The climate and environmental effects of policies for moving freight transport from road to other modes: The case of Sweden

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Abstract

The objective of this paper is to determine how policy instruments which aim to achieve a modal shift of long-haul freight transport from road to rail or sea affect the direct emissions to air of greenhouse gases, nitrogen oxides, sulfur dioxides, volatile organic compounds and particulate matter. The analysis is conducted in two stages. First, a range of forecasts reflecting different assumptions are applied using the Swedish national freight transport model (SAMGODS) to derive a range of possible future developments of emissions levels up to 2030 and 2040. This has involved determining emission factors per tonne-km for each of the SAMGODS model's six road freight vehicle types, eleven freight train variants and 22 ship types. The model outcomes are then compared to those of the base year of 2017. Second, the effects of two hypothetical modal shift policy instruments are analyzed with respect to their potential impact on emissions to air. The effects of these two policy instruments are evaluated for the base-year of 2017 and for the 2030 and 2040 forecasts. The paper also analyzes whether the Swedish climate objective for domestic transport in 2030 can be expected to be fulfilled given different forecasts and policy instruments.

Within the context of a predicted large increase in total freight tonne-km (between 31 and 53%), emissions of greenhouse gases are calculated to decrease by 50 to 60% by 2040. This means that the Swedish freight transport sector will not achieve its share of greenhouse gas emissions reductions necessary to attain the national climate objective of a 70% reduction by 2030. Emissions of nitrogen oxides (NOx) are forecast to reduce by between 60 and 75%, emissions of sulfur dioxides to reduce by between 41 and 50%, emissions of volatile organic compounds to increase by 8 to 30% and emissions of particulate matter (from exhaust and tyre/road wear) are calculated to increase by between 13 and 33%. Using modal shift policy instruments to achieve greenhouse gas reductions is calculated to attain worse results over time, by 2040 it might even be counterproductive.

Keywords

Freight transport, emissions, climate goals, environmental quality objectives, emission factors, forecasts, policy analysis

JEL Codes

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1. Introduction

The emissions to air from transport affect both the global climate and the environment; the climate through greenhouse gas (GHG) emissions and the environment through emissions of acidifying, eutrophying and ozone-forming substances. Road transport mainly gives rise to emissions of GHG, nitrogen oxides (NO_X), hydrocarbons (HC), volatile organic compounds (VOC) and exhaust and wear particulate matter (PM 2.5 and PM10). Shipping fairs better when it comes to GHG emissions but worse considering other emissions. Shipping is also mainly responsible for the emission sulfur dioxide (SO_2). Rail transport gives rise to only very low emissions of exhaust gases and wear PM. In order to manage emissions at a national level, in 1999 the Swedish Government established 16 national environmental quality objectives (Swedish Environmental Protection Agency, 2022), that together provide a set of guidelines that shall apply to sustainable development. In terms of this study of the direct emissions to air from freight transport, the four most relevant national environmental quality objectives are as follows: 'Limited climate impact', 'Fresh air', 'No eutrophication' and 'Only natural acidification'.

In the freight transport sector in Sweden, road and shipping account for almost all GHG emissions (emissions of carbon dioxide equivalents (CO2eq)). Rail transport is mainly electric and, therefore, has very low GHG emissions. The environmental quality goal 'Limited climate impact' stipulates that GHG emissions from domestic transport (excl. aviation) shall be 70 % lower in 2030 compared with 2010 and, as an overall milestone, it is stated that by 2045, Sweden will have no net emissions of GHG into the atmosphere (Swedish Government, 2017). For the other three national environmental quality objectives considered within this paper, similar highly specific targets do not exist.

In general terms, progress towards the national environmental quality objectives can be achieved within Sweden's freight transport sector through (a) improved transport and/or energy efficiency; (b) switching to less environmentally damaging energy carriers; (c) transferring freight to less environmentally damaging modes of transport; and (d) reducing transport demand. The focus of the analysis contained within this paper is on the transfer of freight from road to rail and shipping, based on the underpinning assumption that rail and waterborne transport can perform the same level of transport work, but with a lower energy consumption and/or lower emissions to air.

The EU White Paper "Roadmap to a Single European Transport Area - A Competitive and Resource-Efficient Transport System" has the aim that 30% of long-distance (over 300 km) freight transport that is currently undertaken by road should transfer to rail or waterborne transport by 2030. By 2050, more than 50% of this transport work should have moved to rail and waterborne transport (European Commission, 2011). Sweden does not have the corresponding quantitative transfer targets (Vierth et al., 2019), but the National Freight Transport Strategy contains a commitment to (a) achieving transport policy goals; (b) strengthening the competitiveness of business; and (c) promoting a transfer of freight transport from road to rail and shipping (Swedish Government, 2018). Similarly, the Swedish Transport Administration (2020a) has published a 'Roadmap for the transfer of freight transport from road to rail and shipping'. In connection with infrastructure planning, however, the Swedish Transport Administration (2020b, p.30) explicitly states that "Road transport will continue to be important for maintaining accessibility throughout the country and for transporting goods where shipping or rail is not an option", At both EU and national level, policy instruments are also being implemented to streamline road freight transport and/or reduce its emissions to air. An example in Sweden is the plan to increase the proportion of state roads that allow trucks up to a maximum weight of 74 tonnes, instead of the current maximum of 64 tonnes (Swedish Transport Administration, 2020c). An example at EU level is the regulation of CO_2 emissions from new heavy vehicles that will be reduced by 15% by 2025 and by 30% by 2030, compared to the reference period of 1 July 2019 - 30 June 2020 (EU, 2019).

Within this context, therefore, the objective of this paper is to develop forecasts of the likely impact of policy instruments – a wear and tear tax for road transports and an ecobonus scheme to promote the transfer of Sweden's long-distance freight transport from road to rail and shipping – on the direct

emissions to air of CO_{2e}, NO_X, SO_2, HC/VOC and PM. On the basis of the forecasts derived, the paper then goes on to more specifically analyze whether Sweden's climate targets are expected to be achieved.

The paper is structured as follows: Section 2 sets the scene for the ensuing analysis by describing Sweden's policy context. The current modal split for freight transport is presented, as is the nature of national forecasts of freight transport and the relevance of these to the achievement of national environmental quality objectives. The methodology for the reported analysis is outlined in section 3, with a focus on the nature of the forecast models which are estimated and, more specifically, how emission factors have been calculated for each of the modal alternatives. The results of the analysis are presented in section 4 and the predicted impact of the two potential policy instruments is assessed in section 5. A discussion of the results and their implications for attaining Sweden's national quality objectives is contained in section 6 and conclusions are drawn in section 7.

2. The Swedish policy context

As is shown in Table 1 , in 2017, road transport accounted for approximately 48% of freight transport work on Swedish territory, rail transport accounted for approximately 19% and shipping for approximately 33%. According to official statistics, therefore, road transport gave rise to emissions of 3.3 million tonnes of CO_2-eq, or 76% of the total GHG emissions from freight transport on Swedish territory. Rail transport accounted for about 1% and shipping for about 23%.

Table 1. Transport work and emissions to air from freight transport on Swedish territory in 2017.

Mode	Tonne-km (billions)	CO_2-eq (ktonnes)	NO_X (tonnes)	SO_2 (tonnes)	HC/VOC (tonnes)	Exhaust PM (tonnes)
Road	51.5	3,337	11,611	8.2	266.6	251.7
Rail	20.8	42	497	0.1	40.9	19.1
Shipping[1]	35.6	1,017	23,346	634.6	951.8	317.3
Total*	107.9	4,396	35,454	643.9	1,259.3	588.1

Note: excluding air freight that only accounts for around 0.1 percent of transport work on Swedish territory.
Sources: Traffic Analysis (2021), Statistics Sweden (2021a), Statistics Sweden (2021b), own calculations for freight traffic's share of shipping emissions.

As revealed in Table 2, the average greenhouse gas emissions per tonne-km were thus highest for road transport (0.0648 kg per tonne-km), second highest for shipping (0.0286 kg per tonne-km) and lowest for rail transport (0.0020kg per tonne-km).

Table 2. Average emission factors per transport mode in 2017.

Mode	CO_2-eq (kg/tonne-km)	NO_X (g/km)	SO_2 (g/km)	HC/VOC (g/km)	Exhaust PM (g/km)
Road	0.065	0.226	0.0002	0.005	0.0049
Rail	0.002	0.024	0.0000	0.002	0.0009
Shipping	0.029	0.656	0.0178	0.027	0.0089
Total	0.041	0.329	0.0060	0.012	0.0054

Estimated GHG emissions per tonne-km are lower for shipping than for road transport because shipping is more energy efficient. Emissions of SO_2, NO_X, HC/VOC and exhaust PM per tonne-km are, however, consistently calculated to be higher for shipping than for road transport. This is explained by the fact that there have been gradually stricter emissions requirements for new trucks in the form of environmental classes (Euro classes) for over 30 years (EU, 1987) and that corresponding regulations

[1] Shipping on Swedish territory includes domestic shipping and the part of international shipping that take place on Swedish territory.

for ships and shipping fuels have been implemented much later. For example, the IMO's stricter requirements for sulfur content in fuels, especially within the designated Sulfur emission control areas where the Baltic Sea and the North Sea are included, have only applied since 2015. Stricter requirements for emissions of nitrogen oxides have been applied within the Baltic and North seas from 2021 (IMO, 2021). The emission levels for rail specified in Table 2 refer to diesel-powered passenger and freight trains. Recognizing that the emissions from rail are so much lower than the emissions from both road and sea transport, the analysis undertaken within this paper makes the simplifying assumption of zero emissions from freight transport by rail.

The original plan for the analysis undertaken herein was to test policy instruments against the Swedish Transport Administration's official forecast for freight transport in 2030 (Swedish Transport Administration, 2015). This forecast was structured in such a way that it accounted for both decided and implemented policy instruments, as well as for infrastructure developments that had already been decided upon and/or initiated before 2030. In 2020, however, the Swedish Transport Administration published new official forecasts for passenger and freight transport for the year 2040, which, unlike previous forecasts, assume that the climate goals of 2030 and 2045 will be achieved.

In order to meet the requirement to achieve climate goals by 2030, the official forecast (Swedish Transport Administration, 2020d,e) assumes that energy use from biofuels for the entire road transport sector (passenger and freight transport) will increase from 20 TWh in 2020 (Swedish Energy Agency, 2021a) to 29 TWh by 2030 and that by 2040 the equivalent energy mix will comprise 12 TWh electricity, 22 TWh biofuels and 7 TWh fossil fuels (Swedish Transport Administration, 2020g). This means that biofuel use would need to increase by about 10 TWh over the next about ten years (see Table 3). As of 2020, Sweden's domestic production of biogas is about 2 TWh and there is a production capacity for biofuels (in addition to the biogas) of about 6 TWh. Most of the biofuels used are imported and about 80% of the liquid biofuels (excluding biogas) are based on foreign raw materials (Swedish Energy Agency, 2021b). However, the Swedish Energy Agency (2021b) estimates that it would be possible to produce a total of about 30 TWh of biofuels by 2030, but this would require extensive expansion of production capacity in a very short time.

Table 3: Forecasted need for biofuels and electricity (TWh) in transport sector to achieve Sweden's climate goals.

	2020	2030	2040
Biofuels	20	29	22
Electricity	3.1	6.5	12

Source: Swedish Transport Administration (2020g,h) and Swedish Energy Agency (2021a)

Electricity use within Sweden's domestic transport sector in 2020 was approximately 3.1 TWh. The official forecast for 2040 entails an increase of approximately 9 TWh (see Table 3). An improvement in the energy efficiency of heavy trucks (over 3.5 tonnes) of 35% is assumed in the official forecast for 2040, Swedish Transport Administration, 2020d). This corresponds to an aggregate reduction in fuel consumption per vehicle km of 35% between 2017 and 2040. However, the conditions for electrification are estimated to vary over the size of trucks (Swedish Transport Administration, 2020e). This means that the distance-dependent costs for trucks under 25 tonnes are estimated to be 5 to 12% lower in 2040 compared to 2017 (at fixed prices). In the heavier segment, where electrification is not expected to be so significant, the distance-dependent costs are estimated to be 4 to 8 % higher in 2040 (at fixed prices) since biofuels are expected to drive up the cost of diesel.

In contrast to the assumptions concerning the road freight sector, for rail and sea transport in the official forecast (Swedish Transport Administration, 2020d) does not assume any efficiencies. Furthermore, the same fuel mix is assumed for 2040 as was applicable in the base-case year of 2017, despite the ongoing move towards the use of renewable fuels in the maritime sector, Swedish

Transport Administration (2020d). For shipping, this means that distance-dependent costs increase by almost 35% (in fixed prices) by 2040, mainly because fuel prices are assumed to increase. For railways, higher track charges and increased electricity prices are estimated to lead to approximately 64% higher costs per km. See Johansson et al. (2023) för details regarding costs.

3. Methodology

3.1 Different forecasts

To provide a different perspective and to broaden the possibilities for analysis, a set of alternative forecasts for 2030 and 2040 are developed within this paper that treat all modes of freight transport equally with respect to Sweden's decided policy instruments and expected future technical/industrial developments.

- The forecast FAST ELECTRIFICATION assumes a relatively high degree of electrification within the road freight sector by 2040 (30 % of transport work is handled by electric trucks) and a high use of biofuels for the part not electrified. Fuel consumption is assumed to be 35 % lower in 2040. This is in line with Sweden's official forecast (Swedish Transport Administration, 2020d) and this is deemed required for Sweden to meet set climate goals for 2030 and 2045. In addition to the official forecast it is assumed that: (a) a 35% energy efficiency improvement from 2017 until 2040 is assumed to apply also to electric trucks; (b) for rail traffic, 10% lower electricity consumption is assumed 2040; (c) up to 25% lower fuel consumption is assumed for ships 2040, depending on the particular ship segment considered; and (d) for shipping, an increased use of alternative fuels in certain segments is also assumed, especially for smaller vessels and vessels operating regular services.
- The forecast SLOW ELECTRIFICATION assumes the same development for maritime traffic as the forecast FAST ELECTRIFICATION, but that there is slower technological development within the road transport sector, such that 10% (instead of 30%) of road transport work is handled with electric vehicles and that fuel and electricity consumption is reduced by 15% (instead of 35%) between 2017 and 2040. In addition, railways are assumed to have the same operating costs as in the base year 2017.
- The forecast SLOW ELECTRIFICATION + lower growth is a variant of the forecast SLOW ELECTRIFICATION which assumes a 50% lower growth in freight transport demand.
- The forecast SLOW ELECTRIFICATION + 74 tonne trucks is another tested variant of the forecast SLOW ELECTRIFICATION which allows trucks with a total weight of up to 74 tonnes (instead of 64 tonnes) to be permitted on major national roads in Sweden.

A summary of the assumptions underpinning each of the main forecast models defined above for each of the freight transport modes is shown in Table 4.

Table 4. Overview of assumptions regarding electrification, fuel changes and efficiencies for the various modes of transport in each of the forecasts for 2040

Forecast	Road	Rail	Shipping
FAST ELECTRIFICATION	30% electrification (tkm)	Not relevant	10% electrification (tkm ropax, ferries)
	70% biofuels (fuel used)	Not relevant	53% LNG and biofuels (fuel used)
	35% lower fuel consumption	Same as 2017	Up to 25% lower fuel consumption depending on ship segment according to IMO (2020)
	35% lower electricity consumption	10% lower electricity consumption	Up to 25% lower electricity consumption for electrified vessels
SLOW ELECTRIFICATION	10% electrification (tkm)	Not relevant	10% electrification (tkm ropax, ferries)
	70% biofuels (fuel used)	Not relevant	53% LNG and biofuels (used)
	15% lower fuel consumption	Same operating cost as 2017	25% lower fuel consumption
	15% lower electricity consumption	Same operating cost as 2017	Up to 25% lower electricity consumption for electrified vessels

For the forecasts produced for 2030 freight transport demand between 2017 and 2030 has been assumed to have the same annual growth rate as freight transport demand between 2017 and 2040. The development of efficiency enhancements and policy interventions are assumed to be approximately half completed by 2030.

To evaluate how policy instruments, affect the emissions that result from a freight modal transfer from road to rail and shipping, the various assumptions about the development of vehicles and fuels described in Table 4 are utilized within the Swedish Transport Administration's freight transport model (SAMGODS). In addition to the assumptions specified in Table 4, the model forecasts for 2030 and 2040 are based on the same transport costs and infrastructure used in Swedish Transport Administration (2020d). The structure, workings and application of the SAMGODS model and how it has been applied for our purposes is fully described in Johansson et al. (2023), where the modal transfers achieved under each of the model forecasts have been calculated. The resulting modal split under each of the five forecasts is given in Table 5.

Table 5. Distribution of transport work in base year 2017 and the various model forecasts for 2040 (percentage in Swedish territory)

	Road	Rail	Shipping
Base 2017	47.7	19.3	33.0
FAST ELECTRIFICATION 2040	47.9	19.1	32.9
SLOW ELECTRIFICATION 2040	45.2	20.1	34.8
SLOW ELECTRIFICATION (50% demand) 2040	44.9	21.7	33.4
SLOW ELECTRIFICATION (trucks of 74 tonnes) 2040	47.8	18.4	33.8

The analysis of the effects of specific, but hypothetical, policy instruments – see section 5 – that have the intention to promote a modal transfer from road to rail and shipping is undertaken in two steps. In the first step, the level of emissions of the different modes of transport under the different forecasts are calculated for 2030 and 2040. In the second step, the outcomes are then compared for the two forecast years and for the base-year of 2017 to deduce the differential impacts on emissions to air in the presence, or otherwise, of the policy instruments.

3.2 Calculation of emissions factors

To calculate the emissions associated with each of the forecasts, emission factors related to the amount of predicted transport work undertaken by different vehicle and vessel types in the SAMGODS model have been developed. This relates, therefore, to six truck types, eleven train types and 22 ship types that give rise to per tonne-km CO_2-eq, SO_2, NO_X, HC/VOC and PM. The fact that the emission factors are related to transport work (tonne-km), instead of traffic work (vehicle-km), follows from the fact that the Freight module within the SAMGODS model provides more stable results for transport work. For road traffic, comparisons were made to investigate whether the use of emission factors per tonne-km gives deviating results compared to a calculation based on vehicle km. This showed that there were only small differences in results. A comparison for rail and sea traffic is more difficult to carry out, but it is also the norm for emission factors to be specified in terms of tonne-km (see for example the European Commission's manual for external costs – European Commission, 2019). This section describes the emission factors used in the analysis and the methods and assumptions behind their estimation. For road traffic, emission factors related to transport work with different truck variants have been calculated using NTMCalc (NTM, 2021). The vehicle types and conditions used in the calculations are reported in Table 6. The load factor has been set to a level that causes the emission factors to emit CO_2-eq in line with the statistics for 2017. Results have been produced for Euro classes 3, 4, 5 and 6 and the outcome has been weighted according to the distribution of the number of vehicles in each class in 2017 according to HBEFA (2019).

Table 6. Input values used when extracting road emission factors from NTMCalc 4.0.

	Truck 20-26 tonnes	**Truck 34-40 tonnes**	**Truck 50-60 tonnes**
Distance used for calculation (km)	468.83	468.83	468.83
Fuel type	Diesel B7 – Swe.	Diesel B7 – Swe.	Diesel B7 – Swe.
Road type	Average	Average	Average
Euro class	3,4, 5 & 6	3,4, 5 & 6	3,4, 5 & 6
Hilliness	2%	2%	2%
Average load factor	30%	30%	30%
Capacity (tonnes)	15	28	47
Fuel consumption (l/km)	0.222	0.271	0.352

For the forecast years 2030 and 2040, trucks complying with Euro class 6 have been used. In these cases, the emission factors have been calculated with the reduced fuel consumption assumed in the forecasts outlined in Table 4. The approach results in the emission factors reported in Table 7.

Table 7. Road emission factors with the current fuel mix in 2017, 2030 and 2040 according to calculations with NTMCalc 4.0

Truck segment	CO_2-eq [g / tonne-km]	NO_X [mg / tonne-km]	SO_2 [mg / tonne-km]	HC [mg / tonne-km]	PM [mg / tonne-km]
2017					
Local and regional distribution	118,00	577,51	0,15	16,56	10,11
Remote distribution	77,82	242,71	0,10	4,55	3,40
Heavy transport	59,94	161,41	0,07	3,49	2,26
2030					
Local and regional distribution	97,96	95,45	0,12	4,00	0,57
Remote distribution	64,44	49,06	0,08	2,35	0,27
Heavy transport	49,52	29,25	0,06	1,69	0,21
2040					
Local and regional distribution	77,37	75,40	0,10	3,16	0,45
Remote distribution	50,92	38,77	0,06	1,85	0,21
Heavy transport	38,03	22,46	0,05	1,30	0,16

Note: The calculations using NTMCalc for 2030 and 2040 do not include a higher admixture of biofuels (which is assumed in the forecasts), so this is corrected for when calculating future carbon dioxide emissions (lower tank to wheel emissions). For other emissions, biofuels are assumed to give the same emissions level as the current fuel mix. Source: NTM (2021).

In the forecast we correct the CO_2-eq emissions according to assumed level of bio fuels 2030 and 2040 and tank to wheel emissions from bio fuels set to zero. For other emissions, biofuels are assumed to give the same emissions level as the current fuel mix.

Applying the modelled emission factors as shown in Table 7, the approach gives overall results for the base year of 2017 as shown in Table 8, where the modelled total emission volumes are compared to the national statistics for domestic road freight traffic under diesel operation in 2017.

Table 8. Emissions with estimated transport work according to SAMGOD's base year of 2017 and emission factors according Table 7, as compared to official statistics.

Truck segment	CO_2-eq (ktonnes)	NO_X (tonnes)	SO_2 (tonnes)	HC/VOC (tonnes)	PM (tonnes)
Local and regional distribution	203	885	0.3	29	17
Remote distribution	973	3034	1.2	57	43
Heavy transport	2159	5815	2.7	1.26	81
Total – Estimated	3336	9844	4.2	211.1	141.3
Total – official statistics	3337	11611	8.2	266.6	251.7

Since the method applied for estimating the emission factors is adjusted for CO2 emissions, the outcome for CO2 emissions will naturally fall into line with the national statistics, but other results are lower than the official published statistics. For NOX and HC/VOC, the outcome ends up 15 and 20% lower, respectively, and for SO2 and PM, only just over half of the emission volume reported in the national statistics is obtained.

An explanation for the difference between the estimated outcomes for PM from the SAMGODS model and those from NTMcalc and the national statistics is probably due to differences in the emission

factors used. NTMcalc 4.0 is based on emission factors from HBEFA 3.1, whereas the latest national statistics are based on HBEFA 4.0. Since HBEFA does not contain reliable emission factors for wear PM from road traffic, a national model is used to estimate emissions from tyres, brakes and road wear (see Mawdsley et al., 2015). This model calculates emission factors for PM10 and then uses data from the literature to derive the relationships between PM10 and PM2.5 and between PM10 and total suspended particles (TSP). In addition, NTMCalc relates only to exhaust PM. Obtaining a value for PM from wear has proved difficult, The most up-to-date model for calculating non-exhaust emissions is the 'Nortrip model' (Karvosenoja 2012), in which the estimation method involves multiplying the non-exhaust PM for light vehicles by five to obtain corresponding emissions from heavy vehicles (Denby et al. 2013). In the literature, however, this factor varies between 5 and 100 (Denby et al., 2013), so there is a great deal of uncertainty. In HBEFA (2019), non-exhaust PM10 for heavy vehicles is stated at 0.141 g/vehicle-km in 2017, but the value is stated to apply to Central Europe and not Scandinavia. In order to obtain a factor for wear particles, the emission factor used in Swedish Transport Administration (2020e) of 0.2 g per vehicle km has been combined with statistics on both the traffic work (vehicle-Km) and transport work (tonne-km) for trucks over 3.5 tonnes to produce a value for emissions per tonne-km. This then arrives at a figure of 0.019 g per tonne-km, which is assumed to be fixed over time. In the forecast where 74-tonne trucks are allowed on major national roads in Sweden, emission factors have been developed for this extra heavy segment through a linear projection of the outcome for long-distance distribution and heavy transport, i.e., the segments with trucks of up to 40- and 60-tonnes, respectively.

Due to the high degree of electrification of the Swedish railway network, no emissions of GHG and low levels of other emissions are assumed for rail transport. In the SAMGODS model, 100% electric operation is assumed. Due to this, no emissions from rail traffic are reported.

Shipping emissions are limited solely to emissions that take place on Swedish territory or emissions from domestic traffic (between Swedish ports). This is a consequence of the fact that Sweden's climate target for 2030 applies to domestic transport only (excl. aviation) and that the statistics on shipping are produced for traffic on Swedish territory[2]. Within the 'Freight module' within SAMGODS, various regional delimitations can be analyzed, including transport on international waters, but the calculations that are made are limited to those that apply to target management and official statistics.

THETIS-MRV (2021) data has been used to calculate CO2 emissions per tonne-km for ships calling at Swedish ports in 2018. However, the information in THETIS- MRV (2021) is not sufficient to assign an emission factor to all size classes. Smaller vessels, less than 5,000 in gross tonnage, do not report to THETIS-MRV. In order to be able to estimate a factor for smaller vessels, a relationship has been estimated between deadweight tonne class and average emissions in grams of CO2 per tonne-km. This relationship follows a power function, as exhibited in Figure 1, which has been applied to estimate CO2 emissions per tonne-km for the size classes and segments not included in THETIS-MRV. The outcomes obtained through this process are reported in
Table 9.

[2] www.trafa.se

Figure 1. Relationship between maximum deadweight (tonnes) in different size classes of vessels and average carbon dioxide emissions per tonne-km within each size class (g CO2 per tonne-km)

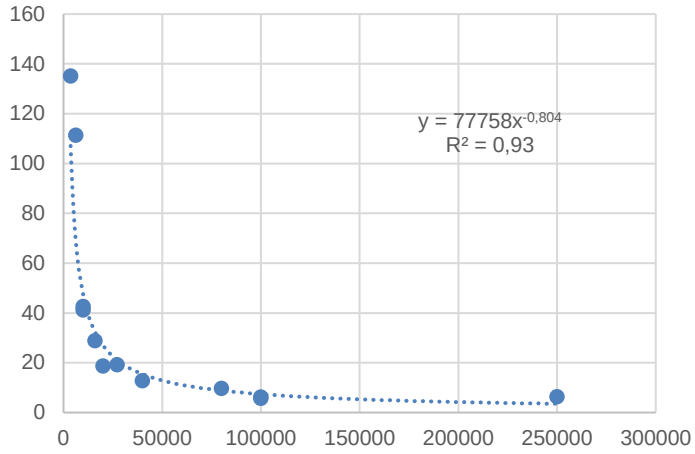


Table 9: Average emissions of CO_2 per tonne-km for the vessels in the SAMGODS model (g CO_2 per tonne-km)

Ship type	Size (DWT)	g CO_2 per tonne-km
Container vessels	5,300	78.78
Container vessels	16,000	28.84
Container vessels	27,200	19.24
Container vessels	100,000	5.70
Tankers, bulk and dry cargo vessels	1,000	301.12
Tankers, bulk and dry cargo vessels	2,500	144.15
Tankers, bulk and dry cargo vessels	3,500	109.98
Tankers, bulk and dry cargo vessels	5,000	82.56
Tankers, bulk and dry cargo vessels	10,000	42.67
Tankers, bulk and dry cargo vessels	20,000	18.67
Tankers, bulk and dry cargo vessels	40,000	12.83
Tankers, bulk and dry cargo vessels	80,000	9.71
Tankers, bulk and dry cargo vessels	100,000	6.30
Tankers, bulk and dry cargo vessels	250,000	6.33
Ro-Ro vessels	3,600	135.19
Ro-Ro vessels	6,300	111.34
Ro-Ro vessels	10,000	41.22
RoPax vessels	2,500	144.15
RoPax vessels	5,000	124.49
RoPax vessels	7,500	89.86
Train ferries	5,000	82.56
Inland waterway vessels	1,750	60.50

Note: As it has been difficult to find a suitable source of data for the calculation of emissions per tonne-km for 'inland waterway vessels', the value has been adjusted to a level similar to that for heavy trucks with trailers.

Since the SAMGODS model is not able to distribute either transport work or traffic work over ship sizes in a way that accords with official statistics, more aggregate emission factors have been developed, as shown in Table 10. These are based on THETIS-MRV as above, but the average within each segment is a weighted average, with the vessels' total reported emissions of carbon dioxide in 2018 being used as the weight.

Table 10. Average emissions of carbon dioxide from MGO by ship segment (g CO_2 per tonne-km)

Ship type	g CO_2 per tonne-km
Container vessels	15.66
Tankers, bulk and dry cargo vessels<=10,000 dwt	32.20
Tankers, bulk and dry cargo vessels>10,000 dwt	13.41
Ro-Ro vessels	46.70
RoPax vessels	113.28
Train ferries	87.98
Inland waterway vessels	60.1

Note: As it has been difficult to find a suitable source of data for the calculation of emissions per tonne-km for 'inland waterway vessels', the value has been adjusted to a level similar to that for heavy trucks with trailers.

For other emissions, the emission factors applied (as shown in Table 11) are sourced from M4Traffic (2019) but have been revised downwards in the forecasts FAST ELECTRIFICATION and SLOW ELECTRIFICATION for 2030 and 2040 because of the assumed more efficient combustion and lower fuel consumption. In addition, it is also assumed that an increased proportion of vessels will comply with the Tier III standard for NO_X emissions.

Table 12 shows the emission factors used for LNG. These are also based on data from M4Traffic (2019). For CO_2 emissions, however, the level has been increased by 38% to take into account the methane that can go unburned and is emitted by LNG engines. This enumeration is based on Ushakov et al. (2019) and Stenersen & Thonstad (2017) who recommend a value for methane emissions from marine LNG engines (average for different types) of 31 grams per kilogram of fuel consumed, which corresponds to methane emissions of 3% per kg. To convert this to CO_2-equivalent, a 'Global Warming Potential' (GWP) factor for 100 years is used. With a GWP_{100} factor for methane of 34 (Myhre et al. 2013, Gasser et al.2017), this gives an emission factor of 1.054 g CO_2-eq per kg LNG, which may be related to the CO_2 emission factor in M4Traffic (2019) at 2.750 g per kilogram of LNG.

Table 11. Emission factors for MGO by ship segment for 2017, 2030 and 2040

Ship segment	CO_2	NO_X	SO_2	HC	PM
	g/tonne-km	mg/tonne-km			
2017					
Container vessels	15.66	420.07	9.77	14.65	4.88
Tankers, bulk carriers and dry cargo vessels <= 10,000	32.20	720.02	20.08	30.13	10.04
Tankers, bulk carriers and dry cargo vessels> 10,000	13.41	359.75	8.37	12.55	4.18
Roro vessels	46.70	1,044.41	29.13	43.70	14.57
Ropax	113.28	2,533.43	70.67	106.00	35.33
Railway ferry	81.98	1,833.43	51.14	76.71	25.57
Inland waterways	59.85	1,341.90	37.45	56.00	18.55
2030					
Container vessels	13.00	268.79	8.11	12.16	4.05
Tankers, bulk carriers and dry cargo vessels <= 10,000	27.04	462.26	16.87	25.31	8.44
Tankers, bulk carriers and dry cargo vessels> 10,000	11.27	232.96	7.03	10.54	3.51
Roro vessels	41.56	710.43	25.93	38.89	12.96
Ropax1	103.08	1,762.02	64.31	96.46	32.15
Railway ferry	74.60	1,275.16	46.54	69.81	23.27
Inland waterways	50.40	861.35	31.50	47.25	15.75
2040					
Container vessels	12.06	113.96	7.52	11.28	3.76
Tankers, bulk carriers and dry cargo vessels <= 10,000	24.63	191.29	15.36	23.05	7.68
Tankers, bulk carriers and dry cargo vessels> 10,000	10.26	212.16	6.40	9.60	3.20
Roro vessels	39.70	308.30	24.76	37.14	12.38
Ropax	99.69	774.23	62.19	93.28	31.09
Railway ferry	72.14	560.31	45.00	67.51	22.50
Inland waterways	45.85	356.30	28.70	43.05	14.35

Notes: (1) The emission factor for Ropax vessels reflects an average for all Ropax vessels calling at a Swedish port. It is not representative of calculations of emissions from domestic traffic as this is dominated by the ferries that operate the lines to and from Gotland. For domestic traffic, the emission factor should therefore be increased by a factor of 3 to 4. (2) As it has been difficult to find a suitable source of data for the calculation of emissions per tonne-km for 'inland waterway vessels', the value has been adjusted to a level similar to that for heavy trucks with trailers. (3) The development to 2030 and 2040 follows from the assumptions about streamlining and efficiency gains, as well as assumptions about the development of the fleet regarding TIER requirements given by M4Traffic (2019).Source: THETIS-MRV (2021) and M4Traffic (2019).

Table 12. Emission factors for LNG by ship segment for 2017, 2030 and 2040

Ship segment	CO_2	NO_X	SO_2	HC	PM
	g/tonne-km	mg/tonne-km			
2017					
Container vessels	18.54	38.10	0.00	14.65	0.88
Tankers, bulk carriers , dry cargo vessels <= 10,000	38.11	78.33	0.00	30.13	1.81
Tankers, bulk carriers , dry cargo vessels> 10,000	15.87	32.63	0.00	12.55	0.75
Roror vessels	55.28	113.62	0.00	43.70	2.62
Ropax	134.09	275.60	0.00	106.00	6.36
Railway ferry	97.04	199.45	0.00	76.71	4.60
Inland waterways *	71.05	145.95	0.00	56.00	3.50
2030					
Container vessels	15.39	31.62	0.00	12.16	0.73
Tankers, bulk carriers, dry cargo vessels <= 10,000	32.01	65.80	0.00	25.31	1.52
Tankers, bulk carriers, dry cargo vessels> 10,000	13.33	27.41	0.00	10.54	0.63
Roror vessels	49.20	101.12	0.00	38.89	2.33
Ropax	122.02	250.80	0.00	96.46	5.79
Railway ferry	88.31	181.50	0.00	69.81	4.19
Inland waterways *	59.50	122.50	0.00	47.25	2.80
2040					
Container vessels	14.27	29.34	0.00	11.28	0.68
Tankers, bulk carriers, dry cargo vessels <= 10,000	29.15	59.92	0.00	23.05	1.38
Tankers, bulk carriers, dry cargo vessels> 10,000	12.14	24.96	0.00	9.60	0.58
Roror vessels	46.99	96.58	0.00	37.14	2.23
Ropax	118.00	242.53	0.00	93.28	5.60
Railway ferry	85.40	175.52	0.00	67.51	4.05
Inland waterways *	54.25	111.65	0.00	43.05	2.45

Notes: (1) As it has been difficult to find a suitable source of data for the calculation of emissions per tonne-km for 'inland waterway vessels', the value has been adjusted to a level similar to that for heavy trucks with trailers. (2) The development to 2030 and 2040 follows from the assumptions about streamlining and efficiency gains, as well as assumptions about the development of the fleet regarding TIER requirements given by M4Traffic (2019).

Applying the emission factors contained in Table 11 and Table 12 yields the emissions for the base-year of 2017, as shown in Table 13.

Table 13. Estimated emissions from shipping for the base-case year of 2017.

	Tonne-km	CO_2-eq (ktonnes)	NOX (tonnes)	SO2 (tonnes)	VOC (tonnes)	PM (tonnes)
Container vessels	833,793	13,1	350	8	12	4
Tankers, bulk carriers and dry cargo vessels <= 10,000	2,240,746	72,1	1 613	45	68	23
Tankers, bulk carriers and dry cargo vessels> 10,000	1,559,897	20,9	561	13	20	7
Roro vessels	1,848,696	86,3	1,931	54	81	27
Ropax vessels	156,758	53,3	1,191	33	50	17
Inland waterways	12,000	0,7	0	0	0	0
In total	6,651,890	246,4	5,647,0	153,3	229,9	76,6

4. Results

The differences in transport work by mode produced by SAMGODS for different sets of assumptions about the future development of vehicles, infrastructure and prices and fees, as embodied within the various forecasts (see Johansson et al., 2023), can be combined with the emission factors developed in section 3 to provide assessments of likely outcomes regarding emissions to air. The following material reports on how estimated emissions of GHG, NO_X, SO_2, VOCs, and PM vary between the model forecasts that have been developed.

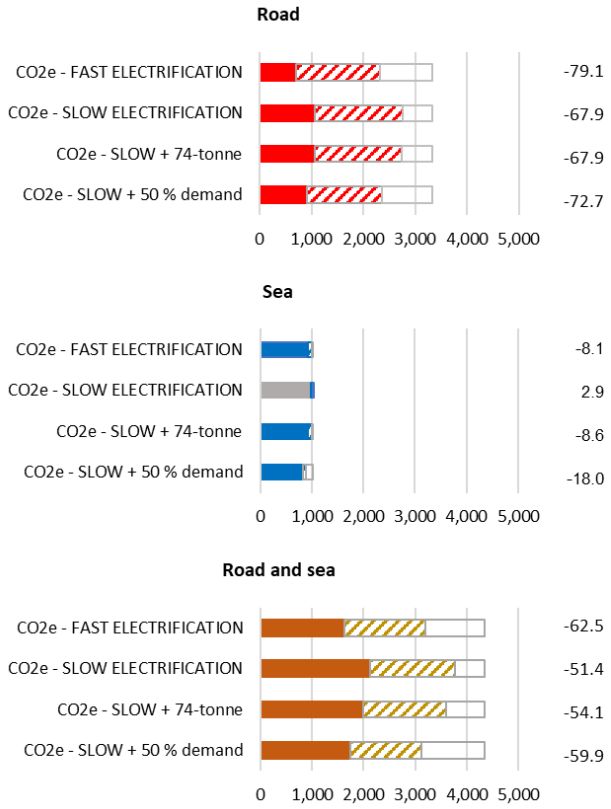
4.1 GHG Emissions

Despite an estimated growth in transport work of between 40 and 50% by road and between 60 and 70% by sea by 2040, total GHG emissions from freight transport is expected to decrease by between 50 and 61% between 2017 and 2040 (see Figure 2). This is in line with what can be observed for the last decade when emissions from heavy trucks have decreased despite an increase in transport work. According to Takman et al. (2020), it is the uptake of hydrogenated vegetable oil (HVO) as high and low admixture that explains this development between 2010 and 2019. According to the reporting format, emissions from biomass are registered in the land use sector and not in the transport sector, i.e., tank to wheel emissions from biofuels is set to zero. To illustrate the effect of the admixture of biofuels, a dashed column has been added in Figure 2, which indicates where the emission reduction would stop if the admixture were to remain at the same level as at present, i.e., 23% biofuels compared with the 70% assumed in the forecast scenarios. This in turn means that assumptions about the share of electric operation and streamlining of vehicles by 2040 account for a reduction in emissions from road transport of about 30% in the forecast FAST ELECTRIFICATION and for about 20% in forecast SLOW ELECTRIFICATION. In the forecasts FAST ELECTRIFICATION and SLOW ELECTRIFICATION, which are based on energy efficiency improvements and changes to electricity and alternative fuels, including for shipping, GHG emissions from shipping are estimated to decrease or increase only marginally.

For road transport, the largest reduction in GHG emissions is estimated in the forecast FAST ELECTRIFICATION at 79%. Under the SLOW ELECTRIFICATION forecast, however, where the proportion of km driven by electric trucks in 2040 is assumed to be lower and where the efficiency of vehicles has not reached as far, GHG emissions are estimated to fall by almost 68% between 2017 and 2040. Allowing trucks of up to 74 tonnes in total weight is estimated to increase the share of road transport by 2.6 percentage points (see Table 5). At the same time, lower GHG emissions per tonne-km are calculated for 74-tonne trucks compared with 60-tonne trucks, which means that GHG emissions are calculated at approximately the same level in 2040 as in the comparable scenario without 74-tonne trucks. The model calculations thus indicate that overall it would be good for the climate when the road network reaches the necessary bearing capacity for heavier road freight vehicles, but that the effects are relatively small.

The reduction in GHG emissions is primarily explained by the higher admixture of biofuels, but also by the streamlining, electrification, and use of alternative fuels. In the light of the emissions reduction this is assumed to provide for road traffic and given that maritime traffic can increase with a maintained emissions level, a halving in growth in freight transport demand provides a relatively marginal contribution to the reduction of greenhouse gases, as illustrated in Figure 2.

Figure 2. Estimated changes in CO_2-eq emissions (ktonnes per year) from road and sea on Swedish territory by 2040 under various forecasts; noted changes in percent.



Notes: (1) The dashed parts indicate the CO_2-eq emissions level when using the same fuel mix as 2017 and the solid bars indicate the CO_2-eq emissions level calculated at 70% admixture of biofuels. (2) Open and closed gray batches indicate the starting position according to the outcome for the base year 2017. (3) The figures indicate changes in % admixture of biofuels and the bars indicate emissions in ktonnes.

An assessment of the reduction of GHG emissions for domestic Freight transport between 2010 and 2030 is given in Table 14. According to the results achieved under the FAST ELECTRIFICATION and SLOW ELECTRIFICATION scenarios, the target that GHG emissions from freight transport will be reduced by 70% between 2010 and 2030 is not achieved. This is despite the fact that the railway share (which is assumed to have zero emissions) may be slightly overestimated. This means that other segments in the transport sector, such as passenger transport by car and bus, need to reduce their emissions by more than 70% in order to achieve the total emissions target. In FAST ELECTRIFICATION, GHG emissions from freight transport are estimated to decrease by approximately 57% and in SLOW ELECTRIFICATION by approximately 53%. The corresponding reductions if only the emissions of truck transport are taken into account are approximately 64 and 60%, respectively. The admixture of biofuels that is assumed until 2030 is then 46%.

Table 14. Estimated percentage change in CO_2-eq from freight traffic between 2010 and 2030; %

Forecast	Road	Shipping	Total
FAST ELECTRIFICATION	-63.9	57.5	-57.0
SLOW ELECTRIFICATION	-60.3	58.6	-53.4

Notes: (1) For GHG emissions, the calculation for shipping has been limited to only movements between Swedish ports, as the Swedish climate target for 2030 only includes domestic transport (excl. flights), defined for maritime transport as movements between Swedish ports. (2) In 2017, transport work from domestic freight traffic accounted for about 20% of the total transport work on Swedish territory. (3) The calculations of the distribution of transport work by the different modes of transport are affected by that available capacity for rail traffic has been set at the same level as for 2040. In other words, the forecasts FAST ELECTRIFICATION and SLOW ELECTRIFICATION for 2030 assume that several railway investments will be completed ahead of time.

According to the Swedish Transport Administration (2020h), GHG emissions from all road traffic (i.e., including light vehicles and buses) are estimated to decrease by about 90% between 2010 and 2040 and by about 70% between 2010 and 2030, if the assumptions described in Table 4 on electrification and the use of biofuels are achieved (plus additional assumptions regarding light vehicles and buses). According to Swedish Transport Administration (2020d), GHG emissions from heavy truck traffic will decrease by almost 86% between 2010 and 2040. However, in the FAST ELECTRIFICATION forecast, a reduction of just over 85% is achieved and in the SLOW ELECTRIFICATION forecast a reduction of just over 77%. In all cases assuming a blend of biofuels in the truck diesel of 70%. If an assessment of emissions from shipping is included, GHG emissions from total domestic freight transport could decrease by just under 81% in the SLOW ELECTRIFICATION forecast and just under 73% in the FAST ELECTRIFICATION forecast. See Table 15.

Table 15. Estimated percentage reduction of CO_2-eq between 2010 and 2040 for emissions on Swedish territory; %

Forecast	Road	Sea	Total
FAST ELECTRIFICATION	-85.1	-9.8	-80.7
SLOW ELECTRIFICATION	-77.1	-1.1	-72.7

All this may mean that Sweden's climate target of a reduction of 70% in GHG emissions for domestic transports by 2030 will not be achieved. The reduction in GHG emissions is primarily explained by a higher admixture of biofuels, but also by the streamlining, electrification, and use of alternative fuels. To improve the probability of achieving the set climate target, there needs to be greater use than predicted of biofuels and a wider proliferation of streamlining, electrification, and the use of alternative fuels. Even under the scenario where freight transport demand is halved, significant interventions are needed if the target for GHG emissions is to be achieved. In this respect, reducing road transport can also be important for other reasons, such as keeping particulate emissions down and reducing future problems with congestion, accidents and noise. While the latter effects fall outside the scope of this analysis, the effect on particulate emissions is outlined in section 4.5 below.

4.2 NO_X, SO2, VOC and PM Emissions

Despite increased transport work, the emission of NO_X from freight transport is expected to decrease by between 60 and 75% by 2040 (see Figure 3). This reduction is primarily due to changes in the vehicle fleet to trucks and vessels with lower emissions levels, but for shipping also a transition to alternative fuels. By 2040, all trucks are assumed to meet the current Euro class 6 requirements and 76% of vessels are expected to meet the TIER III requirements according to the assessment in M4Traffic (2019).

Figure 3. Estimated changes in emissions of NO_X, SO2, VOC and PM (ktonnes per year) from road and maritime traffic on Swedish territory by 2040 under various forecasts; noted changes in percent.



Note; Gray bars (open and closed) indicate the emissions level according to the outcome for the base year 2017.

As shown in Figure 3, road transport's emissions of SO_2 were already very low in the base-case year of 2017. Emissions of SO_2 from freight transport in general, like emissions of NO_X, are largely related to the use of shipping. Thus, efforts to attain the environmental quality target of "Only natural acidification", is largely a matter for shipping. As such, it is clear that model assumptions about efficiencies, electrification and the use of alternative fuels for shipping will strongly affect the outcome. Indeed, model assumptions about

streamlining and the use of LNG result in lower emissions in all the forecasts, where the emissions are estimated to reduce by between 41 and 50%, provided that alternative fuels achieve their expected uptake.

Like the situation for SO_2, the emissions of VOCs on Swedish territory originate mainly from shipping (see Figure 3) and, thus, the sector has a key part to play in efforts to attain the environmental quality objective of "clean air". However, these emissions are expected to increase for maritime transport under all forecasts. The highest growth between 2017 and 2040 is calculated to be about 25% under the SLOW ELECTRIFICATION forecast and the lowest predicted growth of 7% for maritime VOCs is under the SLOW ELECTRIFICATION forecast with 50% lower growth in demand. With this forecast, there is a net estimated 3% reduction in the total VOC emissions from freight transport (road and shipping). For emissions of VOCs, therefore, it may be particularly important to try to limit the increase in transport demand.

Freight transport's emissions of exhaust and wear PM occur primarily in the road transport sector. In 2017, approximately 87% of these emissions consisted of wear PM from tyres, brakes, and the road surface and 13% from exhaust particles. For reduced PM emissions, it will therefore be important to reduce road traffic. The exhaust and wear PM that truck transport gives rise to are expected to increase under all forecasts for 2040; most (about 33%) in the forecast SLOW ELECTRIFICATION +74 tonnes and least (about 7%) in the forecast SLOW ELECTRIFICATION + lower growth forecast where demand is reduced by 50% (see Figure 3). As a result of the use of trucks with better environmental classes (higher Euro classes), approximately 99% of the PM emissions of road transport in 2040 consist of wear PM. However, exhaust PM are generally more harmful than wear particles, (Swedish Transport Administration, 2020f).

Sea transport only gives rise to exhaust PM; these maritime exhaust PM are estimated to increase and decrease by between 30 and 40% under the different forecasts.

When looking at the total PM emissions of freight transport, there is a reduction of about 4% predicted under the SLOW ELECTRIFICATION + lower growth forecast. Under the other forecasts, it is estimated that PM emissions will increase by between 13 and 19%. While it has been revealed earlier that increased electrification in the road transport sector can contribute to the fulfillment of the climate targets, these results illustrate that if this should lead to lower transport costs and increased road traffic, therefore, the amount of wear PM will increase. Thus, what is favorable for contributing to the climate goal can thus compromise the attainment of the environmental quality goal of "Fresh air".

5 The Effects of the Policy Instruments on Emissions

5.1 Ecobonus+

The Ecobonus+ policy instrument is a subsidy that makes rail and shipping more attractive (than road) by assuming 30% lower costs for loading and unloading in all Swedish rail terminals and ports. Under the base 2017, the Ecobonus+ is estimated to lead to just under 2% lower GHG emissions. By 2040, on the other hand, the introduction of the same policy instrument is expected to lead to higher, or at least unchanged, GHG emissions. Under the forecast FAST ELECTRIFICATION, GHG emissions are predicted to increase by 0.6%, while the forecast SLOW ELECTRIFICATION predicts that the Ecobonus+ will lead to a slight reduction in GHG emissions by approximately 0.1% (see Table 16). The explanation lies in the fact that road traffic is assumed to achieve a relatively high degree of electrification by 2040 and that the remaining combustion of diesel does not produce such large emissions because the admixture of biofuels is estimated to reach 70% by 2040. Furthermore, improvements in efficiency are assumed to lead to fuel consumption falling by 35%, which results in a corresponding reduction in the emission

factor for road traffic. The emission factor per tonne-km for heavy trucks then reaches approximately the same level as the current emission factor for smaller tankers, bulk and dry cargo vessels and ro-ro vessels. In the FAST ELECTRIFICATION forecast, it is also assumed that rail and shipping will become more efficient, which means that the outcome will not be as extreme. The SLOW ELECTRIFICATION forecast assumes a lower electrification and streamlining of road traffic, which in combination with streamlining of the vessels results in a slight reduction in total CO_2-eq emissions.

Table 16 suggests that the introduction of an Ecobonus+ policy instrument is expected to lead to an increase in emissions of nitrogen oxides, sulfur dioxide and volatile organic compounds. As previously stated, shipping accounts for most of these emissions. Albeit rational from a transport cost perspective, mass freight modal transfer to shipping is thus not expected to lead to a reduction in the air pollution of freight transport. One explanation for this is that the road transport sector generally uses cleaner fuels and vehicles than the maritime transport sector. The average emission factors for nitrogen oxides, sulfur dioxides and volatile organic compounds were already lower in 2017 for road transport than for sea transport, but with the developments over time which are assumed under the various model forecasts, the differences have increased. The negative effects of an Ecobonus+ policy instrument is therefore estimated to increase over time.

Table 16. Estimated change in emission levels with implementation of Ecobonus+ (%) in base 2017 and forecasts FAST ELECTRIFICATION and SLOW ELECTRIFICATION 2040

Emissions	Base (2017)	FAST ELECTRIFICATION (2040)	SLOW ELECTRIFICATION (2040)
CO_2-eq	- 1.9	0.6	- 0.1
NO_x	1.0	2.0	1.3
SO_2	2.8	3.0	2.9
VOC	1.7	2.6	2.4
PM_exhaust	0.9	2.8	2.6
PM_wear	- 2.9	- 3.0	- 2.7
PM_total	- 1.7	- 2.2	- 1.9

There are two effects for PM emissions; exhaust PM increase as the introduction of Ecobonus+ leads to increased sea transport work, while wear PM decrease as road transport work decreases. The wear PM account for most PM emissions, so the total amount of wear and exhaust PM is estimated to decrease in all cases, by between 1.1 and 2.2%. This means that the introduction of an Ecobonus+ policy instrument makes a positive contribution towards attaining the environmental quality target of 'Fresh air'. For reducing PM emissions an Ecobonus+ policy instrument is estimated to be more effective in the FAST ELECTRIFICATION than in base and in the SLOW ELECTRIFICATION forecast.

Pinchasik et al. (2020) estimate that an Ecobonus system that excludes bulk transport leads to larger transfers to rail, rather than to shipping. The calculations in this case are made for the year 2030. Transfers to shipping are estimated to lead to increased emissions of carbon dioxide, NO_X and PM, which is in line with the results reported in Table 16. The freight modal transfer to rail is expected to lead to only very small climate and environmental effects.

5.2 Wear and tear tax

The second policy instrument makes rail and shipping more attractive by assuming increased costs for road transport. The introduction of a wear and tear tax for trucks on the Swedish road network of up to € 13.8 per vehicle km (depending on vehicle size), as suggested by a government commission *(Swedish Government SOU 2017:11)*, is estimated to reduce emissions of GHG and PM in total by about 3% in the base year of 2017 (see Table 17). At the same time, emissions of NO_X, SO_2, and VOCs are estimated to increase by between 1 and 4%. In the forecasts FAST ELECTRIFICATION and SLOW

ELECTRIFICATION, which include streamlining and the utilization of alternative fuels in shipping, only a slight reduction in GHG emissions is obtained instead (0.1 and 0.7%, respectively).

Table 17. Estimated change in emission levels with the introduction of a road wear and tear tax in base 2017 and forecasts FAST ELECTRIFICATION and SLOW ELECTRIFICATION 2040.

Emissions	Base (2017)	FAST ELECTRIFICATION (2040)	SLOW ELECTRIFICATION (2040)
CO_2-eq	- 3.0	- 0.1	- 0.7
NO_x	1.4	1.8	1.1
SO_2	4.1	3.8	3.0
VOC	2.6	3.3	2.4
PM_exhaust	1.4	3.5	2.7
PM_wear	- 5.2	- 5.5	- 4.3
PM_total	- 3.1	- 4.3	- 3.3

Like Ecobonus+, the wear and tear tax is estimated in all cases to lead to increased emissions of NO_x, SO_2, and VOCs, but lower emissions of wear PM overall. Since a wear and tear tax leads to a sharper reduction in traffic work on the road, this instrument provides a greater reduction in particulate emissions than Ecobonus+ is expected to provide. Unlike Ecobonus+, which primarily benefits container traffic and transport on inland waterways, a wear and tear tax has a positive effect on all shipping segments except for ferry traffic since the reduced truck traffic means that the demand for ferry transport decreases. Road freight traffic is affected more with a wear and tear tax than other modes because heavier trucks, which give rise to more wear, are taxed more highly than smaller trucks. In the presence of a wear and tear tax, therefore, the transport work is thus reduced most for the heaviest trucks. The Ecobonus+ policy instrument will, to a greater extent, affect trucks with a total weight of a maximum of 40 tonnes.

5.3 Fulfilment of climate and environmental targets

To test how well the two policy instruments contribute to the achievement of Sweden's climate target for 2030, results have also been produced for the forecasts FAST ELECTRIFICATION (2030) and SLOW ELECTRIFICATION (2030). The contribution of the two instruments to achieving Sweden's climate target of a 70% reduction in GHG emissions between 2010 and 2030 for domestic transport (with origin and destination in Sweden) is estimated to be positive. As shown in Table 18, the reduction of GHG is estimated to be approximately 0.6 and 1.2 percentage points greater, respectively, if Ecobonus+ or a wear and tear tax is introduced. That the contribution is estimated to be positive is largely explained by road traffic not achieving the same degree of electrification and efficiency by 2030 and also by the fact that the blend of biofuels will be lower in 2030 compared to 2040. In a comparison against the climate target, an equal share of shipping is also not included in the calculations, with only the emissions from traffic between Swedish ports being included.

Table 18. Estimated percentage reductions in CO_2-eq between 2010 and 2030 with and without policy instruments for modal transfer from road. (Note: Shipping is calculated only for traffic between Swedish ports).

Forecasts	Road	Shipping	Total
FAST ELECTRIFICATION	-63.9	57.5	-57.0
FAST ELECTRIFICATION + Ecobonus+	-66.4	69.6	-58.6
FAST ELECTRIFICATION + Wear and tear tax	-65.7	65.3	-58.1
SLOW ELECTRIFICATION	-60.3	58.6	-53.4
SLOW ELECTRIFICATION + Ecobonus+	-61.6	71.6	-53.9
SLOW ELECTRIFICATION + Wear and tear tax	-62.0	66.2	-54.6

When it comes to outcomes for 2040 compared to the climate target reference year 2010, the effects of the policy instruments are calculated to be more limited and, in some cases, even negative (see Table 19). However, these predicted effects may be assessed as being merely short-term since, in the long-run, the instruments could affect freight transport demand. In the analyses conducted, it is assumed that freight transport demand will remain stable. The results are thus based on analyses of how the same transport problem is resolved with different assumptions about future technology, fuel and price development and with two policy instruments that result in lower road transport work.

Table 19. Estimated percentage reductions in CO_2-eq between 2010 and 2040 with and without policy instruments for modal transfer from road.[3] For freight transport on Swedish territory. Note: Shipping is calculated only for traffic between Swedish ports.

Forecast	Road	Shipping	Total
FAST ELECTRIFICATION	-85.1	-9.8	-80.7
FAST ELECTRIFICATION + Ecobonus+	-85.5	1.0	-80.5
FAST ELECTRIFICATION + Wear and tear tax	-85.9	-1.4	-81.1
SLOW ELECTRIFICATION	-77.1	-1.1	-72.7
SLOW ELECTRIFICATION + Ecobonus +	-77.8	9.6	-72.8
SLOW ELECTRIFICATION + Wear and tear tax	-78.1	5.4	-73.3

The summary results presented in Table 20 show that the two policy instruments are expected to lead to the intended modal transfers. However, the picture is more differentiated when the effects on emissions are considered. As previously mentioned, both the introduction of an Ecobonus+ and a wear and tear tax are estimated to lead to an immediate lowering of GHG emissions within the 2017 base, but to have hardly any impact if introduced 2040. In fact, given the assumed efficiencies, electrification and the increased use of biofuels for road transport, the implementation of these policy measures is estimated to lead to more emissions of GHGs, NO_X, SO_2 and VOCs in the 2040 forecasts. However, the transfer from road to rail and shipping is estimated to lead to a reduction in the total amount of PM emissions (both from exhaust gases and wear). For exhaust PM, the assumed technical developments result in a faster reduction of emissions from road than from for shipping, which means that a modal transfer will result in a sharper increase in emissions in 2040 compared to 2017. The wear PM, on the other hand, are reduced when road traffic decreases, which means that the total particle emissions will be lower.

[3] As stated in section 2, the analysis undertaken within this paper makes the simplifying assumption of zero emissions from freight transport by rail.

Table 20. Estimated change in tonne-km and emission levels with Ecobonus + and road wear and tear tax (%) compared to the forecasts without additional modal shift policy instruments.

Forecast	Road	Rail	Shipping	CO_2-eq	NO_X	SO_2	VOC	PM exhaust	PM wear	PM total
Base 2017 + Ecobonus+	- 2.9	3.5	4.5	- 1.9	1.0	2.8	1.7	0.9	- 2.9	- 1.7
Base 2017 + wear and tear tax	- 5.2	5.0	4.4	- 3.0	1.4	4.1	2.6	1.4	- 5.2	- 3.1
FAST ELECTRIF. 2040 + Ecobonus+	- 3.0	3.1	3.9	0.6	2.0	3.0	2.6	2.8	- 3.0	- 2.2
FAST ELECTRIF. 2040 + wear and tear tax	- 5.5	4.4	4.1	- 0.1	1.8	3.8	3.3	3.5	- 5.5	- 4.3
SLOW ELECTRIF. 2040 + Ecobonus+	- 2.7	2.1	3.7	- 0.1	1.3	2.9	2.4	2.6	- 2.7	- 1.9
SLOW ELECTRIF. 2040 **+** wear and tear tax	- 4.3	3.1	3.0	- 0.7	1.1	3.0	2.4	2.7	- 4.3	- 3.3

Although it is difficult to make direct comparisons, the results from our analysis are in line with those of Pinchasik, et al. (2020) which find that policy instruments that have the goal to promote a transfer from road to rail and shipping would only reduce the amount of carbon dioxide by approximately 3.6% by 2030. This is even though their analysis covered several instruments that were combined and introduced simultaneously in Norway, Denmark and Sweden. Pinchasik, et al. (2020) conclude that policy instruments that are to promote the transfer from road to rail and shipping must not be considered as instruments that contribute much to the fulfillment of climate goals, but that these instruments can contribute to achieving other political goals.

6. Discussion

The results produced from the different forecasts reveal that, despite the sharp increase in transport work predicted to take place between 2017 and 2040, GHG emissions are estimated to decline by 50 to 60%. The assumed technical developments and higher shares of biofuels under each forecast are thus estimated to be able to support the forecast tonne-km growth. Model results indicate that technical developments in the road transport sector will mean that the average GHG emissions per tonne-km from road traffic using today's fuel mix may approach the average emission factor for maritime transport using MGO by 2040. With a fuel mix of 70% biofuel use in trucks and a fuel mix of 25% biofuels or other zero-GHG fuels in shipping, it is estimated that the average GHG emissions per tonne-km from shipping could be roughly 70% higher than that of road freight by 2040. The results are also affected by the assumption that a high proportion of km driven by trucks in 2040 can be done under electric power. In contrast, for shipping, it is estimated that some elements of ferry traffic will be able to run under electric power by 2040, but any broader electrification is considered difficult to achieve by 2040.

Irrespective of the model results, access to biofuels and electricity is a major uncertainty and challenge for the entire transport sector. This is especially true for biofuels, where demand is already relatively high but expected to increase relatively fast into the future, partly in the transport sector, partly in other sectors and internationally. In this respect, it may be important to achieve rapid electrification of freight traffic, which, however, requires secure access to green electricity and a network that can support the increased demand for charging. Should freight transport demand develop at a lower rate than what is calculated in the Swedish Transport Administration's official freight transport forecast, the need for biofuels and electricity will be reduced. Lower freight transport demand by 2040 will not have a major effect on estimated GHG emissions given a high proportion of biofuels, a high proportion of electric power and a high proportion of alternative fuels in shipping. Then, of course, a lower growth rate for freight transport demand facilitates the possibility of achieving climate goals, while at the same time it can have a positive effect on the possibility of achieving other transport policy goals.

According to our tested forecasts, the GHG emissions caused by domestic freight transport can be reduced by a maximum of 57% between 2010 and 2030. This means that the heavy goods transport segment does not meet its part of the goal for reducing the GHG emissions by 70%. This in turn means that other segments that are included in domestic transport, i.e. cars, busses and light trucks, will need to reduce their emissions by more than 70% in order to reach the target. If the blend of biofuels in truck diesel is maintained at the current level of 23%, instead of the level of 46% assumed in the forecasts for 2030, GHG emissions from the heavy truck segment are estimated to be reduced by a maximum of only 25%. To attain the climate goal set for 2030, therefore, it is important to be able to achieve a high mix of biofuels.

With respect to other emissions from Sweden's freight transport sector:

- NO_X emissions, which are mainly caused by sea transport, are estimated to be reduced by 60 to 75% by 2040 (compared to the level 2017). This is partly brought about by the IMO's stricter limits on the NO_X emissions of new ships and partly by an expected increased use of LNG. The reduction of nitrogen oxide emissions is thus estimated to be manageable via a renewal of the fleet.
- SO_2 emissions are also mainly linked to maritime transport and are primarily affected by the fuels used. These emissions are estimated to decline by between 41 and 50% by 2040 compared to the 2017 level, in the forecasts FAST and SLOW ELECTRIFICATION.
- Emissions of VOCs are estimated to increase in all forecasts (by between 8 and 30%) except in the forecast where there is a 50% lower growth in transport demand. In the case of the latter, a 3% reduction is calculated.
- The total PM emissions (exhaust and wear & tear) are estimated to increase by between 13 and 33% in all forecasts except for the forecast which assumes a 50% lower growth in transport demand. For the latter forecast, a 4 % reduction has been estimated. For road transport specifically, the amount of exhaust PM is reduced thanks to the transition to higher Euro classes and an increased use of electric trucks. For shipping, emissions of exhaust PM are reduced through increased use of alternative fuels. However, the dominant emissions of PM come from road and tire wear and these increase in all forecasts, because of increased road traffic work. The share of wear PM in total PM emissions increases from 87% in 2017 to 99% in 2040. To reduce PM emissions, therefore, it will be important to limit freight transport by road.

In a policy context it is often argued that it is important to promote a transfer of freight from road to both rail and shipping. To this end, the potential impact of two instruments to promote the transfer of goods have been analyzed: (1) the introduction of an "Ecobonus +" that reduces transhipment costs in Swedish ports and railway terminals by 30%, and (2) a 'wear and tear' tax for trucks on the Swedish road network of up to € 13.8 per vehicle km, depending on the size of the truck.
The effects of the instruments have been analyzed for the base-case year of 2017 and under different forecast scenarios for 2040. Under all scenarios, both instruments are estimated to lead to the expected effects when it comes to the transfer of transport work; making it more attractive to use rail and shipping. To introduce the instruments today yields relatively large reductions in GHG emissions (1.9 and 3% respectively, for the 'Ecobonus+' and the 'wear and tear' tax). Under the SLOW ELECTRIFICATION assumptions, GHG emissions are reduced, but only by 0.1 and 0.7% respectively. In the FAST ELECTRIFICATION forecast, the introduction of 'Ecobonus+' leads to an increase in GHG emissions of 0.6%, while a 'wear and tear' tax gives a reduction of 0.1%.

Introducing either of these two policy instruments to prompt a modal transfer as a way of reducing GHG emissions in 2040 can have limited effect, possibly also a reverse effect. If road traffic is electrified, streamlined and can use biofuels to the extent assumed in the forecasts, shipping in particular needs to achieve similar improvements for a transfer of transport from road to be desirable from a climate perspective by 2040. Transfer to rail will continue to be good for the climate, but the effect is not expected to be as great in 2040 as today.

In terms of Sweden's climate goal for 2030 – i.e., a reduction of GHG emissions from domestic transport by 70% between 2010 and 2030 – 'Ecobonus+' and a 'wear and tear' tax are estimated to lead to added GHG reductions by approximately 0.6 and 1.2 percentage points respectively. In the forecast FAST ELECTRIFICATION, therefore, with both policies implemented the total reduction in GHG emissions between 2010 and 2030 is estimated to be around 59%. Thus, these policy instruments will make a contribution, but they will not lead to the climate goal being achieved for freight transport.

Although it is difficult to make direct comparisons, the results produced by the forecasts for 2030 are in line with the results in a Norwegian-Swedish study (Pinchasik et al., 2020). In their study, different transfer instruments are tested in Norway, individually and in combination, as well as different variants of instrument packages that are introduced simultaneously in Norway, Denmark and Sweden. The results show that the policy instruments would at best reduce the amount of CO_2 in 2030 by 3.6% compared to the reference scenario with current policies. The authors of the report conclude that the transfer instruments should thus not be regarded as instruments for achieving climate goals, but that these instruments can contribute to achieving other political goals.

In all cases, the implementation of the policy instruments is expected to lead to more emissions of NO_X, SO_2 and VOCs. Even in this case, it is important that shipping can achieve an increased use of alternative fuels and electricity, but for NO_X specifically, it is also important that incentives are created for the older part of the fleet to invest in purification equipment for lowering NO_X- emissions.

Both instruments are expected to lead to a reduction in total PM emissions, which will contribute to the fulfillment of the environmental quality goal 'Fresh air'. The reduction is estimated at between 1.7 and 4.3%. The explanation is that the amount of wear particles decreases when the freight transport work on the road decreases. This counteracts the estimated increase in exhaust PM.

It is also important to remember that freight transport gives rise to other non-internalized externalities and that the transfer of freight transport from road to rail and shipping can be important for objectives other than the four environmental quality objectives mentioned in the introduction. The main aim of the 'wear and tear' tax for heavy trucks, for example, is to internalize infrastructure costs. The shift from road to rail and shipping also leads, all other things being equal, to less congestion, lower noise and fewer traffic accidents.

7. Conclusions

The overall results of our analysis show that the two evaluated policy instruments to promote the transfer of freight transport from road to rail and shipping are not viable for all environmental quality objectives. While freight modal transfer is primarily important for reducing PM emissions from road traffic, it can also have positive effects on reducing GHG emissions, but this effect is estimated to be diminishing over time. The effect that can be achieved is of course affected by the extent to which shipping, and road modes succeed in streamlining traffic and increasing the use of alternative fuels and electricity. For other environmental quality objectives, the two evaluated policy instruments for transfer are estimated to have negative effects.

The transfer of freight from road to rail has great potential to reduce freight transport emissions to air, even with the assumptions made for road traffic by 2040. Under the assumption of a fuel mix containing 70% biofuels, road traffic is estimated to give an average of 5.5 times higher emissions of GHG per tonne-km compared with rail transport. Today, GHG emissions per tonne-km from road traffic are estimated to be 32 times higher than for rail transport. However, because of capacity constraints, it is not easy to determine to what extent it is (or will be) possible to increase freight transport work by rail. In this respect, it will be important to investigate the possibilities of making better use of the existing rail track capacity. For example, via a more powerful differentiation of track charges over both

types of freight and time of day, but also via a developed capacity allocation process for freight transport by rail.

With regard to shipping, policies for prompting modal transfer need to be combined with instruments that give shipping an incentive to switch to alternative fuels and accelerate investments in new vessels or upgrades. Above all, this is crucially important in relation to the environmental quality objectives of "Only natural acidification" and "No eutrophication". The latest statistics show that shipping's use of LNG as a fuel has increased in recent years, which in turn opens up the potential for greater use of LBG, particularly if prices should fall.

Our analysis and corresponding results reveal the extent to which regulations have affected certain types of emissions. The EU Euro class rules on air pollution have accelerated the trend towards cleaner engines and lower emissions from road traffic. The IMO's stricter sulfur requirements have had a major effect on the emission of SO_2 from shipping. Corresponding effects are expected from EU requirements for lower CO_2 emissions from new trucks and the IMO's stricter nitrogen requirements for new vessels, as well as its push for reducing the GHG emissions of the sector. It is obvious that technological development is accelerating in the road transport sector, where the turnover of the vehicle fleet is significantly faster than in the rail and sea transport sectors, where trains and ships are beeing used for several decades.

Despite the comprehensive nature of the modelled forecast emissions for the Swedish freight transport sector conducted within this work, there remain several potential opportunities for future research. For example, as a supplementary exercise, a cost-benefit analysis could be implemented based on the results achieved herein. Related to this prospect and to more accurately analyze health and environmental effects in more detail, a regional breakdown of the emissions, as well as calculations based on some meteorological distribution model, could supplement the results. This would be valuable since different emissions exert a variety of effects at different levels of geographic scope; in particular, GHG emissions are the only ones that can be valued regardless of where the emissions occur. Linked to this, there is also a need to develop more vehicle-specific emission factors for wear PM, for example divided into vehicle weight and axle configuration. There are so far to few studies on how wear emissions from electric vehicles relate to wear emissions from vehicles with internal combustion engines. Electric vehicles differ in greater weight, greater torque, but also in different tyres to counteract the greater tyre wear. Furthermore, emission factors for different geographical areas would be desirable. There are also many more macroscopic analyses that could be implemented relating to, for example: 1) the indirect emissions related to freight transport that are derived from the production of alternative fuels, electricity, batteries, vehicles and infrastructure; and 2) future fundamental shifts in technology that bring about changes in relative transport costs that completely alter future production and demand structures.

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