that the three independent variables contribute to decreasing residual variability of the model. As for the model distribution, Figure 24 (QQ-plot) shows normality in the sample distribution (except for Luxembourg and Austria). Nevertheless, the correlation matrix (Figure 25) shows a slight high correlation between road freight and IWT and rail freight too.

```
lm(formula = TotalFreight_Hab_Externalcosts ~ `Infra_Cost_Total_Rail-Freight_(m)` +
    `Infra_Cost_Total_IWT_(m)` + `Infra_Cost_Total_Road-Freight_(m)`,
    data = Hab_cost_1)

Residuals:
       Min         1Q     Median         3Q        Max
-0.0051366 -0.0012687  0.0000798  0.0014403  0.0053845

Coefficients:
                                      Estimate Std. Error t value Pr(>|t|)
(Intercept)                         -2.581e-03  7.535e-04  -3.426  0.00231 **
`Infra_Cost_Total_Rail-Freight_(m)` -4.290e-04  1.981e-04  -2.166  0.04092 *
`Infra_Cost_Total_IWT_(m)`          -1.589e-03  2.392e-04  -6.643 8.91e-07 ***
`Infra_Cost_Total_Road-Freight_(m)`  4.525e-04  5.313e-05   8.517 1.44e-08 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 0.002651 on 23 degrees of freedom
Multiple R-squared:  0.8587,    Adjusted R-squared:  0.8403
F-statistic: 46.59 on 3 and 23 DF,  p-value: 6.212e-10
```

Figure 22: External freight habitat damage costs model results

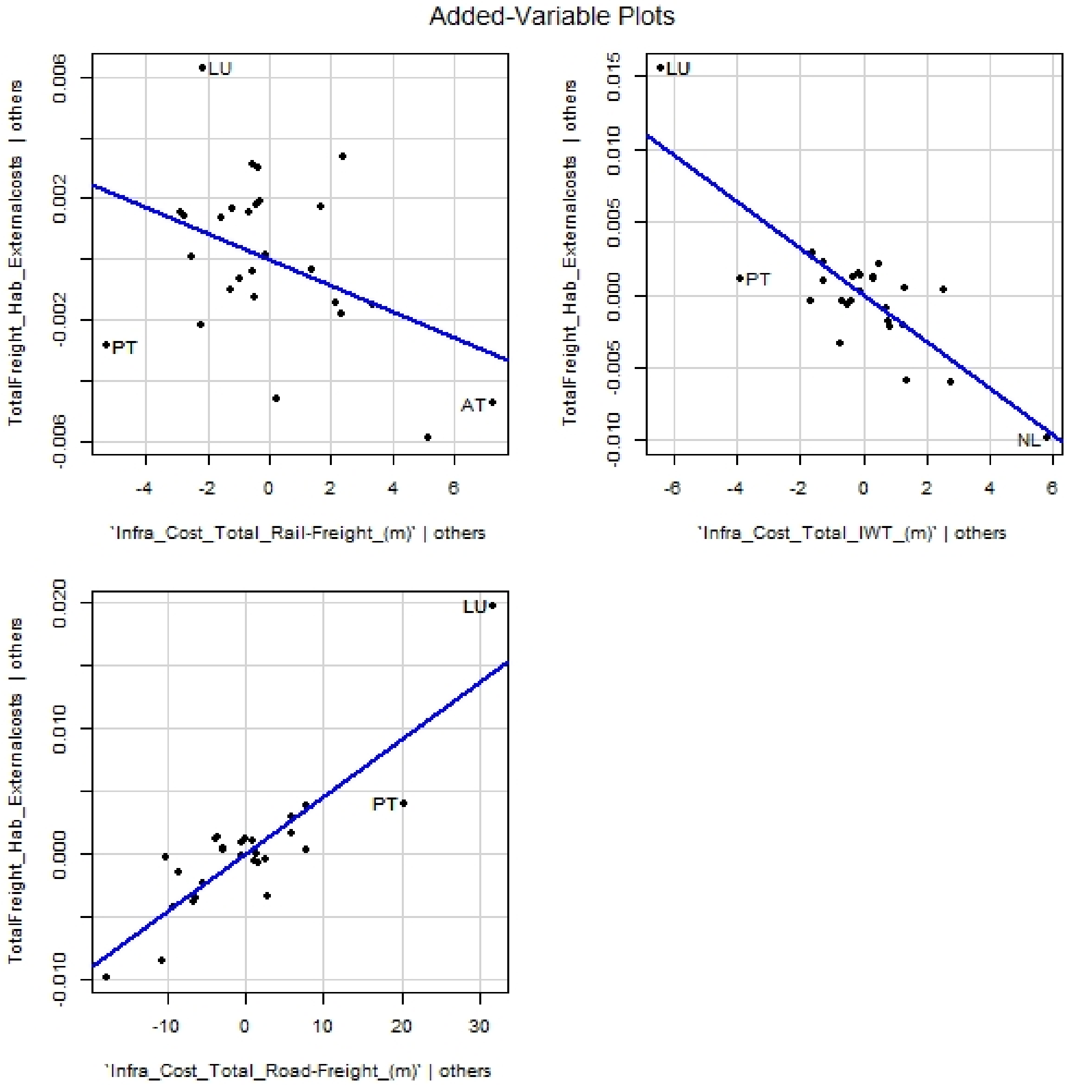

Figure 23: External freight habitat damage costs added-variable residual plot

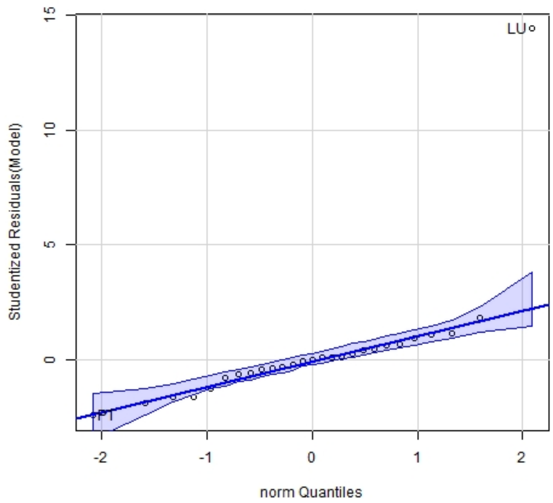

Figure 24: Habitat damage model QQ-plot

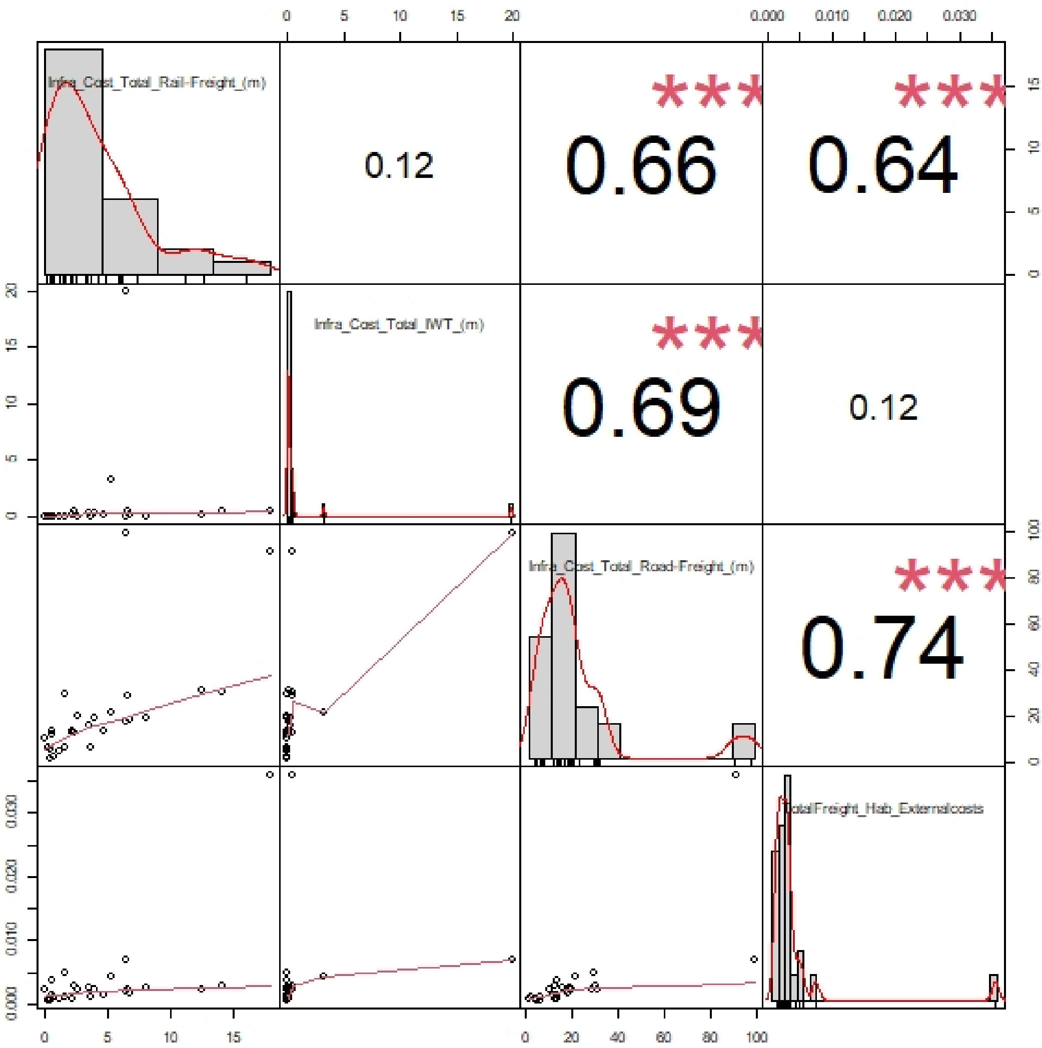

Figure 25: Correlation matrix of habitat damage costs and independent variables

Chapter 5

Conclusions

The current study demonstrates the potential of utilizing open-source data in the assessment of the external cost categories, providing facilitated access to external costs assessment. The study also identifies the two main external factors in the assessment of external costs of freight: mTkm per mode and infrastructure costs per mode (including operation, maintenance, and investment). This outcome can provide future researchers with guidance in the development of new external costs assessment tools. Indeed, further studies could build on the current outcomes to develop a framework for external costs assessment including (1) diagnosis, (2) KPI identification (3) implementation and (4) monitoring. Another interesting topic to be further investigated in future research could be the assessment of external costs for international transport.

The current research outcomes were also limited by the quality of the data available: both in terms of temporal distribution (data only collected at one point in time) and geographical scope (only 27 countries available in the sample).

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Appendix

Table 14: Total external Well-to-Tank costs for land-based modes for the EU28(2016)(Billion €) (European Commission et al., 2020)

Country	LCV-petrol	LCV-diesel	HGV - total	Elec freight train	Diesel freight train	Inland vessel	TotalFreight_WTT_Externalcosts
Austria	0.003	0.107	0.054	0.012	0.003	0.003	0.183
Belgium	0.002	0.093	0.079	0.005	0.002	0.014	0.194
Bulgaria	0.001	0.012	0.043	0.008	0.000	0.004	0.069
Croatia	0.001	0.031	0.022	0.001	0.001	0.001	0.057
Cyprus	0.001	0.009	0.002				0.012
Czech Republic	0.008	0.059	0.138	0.031	0.007	0.000	0.244
Denmark	0.005	0.062	0.037	0.002	0.003		0.109
Estonia	0.000	0.003	0.010	0.000	0.001	0.001	0.016
Finland	0.001	0.033	0.043	0.003	0.001	0.000	0.082
France	0.041	0.925	0.307	0.012	0.010	0.011	1.306
Germany	0.016	0.326	0.881	0.240	0.043	0.082	1.588
Greece	0.044	0.023	0.031	0.000	0.000		0.099
Hungary	0.003	0.050	0.083	0.008	0.004	0.002	0.150
Ireland	0.000	0.116	0.027	0.000	0.001		0.144
Italy	0.024	0.552	0.224	0.029	0.005	0.000	0.834
Latvia	0.001	0.005	0.023	0.000	0.009		0.038
Lithuania	0.001	0.014	0.061	0.000	0.007		0.082
Luxembourg	0.001	0.046	0.030	0.000	0.000	0.001	0.078
Malta	0.000	0.001	0.005				0.006
Netherlands	0.004	0.170	0.214	0.009	0.002	0.065	0.465
Poland	0.016	0.092	0.431	0.094	0.004	0.000	0.637
Portugal	0.001	0.100	0.048	0.004	0.001		0.154
Romania	0.013	0.032	0.068	0.011	0.003	0.012	0.139
Slovakia	0.005	0.020	0.071	0.004	0.002	0.001	0.103
Slovenia	0.002	0.020	0.033	0.004	0.001		0.059
Spain	0.004	0.131	0.316	0.018	0.004		0.473
Sweden	0.007	0.066	0.075	0.002	0.001		0.150
United Kingdom	0.021	0.469	0.352	0.005	0.018	0.000	0.865
Norway	0.004	0.082	0.048	0.000	0.001		0.136
Switzerland	0.009	0.032	0.025	0.001	0.001	0.000	0.067

Table 15: Total external noise costs for land-based modes for the EU28(2016) (Billion €)(European Commission et al., 2020)

Country	LCV	HGV total	Elec freight train	Diesel freight train	TotalFreight_Noise_Externalcosts
Austria	0.135	0.117	0.322	0.030	0.603
Belgium	0.262	0.304	0.056	0.016	0.638
Bulgaria	0.026	0.193	0.001	0.000	0.221
Croatia	0.019	0.024	0.002	0.002	0.046
Cyprus	0.024	0.007			0.031
Czech Republic	0.096	0.348	0.019	0.004	0.467
Denmark	0.113	0.115	0.002	0.003	0.233
Estonia	0.007	0.038	0.000	0.003	0.048
Finland	0.026	0.053	0.025	0.015	0.119
France	0.848	0.465	0.191	0.025	1.529
Germany	0.253	1.049	0.791	0.119	2.211
Greece	0.116	0.110	0.000	0.001	0.228
Hungary	0.079	0.218	0.013	0.004	0.313
Ireland	0.214	0.062	0.000	0.001	0.277
Italy	1.286	0.757	0.322	0.012	2.376
Latvia	0.013	0.106	0.000	0.012	0.131
Lithuania	0.018	0.125	0.000	0.003	0.145
Luxembourg	0.040	0.032	0.005	0.001	0.078
Malta	0.001	0.008			0.009
Netherlands	0.181	0.272	0.023	0.006	0.483
Poland	0.197	1.519	0.078	0.021	1.815
Portugal	0.193	0.137	0.019	0.011	0.360
Romania	0.182	0.585	0.036	0.016	0.819
Slovakia	0.031	0.170	0.047	0.015	0.263
Slovenia	0.015	0.044	0.008	0.002	0.069
Spain	0.448	1.479	0.025	0.006	1.958
Sweden	0.056	0.103	0.078	0.007	0.245
United Kingdom	0.552	0.650	0.016	0.101	1.319
Norway	0.105	0.083	0.027	0.007	0.221
Switzerland	0.184	0.244	0.198	0.004	0.630

Table 16: Total external climate change costs for land-based modes for the EU28(2016) (Billion €)(European Commission et al., 2020)

Country	LCV-petrol	LCV-diesel	HGV - total	Diesel freight train	Inland vessel	TotalFreight_ClimateChange_Externalcosts
Austria	0.01	0.32	0.11	0.00	0.00	0.44
Belgium	0.00	0.31	0.18	0.00	0.03	0.53
Bulgaria	0.00	0.07	0.19	0.00	0.01	0.28
Croatia	0.00	0.13	0.05	0.00	0.00	0.18
Cyprus	0.00	0.05	0.01	0.00		0.06
Czech Republic	0.02	0.21	0.36	0.01	0.00	0.61
Denmark	0.01	0.24	0.13	0.00		0.38
Estonia	0.00	0.02	0.03	0.01	0.00	0.06
Finland	0.00	0.16	0.18	0.01	0.00	0.35
France	0.11	2.91	0.83	0.01	0.02	3.88
Germany	0.04	0.98	1.80	0.04	0.15	3.00
Greece	0.17	0.13	0.11	0.00		0.42
Hungary	0.01	0.18	0.23	0.00	0.00	0.42
Ireland	0.00	0.48	0.05	0.00		0.53
Italy	0.07	1.95	0.55	0.00	0.00	2.56
Latvia	0.00	0.02	0.08	0.04		0.15
Lithuania	0.00	0.07	0.16	0.03		0.26
Luxembourg	0.00	0.10	0.04	0.00	0.00	0.14
Malta	0.00	0.01	0.02	0.00		0.02
Netherlands	0.01	0.59	0.41	0.00	0.13	1.15
Poland	0.05	0.41	1.18	0.02	0.00	1.66
Portugal	0.00	0.44	0.15	0.00		0.61
Romania	0.05	0.15	0.21	0.01	0.03	0.45
Slovakia	0.01	0.08	0.16	0.00	0.00	0.26
Slovenia	0.00	0.07	0.09	0.00		0.17
Spain	0.02	0.58	1.03	0.01		1.63
Sweden	0.02	0.28	0.29	0.00		0.59
United Kingdom	0.06	1.52	1.01	0.04	0.00	2.63
Norway	0.01	0.29	0.09	0.00		0.39
Switzerland	0.02	0.10	0.06	0.00	0.00	0.19

Table 17: Total external habitat damage costs for land-based modes for the EU28(2016) (Billion €)(European Commission et al., 2020)

Country	LCV-petrol	LCV-diesel	HGV - total	Elec freight train	Diesel freight train	Inland vessel	TotalFreight_Hab_Externalcosts
Austria	0.004	0.138	0.049	0.033	0.003	0.002	0.230
Belgium	0.001	0.089	0.050	0.009	0.003	0.010	0.163
Bulgaria	0.001	0.015	0.048	0.012	0.003	0.002	0.080
Croatia	0.001	0.022	0.014	0.005	0.004	0.004	0.051
Cyprus	0.001	0.014	0.002				0.017
Czech Republic	0.006	0.047	0.086	0.028	0.007	0.003	0.177
Denmark	0.007	0.097	0.047	0.003	0.003		0.158
Estonia	0.001	0.011	0.026		0.015	0.002	0.055
Finland	0.003	0.104	0.097	0.033	0.020	0.072	0.328
France	0.050	1.235	0.305	0.121	0.016	0.038	1.765
Germany	0.019	0.386	0.802	0.221	0.033	0.066	1.527
Greece	0.039	0.023	0.026	0.000	0.002		0.090
Hungary	0.005	0.088	0.116	0.015	0.004	0.007	0.235
Ireland	0.000	0.135	0.021		0.001		0.158
Italy	0.021	0.461	0.160	0.036	0.001	0.008	0.688
Latvia	0.001	0.014	0.049		0.017		0.081
Lithuania	0.001	0.023	0.072		0.017		0.114
Luxembourg	0.002	0.060	0.030	0.001	0.000	0.000	0.093
Malta	0.000	0.001	0.003				0.003
Netherlands	0.002	0.131	0.102	0.007	0.002	0.046	0.290
Poland	0.010	0.063	0.247	0.077	0.021	0.017	0.435
Portugal	0.004	0.224	0.214	0.005	0.003		0.450
Romania	0.017	0.044	0.077	0.023	0.010	0.006	0.177
Slovakia	0.004	0.019	0.052	0.013	0.004	0.001	0.093
Slovenia	0.001	0.019	0.025	0.006	0.002		0.054
Spain	0.007	0.247	0.479	0.034	0.008		0.775
Sweden	0.018	0.196	0.186	0.092	0.008		0.501
United Kingdom	0.012	0.296	0.173	0.005	0.031	0.007	0.524
Norway	0.006	0.125	0.055	0.022	0.006		0.213
Switzerland	0.010	0.042	0.023	0.021	0.000	0.000	0.098

Table 18: Total external air pollution costs for land-based modes for the EU28(2016) (Billion €)(European Commission et al., 2020)

Country	LCV-petrol	LCV-diesel	HGV - total	Electric freight train	Diesel freight train	Inland vessel	TotalFreight_AirPollution_Externalcosts
Austria	0.00	0.65	0.24	0.00	0.03	1.93	2.86
Belgium	0.00	0.45	0.36	0.00	0.02	1.93	2.76
Bulgaria	0.00	0.04	0.18	0.00	0.00	0.03	0.25
Croatia	0.00	0.13	0.09	0.00	0.00	0.13	0.34
Cyprus	0.00	0.02	0.00	0.00	0.00	0.02	0.05
Czech Republic	0.03	0.44	0.71	0.00	0.02	0.01	1.20
Denmark	0.00	0.19	0.13	0.00	0.01		0.32
Estonia	0.00	0.01	0.02	0.00	0.01	0.00	0.03
Finland	0.00	0.12	0.09	0.00	0.01		0.22
France	0.06	3.68	1.51	0.00	0.04	0.00	5.29
Germany	0.01	1.80	3.37	0.01	0.23	0.00	5.42
Greece	0.03	0.08	0.10	0.00	0.00	0.10	0.31
Hungary	0.01	0.24	0.36	0.00	0.01	0.90	1.51
Ireland	0.00	0.44	0.06	0.00	0.00		0.50
Italy	0.06	2.58	1.25	0.00	0.02	0.02	3.93
Latvia	0.00	0.01	0.06	0.00	0.06		0.14
Lithuania	0.00	0.09	0.21	0.00	0.03	0.00	0.33
Luxembourg	0.00	0.32	0.13	0.00	0.00		0.44
Malta	0.00	0.00	0.01	0.00	0.00		0.01
Netherlands	0.01	0.84	0.66	0.00	0.01	0.01	1.52
Poland	0.02	0.39	1.49	0.00	0.05		1.96
Portugal	0.00	0.29	0.12	0.00	0.01	0.58	1.00
Romania	0.06	0.14	0.39	0.00	0.01	0.00	0.60
Slovakia	0.01	0.10	0.31	0.00	0.01		0.42
Slovenia	0.00	0.06	0.14	0.00	0.00	0.11	0.32
Spain	0.01	0.56	1.09	0.00	0.03	0.01	1.68
Sweden	0.01	0.14	0.18	0.00	0.02		0.34
United Kingdom	0.01	1.37	0.71	0.00	0.04		2.13
Norway	0.01	0.37	0.16	0.00	0.01		0.55
Switzerland	0.01	0.18	0.11	0.00	0.02	0.00	0.32

Table 19: Total external accident costs for land-based modes for the EU28(2016) (Billion €)(European Commission et al., 2020)

Country	LCV	HGV	FreightTrain	InlandVessel	TotalFreight_Accident_Externalcosts
Austria	0.500	0.600	0.009	0.002	1.110
Belgium	1.100	0.800	0.002	0.006	1.910
Bulgaria	0.000	0.300	0.004	0.002	0.300
Croatia	0.100	0.200	0.003	0.001	0.300
Cyprus	0.000	0.000	0.000	0.000	0.050
Czech Republic	0.200	0.600	0.003	0.000	0.860
Denmark	0.100	0.300	0.001	0.000	0.400
Estonia	0.000	0.000	0.004	0.003	0.030
Finland	0.100	0.300	0.002	0.000	0.420
France	2.600	2.400	0.010	0.005	5.070
Germany	3.200	6.100	0.036	0.038	9.410
Greece	0.300	0.200	0.000	0.000	0.500
Hungary	0.500	0.400	0.015	0.001	0.990
Ireland	0.200	0.100	0.000	0.000	0.280
Italy	2.100	2.200	0.007	0.000	4.400
Latvia	0.000	0.100	0.021	0.000	0.160
Lithuania	0.000	0.100	0.022	0.000	0.180
Luxembourg	0.000	0.000	0.000	0.000	0.070
Malta	0.000	0.000	0.000	0.000	0.030
Netherlands	1.200	0.600	0.000	0.024	1.830
Poland	0.000	2.600	0.076	0.000	2.690
Portugal	0.800	0.300	0.003	0.000	1.060
Romania	1.600	0.300	0.023	0.006	1.940
Slovakia	0.000	0.400	0.018	0.000	0.460
Slovenia	0.000	0.100	0.000	0.000	0.150
Spain	2.000	1.500	0.005	0.000	3.520
Sweden	0.200	0.300	0.004	0.000	0.560
United Kingdom	2.500	2.000	0.002	0.000	4.470
Norway	0.100	0.200	0.000	0.000	0.240
Switzerland	0.400	0.300	0.004	0.000	0.680

Table 20: Total external congestion costs for road for the EU28(2016) (Billion €)(European Commission et al., 2020)

Country	Delay cost LCV	Delay cost HCV	TotalFreight_Congestion_Externalcosts
Austria	0.90	0.17	1.10
Belgium	1.50	0.31	1.80
Bulgaria	0.10	0.13	0.20
Croatia	0.30	0.07	0.40
Cyprus	0.10	0.01	0.10
Czech Republic	0.70	0.38	1.10
Denmark	0.80	0.15	0.90
Estonia	0.00	0.03	0.10
Finland	0.30	0.07	0.40
France	9.60	1.02	10.60
Germany	4.90	3.08	8.00
Greece	0.70	0.15	0.90
Hungary	0.60	0.29	0.90
Ireland	4.20	0.09	4.30
Italy	6.80	1.13	7.90
Latvia	0.10	0.09	0.20
Lithuania	0.20	0.13	0.30
Luxembourg	0.60	0.10	0.70
Malta	0.00	0.02	0.00
Netherlands	3.40	0.47	3.90
Poland	1.90	2.75	4.60
Portugal	3.10	0.18	3.30
Romania	1.00	0.67	1.60
Slovakia	0.20	0.21	0.40
Slovenia	0.10	0.05	0.10
Spain	4.10	1.04	5.20
Sweden	1.30	0.23	1.50
United Kingdom	8.00	1.59	9.50
Norway	0.80	0.10	0.90
Switzerland	0.40	0.13	0.50