DATA 70202 Applied Data Science:

Estimating potential reduction in externalities by a modal shift of deep-sea containers from 100% road trucking to rail between Sohar and Muscat

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Word count: 2187

1. Introduction

This study aims to identify the potential reduction in externalities by a modal shift from trucking to rail for deep-sea containers between Sohar and Muscat. Externalities of transport refer to any negative effect caused by transport users and borne by society (European Commission, 2019). Align with the project 'Rail Growth Limited Carbon Footprint', this study provides a way to determine if the modal transition can be justified in terms of externalities other than CO_2 emission. Negative externalities of transport include noise, accidents, congestion, and environmental damage (Santos et al., 2010). Considering the data availability and the difference between trucks and trains, this study focuses on noise, accidents, and congestion to discuss how much external costs can be reduced for each category.

2. Materials and methods

2.1. The basic structure and assumptions

The three transport options – trucks, diesel trains, and electric trains – will be compared in terms of externalities in noise, accidents, and congestion.

The Handbook on the external costs of transport (EC, 2019) provides useful insights and unit costs of each externality for various transport modes in euro cents (€). However, the unit costs need adjustment according to the regional scope of the study (i.e., Oman) because they are based on European statistics, such as Eurostat or EU's Community Road Accident Database (CARE). After adjusting the unit costs, the total amount of potential reduction in the external costs will be estimated.

Figure 1 shows the suggested routes for trains and trucks. We assume that the percentage of choosing each route is 50%. Batinah Expressway route is longer than Muscat Expressway but has less congestion due to less population nearby.

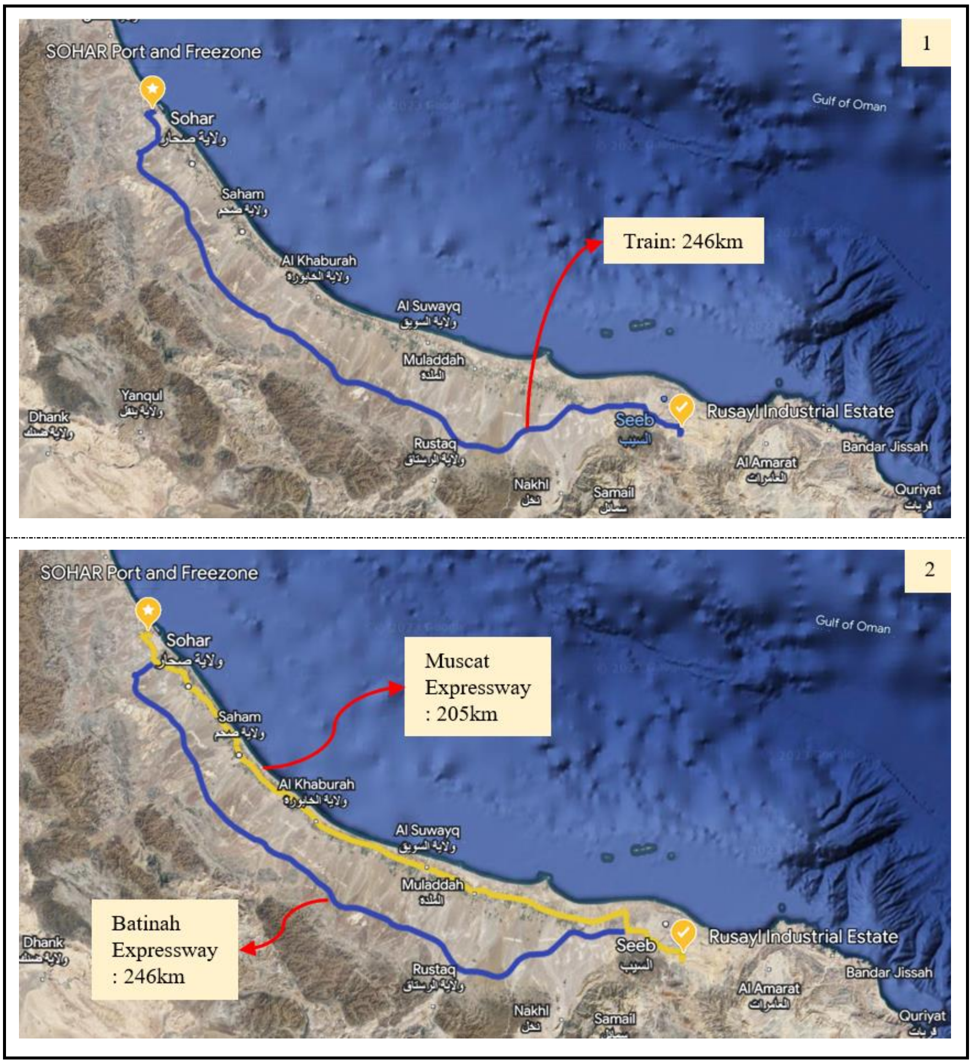

Figure 1. The suggested routes for train (1) and truck (2), Google Earth

Table 1 shows the other assumptions, such as weight and number of rounds. Further detailed assumptions on the calculation methods for each external cost will be given in the following section.

Category	**Transport mode**	
	Truck (Euro-3)	**Train (Diesel, Electric)**
Net weight	15t	1,000t
Payload	40t	4,000t
Gross weight	55t	5,000t
Daily loadout	100,000t	
No. of rounds per day	100,000/40 = 2,500	100,000/4,000 = 25

Table 1. The assumptions of the study

Each transport mode is assumed to be working 24 hours with 320 work days fully-loaded and always available to meet the daily loadout on work days.

2.2. Externalities

2.2.1. Accident cost

a. The approach by EC (2019)

According to EC (2019), accident cost consists of six components as below (Table 2).

Component	Description
(a) Human cost	The pain and suffering caused by traffic accidents in monetary value
(b) Medical cost	The cost of medical treatment, appliances, and medicines
(c) Administrative cost	The expenses of the deployed police force, fire service, and other services that assist at the crash location site
(d) Production loss	The lost output per casualty due to reduced working time and the human capital replacement costs
Material damage	The monetary value of damages to vehicles, infrastructure, freight and personal property resulting from accidents
Other costs	All other costs not stated above

Table 2. The components of accident costs (EC, 2019)

Each component is calculated using statistics (Eurostat, CARE) and methods from other research (Table 3). Material damages and other costs were assumed to be fully internalised; thus, they are not included in the accident external cost.

Component	Estimation method & source
(a) Human cost	The Value of Statistical Life (VSL) by the willingness to pay (WTP) approach (OECD, 2012)
(b) Medical cost	The social medical costs of road crashes in 31 European countries from Wijnen et al. (2017)
(c) Administrative cost	Alfaro et al. (1994): Standard administrative costs Wijnen et al. (2017): The total administrative costs of road crashes in EU
(d) Production loss	The human capital approach from Wijnen et al. (2017)

Table 3. The sources and estimation methods of each accident cost component (EC, 2019)

To get the average accident costs, EC (2019) calculates the total accident cost first and then allocates it to each transport mode by responsibility factor. The responsibility factor reflects each mode's responsibility portion per accident based on CARE and Eurostat. The paper does not provide the equation, but it can be inferred as below:

Average accident cost of a transport mode (m) during the period (t):

$$C_{m,t} = \frac{\{c_a * (1-i_a) + c_b * (1-i_b) + c_c * (1-i_c) + c_d * (1-i_d)\} * n_t}{r_m}$$

c: external cost of category (a~d, Table 2) per casualty *i: insurance coverage rate of category (a~d)*

n_t: number of casualties of period t

r_m: responsibility factor of the transport mode m

We can see each external cost is reduced by the insurance coverage rate (Internalisation). Table 4 shows the insurance coverage rates for each component (EC, 2019).

	Human costs	Production loss	Medical costs	Administrative costs
Insurance coverage rate (%)	50*	45	50	70

* *Fully internal for the individuals responsible for the accident, fully external for the others*

Table 4. The insurance coverage rate for each accident cost component (EC, 2019)

We can describe the accident cost estimation method from EC (2019) below (Figure 2).

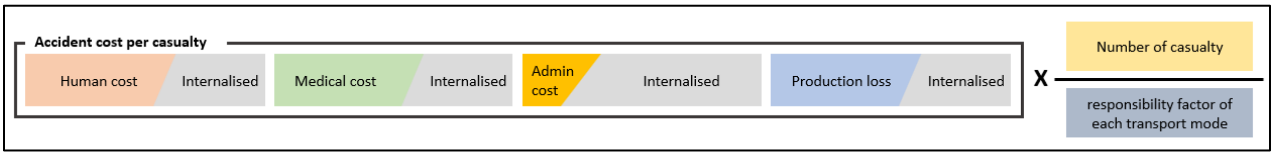

Figure 2. Estimation method of accident cost for EU28

Table 5 shows the average accident costs for each transport mode given by EC (2019).

Transport mode	Average accident cost (€-cent per tkm)
HGV	1.3
Diesel freight train	0.1
Electric freight train	0.1

Table 5. The average accident cost of each mode for EU28 (EC, 2019)

b. Suggested approach

The equation below represents the external accident costs for the regional scope of this study (i.e., Oman):

$$C^*_{m,t} = \{c^*_a * (1 - i^*_a) + c^*_b * (1 - i^*_b) + c^*_c * (1 - i^*_c) + c^*_d * (1 - i^*_d)\} * \frac{n^*_t}{r_m}$$

By assuming the ratio of each cost component to the total is identical between EU28 and Oman (Table 6), we can get an approximation of the weighting factor $w_{m,t}$ as follows:

$$\frac{C^*_{m,t}}{C_{m,t}} = w_{m,t}$$

$$\approx \left(0.8944 * r_{c(a)} * r_{i(a)} + 0.1015 * r_{c(b)} * r_{i(b)} + 0.0031 * r_{c(c)} * r_{i(c)} + 0.0010 * r_{c(d)} * r_{i(d)}\right) * r_{n,t}$$

r_c: The ratio of the external cost of category per casualty (c^*/c)

r_i: The ratio of (1 - insurance coverage rate) of each category $((1 - i_a^*)/(1 - i_a))$

$r_{n,t}$: The ratio of the number of casualties during period t (n_t^*/n_t)

	Human costs	Production loss	Medical costs	Administrative costs	Total
Cost (€)	3,408,522	386,885	11,823	3,785	3,811,015
Ratio (%)	**89.44**	**10.15**	**0.31**	**0.10**	100

Table 6. The composition of accident cost from EC (2019)

By calculating each element (r_c, r_i, $r_{n,t}$) by the difference between EU28 and Oman, we can obtain $w_{m,t}$, by which we can multiply the costs for EU28 to get the ones for Oman.

Table 7 shows the calculation methods for each element. We assume that the responsibility factor (r_m) is identical between countries.

Element	Calculation method	Source
$r_{c(a)}$	Life expectancy ratio (EU28/Oman)	World Bank (2023)
$r_{c(b)}$	Healthcare development index ratio (EU28/Oman)	Statista (2023)
$r_{c(c)}$	Government effectiveness index ratio (EU28/Oman)	World Bank (2023)
$r_{c(d)}$	Labour productivity ratio (GDP per person employed, Oman/EU28)	World Bank (2023)
$r_{i(n)}$	k = The ratio of insurance premium to GDP (Oman/EU28) $(1 - i_n^* * k)/(1 - i_n)$ for n = a ~ d	Statista (2023)
$r_{n,t}$	Population density ratio (Oman/EU28), Oman: 0.5 * Population_density_of_Muscat_Expressway + 0.5 * Population_density_of_Batinah_Expressway	Geo-ref (2023), Luminocity3D (2023)
s	$PPP_{2016(Oman/EU28)}$ * (1 + inflation $rate_{2016\text{-}2021(Oman)}$) * (0.85 * the ratio of mortality rate*)	World Bank (2023)

** Mortality caused by road traffic injury per 100,000 population (World Bank, 2023)*

Table 7. The calculation methods for each element of the accident cost weighting factor

The human cost is calculated using VSL; thus, it can be adjusted by the difference in life expectancy (years) ($r_{c(a)}$). Medical costs, administrative costs, and production loss may differ by medical or administrative system efficiency, or labour productivity ($r_{c(b)}$, $r_{c(c)}$, and $r_{c(d)}$).

The population density ratio is to reflect the difference in the number of casualties ($r_{n,t}$). The two suggested routes have different population densities nearby. Figure 3 shows that the railway and the Batinah Expressway go through less populated areas than the Muscat Expressway.

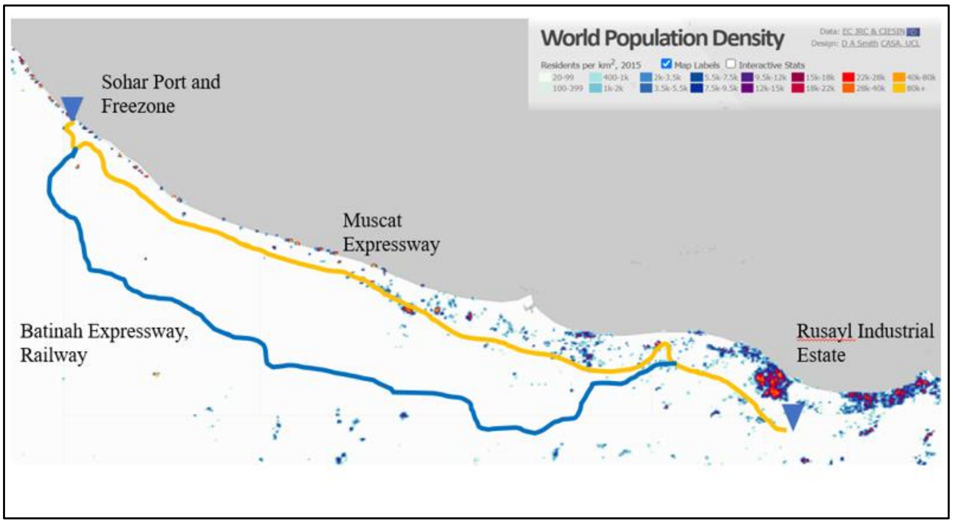

Figure 3. The population density around the transport routes (Luminocity3D)

Table 8 shows the calculation of population density for each route based on Geo-ref (2023, Figure 4). Weighted averages were calculated based on the regional coverage ratio and the spot density nearby.

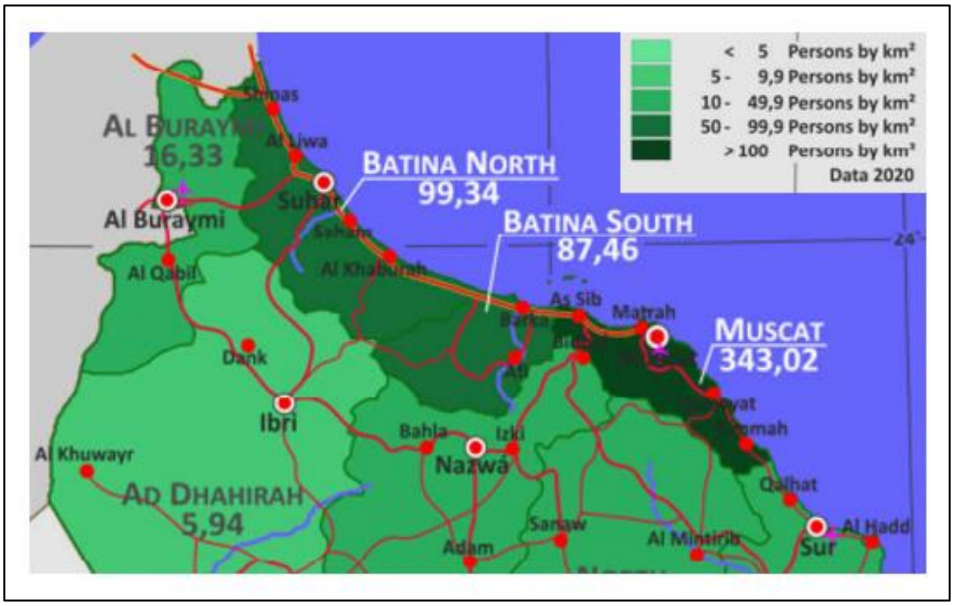

Figure 4. The average population density around the transport routes (Geo-ref, 2023)

Route	Population density	Note
Muscat Expressway	(0.33 * 343.02 + 0.33 * 87.46 + 0.33 * 99.34) * 2.5 = 437.10 (Persons / km^2)	Regional weight (Muscat:Batina South:Batina North) = 1:1:1 Spot density weight = 2.5
Batinah Expressway, Railway	(0.2 * 343.02 + 0.6 * 87.46 + 0.2 * 99.34) * 0.2 = 28.18 (Persons / km^2)	Regional weight = 1:3:1 Spot density weight = 0.2

Table 8. The calculation of population density for each route

The total cost is adjusted by the ratio of mortality rate because the costs due to fatalities tend to be much higher than injuries (Table 9). The ratio is multiplied by 0.85, the part of fatalities cost in the total cost. Purchasing power parity (PPP) and inflation rate are used to adjust the regional and temporal difference in the price level, as suggested by EC (2019).

	Cost (€)					Ratio (%)
	Human costs	**Production loss**	**Medical costs**	**Administrative costs**	**Total external cost per casualty**	
Fatalities	2,907,921	361,358	2,722	1,909	3,273,910	**85.01**
Serious injuries	464,844	24,055	8,380	1,312	498,591	13.08
Slight injuries	35,757	1,472	721	564	38,514	1.01
Total	3,408,522	386,885	11,823	3,785	3,811,015	100

Table 9. The accident cost per casualty by components (EC, 2019)

Figure 5 describes the adjustment method of the accident cost.

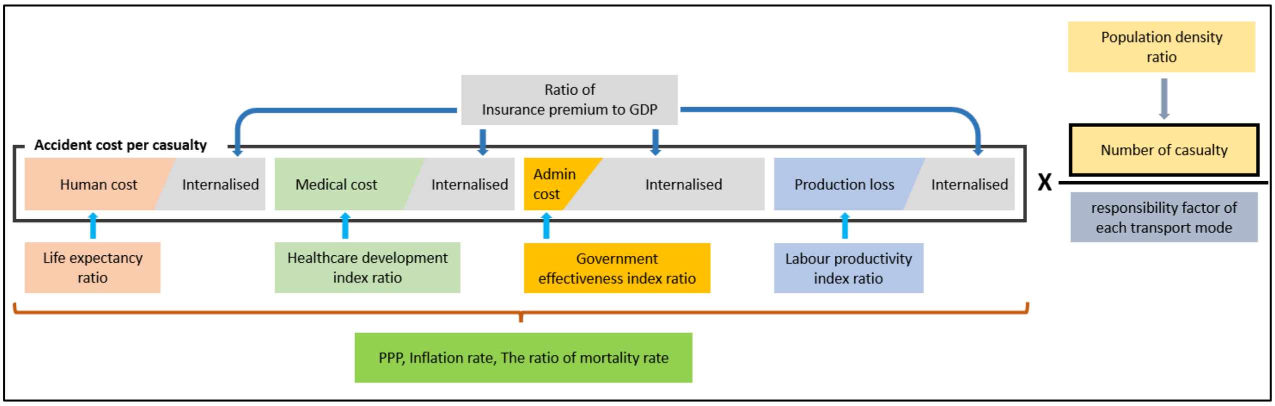

Figure 5. The calculation method of accident cost weighting factor

The weighting factor ($w_{m,t}$) and the average accident cost of each transport mode are calculated as below (Table 10).

Transport mode	**Weight**	**Average accident cost (€-cent per tkm)**
HGV	5.69	7.40
Diesel freight train	0.69	0.07
Electric freight train		0.07

Table 10. The average accident cost of each mode for Oman

2.2.2. Noise cost

a. The approach by EC (2019)

EC (2019) categorises the noise cost into the annoyance cost and health cost (Table 11).

Component	Description
Annoyance cost	The negative responses to traffic noise: irritation, disappointment, anxiety and exhaustion (WHO, 2011)
Health cost	Negative health effects of traffic noise: sleep disturbance, stroke, and diabetes (WHO, 2018)

Table 11. The categories of noise costs (EC, 2019)

EC (2019) calculates the total noise cost first by multiplying the noise cost per person and the number of people exposed to noise, then allocate it to each transport mode using transport performance factor from CE Delft, INFRAS and Fraunhofer ISI (2011), CE Delft and VU (2014), and VROM (2006).

The number of people exposed to noise is extrapolated from Eurostat (2018), and noise cost per person is based on Bristow et al. (2015), Defra (2014), and EEA's noise maps. We can describe the noise cost estimation method from EC (2019) below (Figure 6).

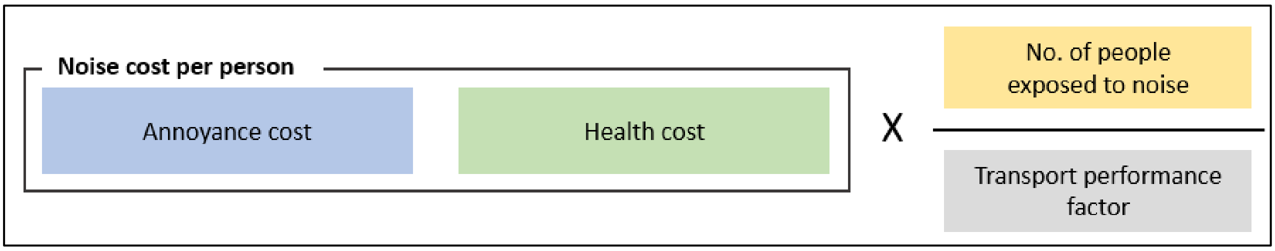

Figure 6. Estimation method of noise cost for EU28

Based on the explanations from EC (2019), we can infer the equation to calculate the noise cost as below:

Noise accident cost of a transport mode (m) during the period (t):

$$C_{m,t} = \frac{(c_a + c_b) * n_t}{r_m}$$

c_a, c_b: *Annoyance cost, Health cost*

n_t: *number of people exposed to noise during the period t*

r_m: *performance factor of the transport mode m*

Table 12 shows the average noise costs from EC (2019).

Transport mode	Average noise cost (€-cent per tkm)
HGV	0.4
Diesel freight train	0.4
Electric freight train	0.6

Table 12. The average noise cost for modes for the EU28 (EC, 2019)

b. Suggested approach

The following equation is to calculate noise cost for Oman:

$$C^*_{m,t} = \frac{(c^*_a + c^*_b) * n^*_t}{r_m}$$

Assuming the performance factor r_m is identical across countries (EC, 2019), the weighting factor $w_{m,t}$ can be written as follows:

$$\frac{C^*_{m,t}}{C_{m,t}} = w_{m,t} = r_c * r_{n,t}$$

r_c: The ratio of cost per person $(c^*_a + c^*_b)/(c_a + c_b)$

$r_{n,t}$: The ratio of the number of people exposed to the noise during period t (n^*_t/n_t)

According to EC (2019), the robustness of the results depends on the number of people exposed, which can be extrapolated from the population density data. They also suggest considering the medical costs, which can be adjusted by the healthcare development index. Meanwhile, PPP and the inflation rate are used for the price level difference. Table 13 and Figure 7 show the adjustment method to calculate the weighting factor $w_{m,t}$ for noise cost.

Element	Calculation method	Source
r_c	$PPP_{2016} * (1 + \text{inflation rate}_{2016\text{-}2021})$	World Bank (2023)
	Healthcare development index ratio (EU28/Oman)	Statista (2023)
$r_{n,t}$	Population density ratio (Oman/EU28), Oman: 0.5 * Population_density_of_Muscat_Expressway + 0.5 * Population_density_of_Batinah_Expressway	Geo-ref (2023), Luminocity3D (2023)

Table 13. The calculation methods for each element of the noise cost weighting factor

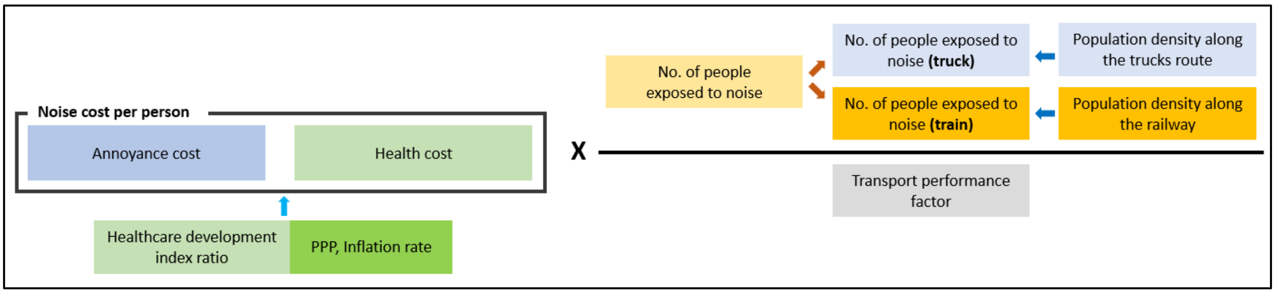

Figure 7. The calculation method of noise cost weighting factor

The calculated weighting factor and average noise cost of each transport mode are as follows (Table 14).

Transport mode	Weighting factor	Average noise cost (€-cent per tkm)
HGV	1.76	0.70
Diesel freight train	1.24	0.50
Electric freight train		0.75

Table 14. The weighting factor and average noise cost of each mode for Oman

2.2.3. Congestion cost

a. The approach by EC (2019)

EC (2019) suggests two approaches to calculate the congestion cost; delay cost and deadweight loss (DWL) (Table 15).

Component	Description
Delay cost	The value of time lost relative to a free-flow situation
Deadweight loss (DWL)	Social cost in addition to the delay cost by slowing down the other vehicles on the road

Table 15. The categories of congestion costs (EC, 2019)

Figure 8 shows the graphical method of Delay cost and DWL.

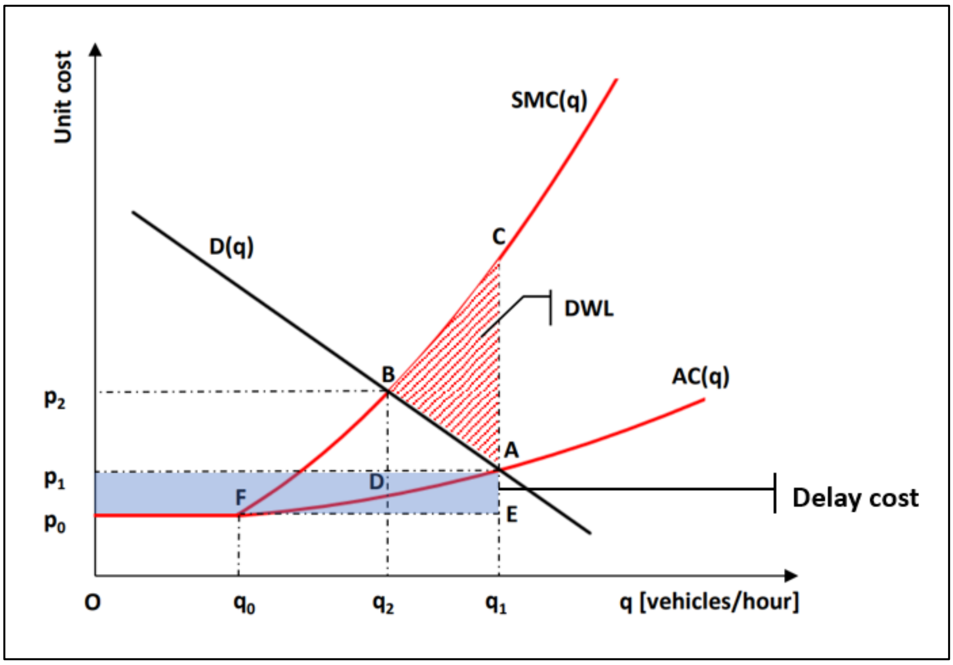

Figure 8. The delay cost and the deadweight loss of noise externalities (EC, 2019)

Table 16 contains the descriptions of the components for calculating Delay cost and DWL.

Component	Description
D(q)	The demand curve; represents the demand on the road usage in the number of vehicles according to each unit cost
Unit cost	The value of time (VOT) spent on the road
q_0	Congestion threshold; the number of vehicles above q_0 leads to congestion, increasing the average cost (AC) and the social marginal cost (SMC)
AC(q)	Average unit cost for the road users with q vehicles/hour
SMC(q)	Social marginal unit cost with q vehicles/hour, including the social cost by slowing down all the other vehicles for adding one more vehicle to the road, in addition to AC(q)

Table 16. The descriptions of each congestion cost component (EC, 2019)

AC(q) and SMC(q) are from speed-flow functions; thus, they get affected by the road capacity (lower capacity, higher AC(q) and SMC(q) for the same vehicle number, again leading to higher delay cost and DWL).

Delay cost is the area of p0EAp1, the cost of delay for road users due to congestion. DWL refers to the additional social cost of congestion.

EC (2019) first calculates the total congestion cost of passenger cars based on the information from Table 17. Then, they use the Passenger Car Equivalent coefficient (PCEs) to calculate the average congestion cost for each vehicle type. For trains, EC (2019) stated that the value varies greatly in the range of 0.0 to 43.20 €-cent/tkm by studies.

Component	Estimation method & source
D(q)	r = m * AC + k, r: flow/capacity ratio, AC: average time cost of driving, m: cost elasticity, k: constant factor, Litman (2010), Oum et al. (1990)
VOT	HEATCO (2006), Comité National Routier (2016), Significance, VU University Amsterdam, and John Bates Services (2012)
Road network characteristics	Transport eUropean Simulation Tool (TRUST)
Population	Eurostat
PCEs	The relative size of the other vehicle types to passenger car (car=1, HGV=2), TRUST

Table 17. The sources and estimation methods of each congestion cost component (EC, 2019)

Based on the components from Table 14, the delay cost and DWL can be calculated below (EC, 2019):

$$Delay\ cost\ (C_d/vkm) = (T - T_0) * VOT * \ OF$$

T: The actual travel time in the assumed congestion condition

T_0: The travel time in free flow condition

OF: Occupancy factor (The average number of people per vehicle)

$$DWL\ (C_{dwl}/vkm) = \frac{(l_1 - l_2)*(SC_1 - PC_1)}{2} * \frac{1}{l_1}$$

l_2: optimal load/capacity ratio, l_1: actual load/capacity ratio

SC_1: social congestion cost, PC_1: private congestion cost

As congestion is more about the number and size of vehicles than weight, each cost is estimated per vehicle-km (vkm). We can describe the congestion cost estimation method from EC (2019) below (Figure 9).

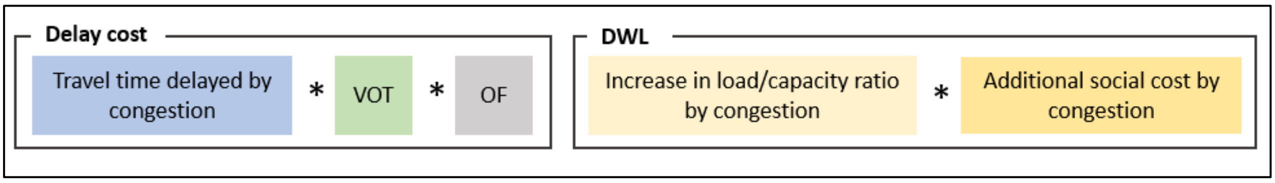

Figure 9. Estimation method of congestion cost for EU28

Table 18 shows the congestion cost for HGV from EC (2019).

Transport mode	Average noise cost (€-cent per vkm)	
	Delay cost	Deadweight loss cost
HGV (Inter-urban)	0.45	0.05

Table 18. The average congestion cost of HGV for the EU28 (EC, 2019)

b. Suggested approach

According to EC (2019), some factors affect the congestion cost but are not explicitly shown in the equations. First, the population density affects the congestion cost (higher density, higher cost). Also, the road traffic information is calculated by assuming 230 work days, and the congestion cost is proportional to work days.

Delay cost and DWL for Oman can be written as below:

$$Delay\ cost\ (c_d^*/vkm) = (\overline{T - T_0}) * VOT^* * \ \overline{OF}$$

$$DWL\ (c_{dwl}^*/vkm) = \frac{(l_1^* - l_2^*)*(SC_1^* - PC_1^*)}{2} * \frac{1}{l_1^*}$$

The weighting factors for delay cost (w_d) and DWL (W_{dwl}) can be written as follows:

$$\frac{C_d^*}{C_d} = w_d = r_v$$

$$\frac{C_{dwl}^*}{C_{dwl}} = w_{dwl} = r_l * r_{adc}$$

r_v: The ratio of VOT (VOT^*/VOT)

r_l: The ratio of increase in load/capacity ratio by congestion ($\frac{(l_1^* - l_2^*)/l_1^*}{(l_1 - l_2)/l_1}$)

r_{adc}: The ratio of additional social cost by congestion ($(SC_1^* - PC_1^*)/(SC_1 - PC_1)$)

Figure 10 and Table 19 show the calculation method of congestion cost weighting factor. Delay cost is adjusted by life expectancy ratio. DWL is adjusted by multiple factors. First, we assume r_l can directly be adjusted by the population density ratio and road capacity ratio (r_l increases with higher density and lower capacity). Secondly, r_{adc} is assumed to increase with more workdays or higher labour productivity.

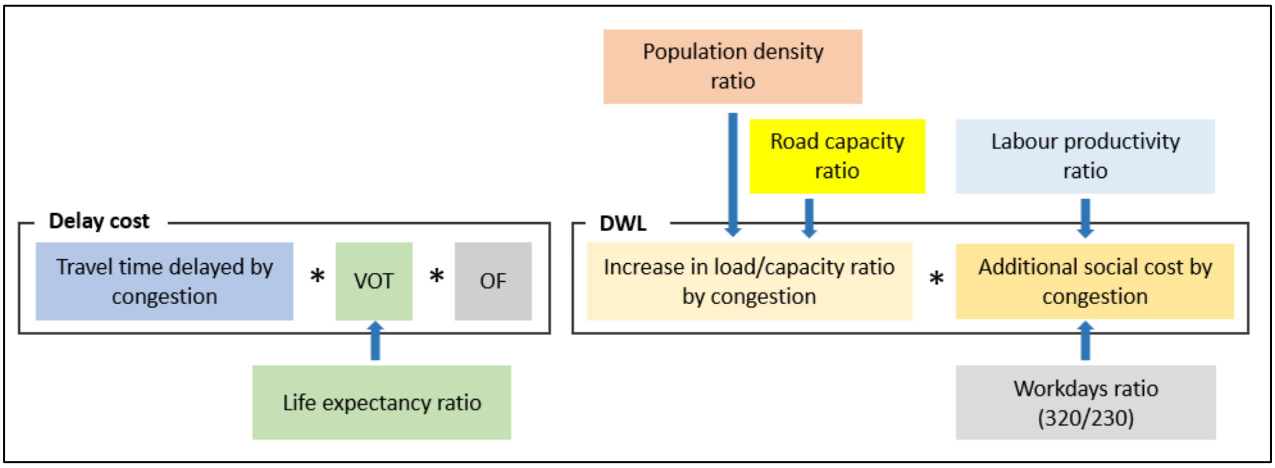

Figure 10. The calculation method of congestion cost weighting factor

Element	Calculation method	Source
r_v	Life expectancy ratio (EU28/Oman)	World Bank (2023)
r_l	Population density ratio (Oman/EU28), Oman: 0.5 * Population_density_of_Muscat_Expressway + 0.5 * Population_density_of_Batinah_Expressway	Geo-ref (2023), Luminocity3D (2023)
	Road capacity ratio (EU28/Oman), Muscat and Batinah Expressway: eight-lane highway, EU28: two to four lanes (average: three), EU28/Oman = 3/8	Muscat and Batinah: Times of Oman (2018), EU28: EC (2019)
r_{adc}	Labour productivity ratio (Oman/EU28)	World Bank (2023)
w_d, w_{dwl}	PPP_{2016} * (1 + inflation $rate_{2016\text{-}2021}$)	World Bank (2023)

Table 19. The calculation methods for each element of the congestion cost weighting factor

Table 20 shows the average congestion cost for Oman. We assume that the railway will be built with capacity to meet the expected freight demand; thus, each cost will be 0.1 and 0.01.

Transport mode	Delay Cost		DWL	
	Weight	Cost (€-cent per vkm)	Weight	Cost (€-cent per vkm)
HGV (Inter-urban)	0.88	0.40	0.64	0.03
Diesel freight train	N/A	0.10	N/A	0.01
Electric freight train	N/A	0.10	N/A	0.01

Table 20. The weighting factor and average congestion cost of each mode for Oman

3. Results

Table 21 summarises the average external costs of each category for Oman.

	Average cost			
Transport mode	Accident cost (€-cent / tkm)	Noise Cost (€-cent / tkm)	Congestion Cost (€-cent / vkm)	
			Delay cost	DWL
HGV (Inter-urban)	7.40	0.70	0.40	0.03
Diesel freight train	0.07	0.50	0.10	0.01
Electric freight train	0.07	0.75	0.10	0.01

Table 21. The average external costs for Oman

Table 22 shows the total external costs per vehicle category based on the assumptions from Table 1.

	Total cost (€-cent)		
Transport mode	Accident cost	Noise Cost	Congestion Cost
HGV (Inter-urban)	229,446,250	21,704,375	242,412.50 (= 225,500 + 16,912.50)
Diesel freight train	2,152,500	15,375,000	676.50 (= 615 + 61.50)
Electric freight train	2,152,500	23,062,500	676.50 (= 615 + 61.50)

Table 22. The total external costs for Oman

To compare each mode, we can calculate net costs below (Table 23). The result shows that the modal transition to diesel trains reduces externalities equal to 2,034,624.29 £ every workday, and electric trains equal to 1,967,743.04 £.

	Net cost compared to HGV (£, 1 €-cent = 0.0087 £, per workday)			
Transport mode	Accident cost	Noise Cost	Congestion Cost	Total
Diesel freight train	-1,977,455.63	-55,065.56	-2,103.10	-2,034,624.29
Electric freight train	-1,977,455.63	11,815.69	-2,103.10	-1,967,743.04

Table 23. The net external costs compared to HGV for Oman

The yearly net cost is 651,079,773.02 £ in total for diesel trains and 629,677,773.02 £ for electric trains (320 work days).

4. Discussion

The calculation of intermodal transport externalities tells us how feasible the modal transition is in terms of public interest. Diesel freight trains seem to be the most feasible option, followed by electric trains. This is because EC (2019) assumed higher noise level for electric trains than diesel trains. Further research is required to compare these two modes using detailed noise levels and ranges.

The overall issue with the calculation methods is that detailed calculations or statistics were not provided in EC (2019). The adjustment methods by ratio or weights were chosen to avoid this issue as much as possible. However, this study still needs improvement with more statistics and sophisticated methods. Even the currently developed and used methods are often regarded as uncertain (Schroder et al., 2022). Therefore, comprehensive studies on the estimation methodology itself are also necessary.

Moreover, this study does not consider any cost of electricity generation, which may lead to different results in terms of cost or the superiority relationship between options. Even the soring energy cost itself can make operators switch from electric to diesel trains, according to Lancefield (2021) and Hern (2022). Thus, further studies that include the generation costs regarding externality and market profit are needed.

5. Conclusion

This paper presented an intermodal externality study for deep-sea containers between Sohar and Muscat, aligned with the project ‘Rail Growth Limited Carbon Footprint’. The unit costs from the Handbook on the external costs of transport (EC, 2019) were adjusted by statistics on population, insurance premium to GDP, labour productivity, life expectancy, road capacity, purchase power parity, inflation rate, healthcare development, government effectiveness, and the mortality rate of traffic accidents. The diesel train option appears to be the most feasible, followed by electric trains and trucks. However, this study needs improvement regarding the calculation method or the generation cost for electric trains. Also, the costs or the superiority between modes can change anytime by circumstances, including technological progress. Further studies are needed to determine the best option for both externalities and profits.

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