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DOI
10.1016/j.cstp.2020.05.013

Publication date
2020

Document Version
Final published version

Published in
Case Studies on Transport Policy

Case Studies on Transport Policy 8 (2020) 887–894

Contents lists available at ScienceDirect

Case Studies on Transport Policy

journal homepage: www.elsevier.com/locate/cstp

Exploring the impacts of an emission based truck charge in the Netherlands

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ARTICLE INFO

Keywords:
Pricing policies
Emission based truck charge
The Netherlands
Vehicle type and shipment size choice
Freight transport demand

ABSTRACT

In this paper we explore the possible impacts of a distance- and emission-class based truck charge in The Netherlands. Earlier studies suggest that shifts may occur towards heavy vehicles, due to the relative inefficiency of lighter vehicles types. However, these studies have not taken into account the effects of changes in shipment size, as a response to pricing measures. Also, these studies have not considered emission-class dependent charges. Thirdly, no empirical disaggregate models or studies are available for the Netherlands for this problem. We present a discrete choice model for the joint choice of vehicle type and shipment size, estimated on a large dataset of disaggregate carrier freight trip data. The model explains variations in vehicle type choice for different transport purposes and contexts (e.g. commodity type, long-haul, urban transport, to/from logistic nodes). The analysis of emission based truck charging schemes shows that substitution towards low emission vehicles can be expected within the same vehicle class. It is also not likely that the truck charge will lead to a significant increase of shipment sizes or to substitution between vehicle types: a distance based truck charge increases transport costs but inventory costs restrain a shift to larger shipment sizes. This result points to a limited capability of supply chains to absorb transport cost increases by logistics re-organisation.

1. Introduction

Truck charging schemes are an important policy instrument to encourage more sustainable or efficient road freight transport: several European countries have introduced a form of truck charging, such as Austria, Germany, the Czech Republic, Belgium and Poland (for an overview see McKinnon, 2006; Tillema et al., 2018; Francke and Tillema, 2018). KPMG (2018) compared eleven toll schemes in Europe and found that these systems are to certain extent comparable:

- An important starting point for introducing a distance based charge in the different countries is to gain (additional) funding for infrastructure on the basis of the 'polluter pays'-principle.
- Most toll systems have implemented tolls for trucks with a maximum allowable weight of 3.5 tonnes.
- Most systems are implemented on highways.
- The impact of (heavy) trucks on the environment has played an explicit role in the design of the truck charge in several countries such as Belgium, Hungary, Germany, Slovenia, France and in Switzerland. The schemes in these countries are differentiated according to EURO-emission class with the aim of reducing emissions.

Recently, also the Dutch government has decided to introduce a truck charge. Different types of distance based charges are possible: a flat charge, location based, or by vehicle type. The most likely scheme is a charge that is distance and vehicle type specific, with a differentiation of the charge to vehicle size and emission class (see MuConsult et al., 2018). Likely responses to such a scheme is a change to different shipment sizes and a shift to different vehicle types. However, empirical evidence of the impact of vehicle type specific measures is scarce: ex-post studies based on monitoring statistics after introduction are biased by impacts from other developments taking place, and modelling studies are mostly based on elasticity reviews from empirical modelling studies.

In this paper we particularly focus on the impacts of emission and distance based road pricing charges for the Netherlands. Based on the limited literature available, it appears that a number of behavioral reactions may occur, depending on the design of the measure. Ex-ante studies first of all indicate there may be a shift in the use of lighter to heavier trucks. In an early policy analysis for Europe, Raha et al. (2003) describe the impact of a road pricing measure in which the external costs caused by trucks are internalized. The effects were modeled using the SCENES Regional Economic and Transport model, where vehicle

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https://doi.org/10.1016/j.cstp.2020.05.013
Received 24 June 2019; Received in revised form 20 April 2020; Accepted 12 May 2020
Available online 21 May 2020

type choice was included as part of an aggregate nested mode choice model. The toll level scheme involved a higher toll in areas with a higher population density. Because the costs per tonne increase faster for small and medium-sized trucks, the use of more heavy vehicles increased. Henstra et al. (2005) calculated the effects of a MAUT for trucks on motorways as replacement of the Eurovignette. Just like Raha et al. (2003), they find a shift from lighter to heavier trucks (light: −15 percent tonne-kilometer; medium weight: −2 percent; heavy +0.7 percent). Both studies, however, did not include a distance based charge differentiated according to EURO-emission class and only considered transport costs: possible impacts on shipment size choice and the logistic costs associated to it, were not taken into account. Therefore these results are likely to overestimate the impacts of a distance based charge.

Literature based on ex-post evaluations of distance-based truck charges is even more scarce compared to ex-ante studies. Vierth and Schleussner (2012), indicate that a heavy vehicle charge does seem to lead to a cleaner fleet and kilometers in practice. A comparison between Germany, where a truck tax applies, and Sweden, where a Eurovignette is in force, shows that both the fleet and the kilometers driven have become cleaner in Germany than in Sweden (Vierth and Schleussner, 2012). In Germany there were relatively many trucks in the clean Euro classes IV and V and a relatively large number of kilometers were driven in those vehicles. However, this is also partly due to a compensation program in Germany for the purchase of trucks in Euro Class V. A similar effect applies for Switzerland. There, the truck levy has led to higher sales and therefore a higher share of new, relatively clean, freight kilometers (Significance & CE Delft, 2010, based on other sources). Here, too, the truck charge is not the only cause. The changes were partly the result of a change in the weight limit. In addition to a (slight) shift to heavier vehicles (part of the logistics efficiency; see the following point), there is a chance that part of the goods will actually be transported more by delivery vans, at least if there is no (truck) levy for vans. There are suspicions about this based on Belgian practice, but at the same time there is no evidence (yet). The truck tax in Belgium was actually introduced in April 2016. According to the Mobility and Public Works department of the Flemish Region, revenues in the first year were slightly lower than expected. First of all because there were fewer heavy vehicles (> 32 tonnes), and second because the renewal / change of the fleet with Euro VI vehicles went faster than expected. Also there have been more delivery vans (< 3.5 tonnes) than expected (MOW Vlaams Gewest, 2017). However, no direct link can be established between the increase in the number of delivery vans and the introduction of the truck levy that only applies to lorries over 3.5 tonnes.

Modelling practices have evolved since the late 90′s, moving from aggregate to disaggregate modelling with a better representation of logistics costs. Economic order quantity (EOQ) theory, dates back centuries ago, but is still an important theory behind recent studies after vehicle and shipment size choice (De Jong and Ben-Akiva, 2007; Combes, 2012; Birbil et al., 2014). Distance- and emission class based charges may affect the logistics of ordering goods in the sense of the size of orders. Therefore, many empirical studies analyse these decisions jointly: Windisch et al (2010); Combes (2012); Pourabdollahi et al (2013); Stinson et al. (2017) study shipment size and mode choice, Holguín-Veras (2002) studied combined vehicle type choice and shipment size choice for Guatemala, Abate and De Jong (2014) for Denmark and Irannezhad et al., 2017 for Iran, and Keya et al., 2019, for the US. Hensher et al. (2013) provide elasticities for Australia. Piendl et al (2016) develop a model for interregional road freight including shipment size choice for Germany. The models are markedly different in approach, empirical data used and form, and allow no direct comparison of parameters. Also, none of the above models have been applied for the evaluation of policy case studies. Finally, no model is available with valid parameters for the Netherlands.

Given the above, the objective and the contribution of this paper is the exploration of possible impacts of a distance and emission class-based truck charge in The Netherlands, with a focus on the joint choice of vehicle type and shipment size. For this purpose, a new empirical model is presented and estimated on a very large and dense micro-dataset with truck trip diaries, collected by Statistics Netherlands.

The paper is organized as follows. In Section 2, we describe the model that was used for the analysis, including the data and the estimation of coefficients. Section 3 discusses on the application of the model for the analysis of a distance- and emission class based truck charge. In Section 4, conclusions are drawn on the possible impacts of an emission based truck charge, and recommendations are made on the applicability of choice models for this type of explorative policy studies.

2. Vehicle and shipment size choice model

The logistic costs are the main explanatory drivers behind vehicle and shipment size choice. The original economic order quantity (EOQ) model, dates back centuries ago, but is still an important theory behind recent studies after shipment size and vehicle/mode choice (De Jong and Ben-Akiva, 2007; Combes, 2012; Birbil et al., 2014). EOQ theory assumes a trade-off between transport costs and cost of inventory within the total logistic costs function. Increasing shipment sizes are more efficient for transport costs but also lead to higher inventory costs. In this study we apply a discrete choice model that is often used to simulate the combined shipment size and vehicle type choice (Holguín-Veras, 2002; De Jong and Ben-Akiva, 2007; Abate and De Jong, 2014; Irannezhad et al., 2017). The yearly logistic cost L for transporting goods with vehicle type v and shipment size s is described as:

$$L_{v,s} = K_{v,s} + I_s \tag{1}$$

With transport costs K and cost of inventory I. The transport costs K are a function of shipment size, vehicle type, frequency of the shipment, and the transport time and distance (De Jong and Ben-Akiva, 2007). Transport costs are calculated based on the minimal number of vehicles needed to carry the shipment, and the transport costs needed to be paid for the complete vehicle. Therefore, the number of vehicles needed for the transport is calculated as the ratio of shipment size and the carrying capacity of the vehicle, rounded up to the nearest integer:

$$\lceil \frac{S_s}{cw_v} \rceil \tag{2}$$

with shipment size S_s and cw_v as the carrying weight of vehicle type v. The full transport costs function can be written as:

$$K_{v,s} = (c_{t,v} \cdot t + c_{d,v} \cdot d) \cdot \lceil \frac{S_s}{cw_v} \rceil \cdot f_s \tag{3}$$

With:

t: transport time (h);
d: transport distance (km)
$c_{t,v}$: vehicle cost per time unit for vehicle type v (€/h/vehicle)
$c_{d,v}$: vehicle cost per distance unit for vehicle type v (€/km/vehicle)
S_s: weight of shipment size class s (tonnes);
cw_v: carrying weight of vehicle type v (tonnes/vehicle);
f_s: frequency of shipments per year.

The available data, that will be described in the next section, does not provide the total annual demand but only the shipment size of the observation. Like in previous studies based on commodity flow surveys or carrier surveys such as De Jong and Ben-Akiva (2007) and Windisch et al. (2010) the assumption was made that total demand is proportional to the observed shipment size. If the shipment size of the alternative is smaller than the observed shipment size, this means frequency has to go up by the ratio of observed shipment size S_o and the shipment size of the alternative S_s. If the shipment size of the alternative is bigger than the observed shipment size, the frequency has to go down by the same ratio:

Table 1
Frequency table of the alternatives: by vehicle type and shipment size class.

Vehicle type			Shipment size classes						Total
			< 3 T	3–6 T	6–10 T	10–20 T	20–30 T	> 30 T	
Truck 	< 10 T	High em.	638	7	6	4	0	4	659
		Low em.	2378	54	18	48	4	0	2502
	10–25 T	High em.	312	201	161	1109	597	29	2409
		Low em.	775	341	319	980	1103	0	3518
	> 25 T	High em.	7	0	0	5	20	38	70
		Low em.	99	154	158	390	1188	1684	3673
Truck + trailer	< 15 T *	High em.	23	2	4	53	4	2	88
		Low em.	2632	201	235	171	35	11	3,285
	> 15 T*	High em.	132	6	5	74	223	26	466
		Low em.	10,585	845	211	192	115	42	11,990
Tractor + trailer 		High em.	2004	246	117	126	253	178	2924
		Low em.	36,441	4532	1549	2207	25,322	3,270	73,321
Special Vehicle 		High em.	13	8	6	4	0	0	31
		Low em.	20	9	7	3	0	0	39
Total			56,059	6606	2796	5366	28,864	5284	104,975

$$f_s = \lambda \bullet \frac{S_o}{S_s} \tag{4}$$

An unobserved constant λ, which has units of shipments per year, is used to convert the shipment size of the observation to annual frequency. Thus, Eq. (4) shows both how annual frequency is derived as well as how it is adjusted when alternative shipment sizes are tested.

Inventory costs depend on storage costs and the value of goods. Since the registered value of goods is unreliable or often missing, we made a simplifying assumption that the value density is constant within each commodity type. Furthermore the storage costs are a function of the weight to be stored, so we take the shipment size as explanatory value, in which α is a monetary value for storage costs per weight unit:

$$I_s = \alpha \bullet \frac{S_s}{2} \tag{5}$$

The utility function consists of the logistic cost function (1) and alternative specific constants to measure unobserved differences between the alternatives. In addition, interaction terms are added to measure taste preferences in market segments for particular choice alternatives: smaller vehicles in dense urban areas. For vehicle type interaction terms are used with type of stop location or transport type (own- or hired account, international). For shipment size interaction terms are used with goods type. The total utility function is specified as:

$$U_{v,s} = \beta_K \bullet \left((c_{t,v} \bullet t + c_{d,v} \bullet d) \bullet \lceil \frac{S_s}{cw_v} \rceil \bullet \lambda \bullet \frac{S_o}{S_s} \right) + \beta_I \bullet \alpha \bullet \frac{S_s}{2} + \delta_v + \delta_e + \delta_s + \sum_m (\delta_m \bullet X_m) + \varepsilon_{v,e,s} \tag{6}$$

With:

β_K: estimated coefficient for transport costs
β_I: estimated coefficient for inventory costs
δ_v: alternative specific constant for vehicle type
δ_e: alternative specific constant for emission class
δ_s: alternative specific constant for shipment size class
δ_m: taste variation for interaction term m
: interaction term m, between vehicle-, location- or transport type, or shipment size and goods type
$\varepsilon_{v,e,s}$: unobserved part of the utility

For the α parameter for storage costs per weight unit, we have no reliable data available, so we estimated the cost parameter for inventory costs, without α. This implies that the storage costs unit price is implicitly accounted for in the inventory cost parameter. The same goes for the frequency constant λ: this constant is absorbed in the estimated transport cost parameter.

3. Data

In this study we use a very large and dense dataset with trip diaries from road freight carriers, that is collected by Statistics Netherlands. For data collection, a unique, automated procedure is used to record complete freight trip patterns from the transport management systems of carriers, at the level of individual trucks. This provides much more dense and complete data compared to conventional surveys. The data includes shipment attributes (commodity type, weight), truck attributes (vehicle type, loading capacity, emission class) and tour attributes (tour composition, delivery/pick-up location). Although the micro-data is privacy sensitive and proprietary it can be analysed in a secured environment. Since transport management systems are most heavily used by road freight carriers, the sample consists mainly of transport data from large road freight carriers. In 2017, these carriers made up for 83% of the vehicle kilometres in The Netherlands. The dense micro-data contains information on the shipment and vehicles that were used and where it was loaded and unloaded. Information on shippers and receivers of goods can be obtained by linking location attributes, such as type of logistic location (Distribution center, Multimodal transshipment terminal, or other) and urban density.

For this study we analyse the observed shipment sizes and vehicle types used. Vehicle types are distinguished on form, carrying capacity and emission class (high: EURO 1–4, low: EURO 5 and 6). Truck types distinguished in the data include: truck (a rigid truck or lorry), truck + trailer (a rigid truck with a trailer), tractor and trailer (also known as semi-trailer-truck or articulated lorry), and finally vehicles with a specialized form and function such as tank wagons and kipper trucks. We distinguish six shipment size classes: < 3T, 3–6 T, 6–10 T, 10–20 T, 20–30 T and > 30 T. Table 1 shows the market share of each vehicle type in the dataset. In spite of the large range of vehicle types, tractor and trailer combinations with a capacity > 15 T are the dominant vehicle type in the road transport market. In total this leads to 84 unique combinations of vehicle type and shipment size.

4. Model estimation

A conventional MNL-logit model was formulated, with a segmentation in non-bulk and bulk commodity groups. The models were estimated in R using the maxLik package (Henningsen and Toomet, 2010). The model distinguishes 14 vehicle types, varying in type, carrying capacity and emission class. Shipments are categorized into six shipment size categories. In theory this leads to 84 alternatives, but alternatives can only be included if they have been chosen in one of the

Table 2
MNL model estimates for commodity group 1 (non-bulk) and 2 (bulk) (** = p-value < 0.01; * = p = value < 0.05).

			Comm group 1			Comm group 2		
			Coeff.	SE		Coeff.	SE	
Cost attributes:								
Transport costs			−0.021	0.000	**	−0.041	0.001	**
Inventory costs			−0.280	0.014	**	−0.221	0.004	**
Vehicle specific constants:								
Truck 	< 10 t	ASC	−4.082	0.029	**	−2.069	0.089	**
		Own-account carrier	3.299	0.045	**	3.636	0.132	**
		Transport to distribution center	0.321	0.045	**			
	10–25 t	ASC	−4.287	0.035	**	0.925	0.050	**
		Transport to distribution center	0.321	0.045	**			
	> 25 t	ASC	−5.561	0.070	**	0.483	0.050	**
Truck + Trailer 	< 15 t	ASC	−3.297	0.022	**	−1.854	0.081	**
		Transport to distribution center	0.321	0.045	**			
	> 15 t	ASC	−1.277	0.011	**	−2.763	0.093	**
		Urban unloading location	−1.537	0.030	**			
Tractor + trailer 		ASC (ref.)	–			–		
		International inbound	0.287	0.117	*	3.165	0.187	**
		International outbound				3.461	0.202	**
		Urban loading location	−0.316	0.023	**	−0.669	0.064	**
		Urban unloading location	−1.537	0.030	**	−1.316	0.056	**
		(Un)loading at distribution center				1.536	0.057	**
		(Un)loading at multimodal terminal	1.394	0.029	**	3.365	0.068	**
Special vehicle 		ASC	−6.722	0.120	**			
High emission class		ASC (ref.)	–			–		
Low emission class		ASC	2.963	0.016	**	2.002	0.021	**
Shipment size specific constants								
Ship. < 3 t (ref)		ASC (ref.)	–			–		
		Agricultural products	0.690	0.033	**			
		Petroleum products				12.876	0.590	**
Ship. 3–6 t		ASC	−2.855	0.034	**	−2.659	0.045	**
		miscellaneous goods	0.809	0.033	**			
Ship. 6–10 t		ASC	−3.755	0.051	**	−3.047	0.045	**
Ship. 10–20 t		ASC	−3.459	0.095	**	−1.819	0.024	**
Ship. 20–30 t		ASC	−3.339	0.164	**			
		miscellaneous goods	3.203	0.041	**			
Ship. 30–50 t		ASC	−1.339	0.261	**	0.512	0.044	**
		Minerals. building materials	3.506	0.056	**			
Observations			81,474			23,501		
Alternatives			72			53		
Final Log-Likelihood			−118,145			−40,001		
Null Log-likelihood			−348,437			−93,306		
Log-Likelihood (C)			−166,972			−50,225		
ρ^2 (0)			0.661			0.571		
ρ^2 (C)			0.292			0.204		

observations in the database. For non-bulk commodities we have 72 alternatives available and for bulk 53. We have tried several models, varying the number of dummies and parameters in the model, and the best model was retained. Signs of the cost coefficients remained consistent throughout, which indicates a robust model. Below we discuss the estimation results for the final model that was used in the policy analysis. Table 2 summarises the final model specifications for the non-bulk and bulk commodity groups that are used in the presented case study. The first commodity group includes goods types with small shipment sizes, mainly non-bulk goods. The second commodity group on average has a much larger shipment size and consists of bulk goods mainly (petroleum products, ore and metal waste, and chemicals).

The second group has a stronger cost coefficient (−0.041) compared to group 1 (−0.021), reflecting the higher cost sensitivity for transporting bulk material. The estimated parameters for inventory costs are significant and negative, implying a tendency to reduce shipment size to lower the inventory costs. This creates the trade-off in the model between the opposite impacts of shipment size on transport costs (larger shipment size, more cost efficiency) and inventory costs (larger shipment size, higher inventory costs).

The smallest shipment size is the reference category. In commodity group 1, small shipment sizes are preferred, with all negative parameters for larger shipment size classes. In commodity group 2 we see a positive coefficient for the largest shipments size class (> 30 t), implying this is the most preferred shipments size class, followed by small shipments (< 3 t), the reference category. Interaction terms reveal significant shipment size preferences. For instance: within commodity group 1 we observe a strong preference for the largest shipments sizes for goods in building materials (NST/R 6).

The vehicle type tractor + trailer is the reference category, and is the main vehicle type as could already be observed in the market shares presented in Table 1. This is plausible, since tractor + trailer is the most cost efficient vehicle type. This preference is particular strong in international (long-haul) transports: this is confirmed in the positive parameters for import and export. Tractor + trailer combinations are also preferred for transports to/from multimodal transhipment terminals: most road freight transports to multimodal terminals are containerised. For this type of transport tractor and trailer combinations are the only viable possibility. However, tractor + trailer combinations are less likely to be used for transports with loading or unloading locations in dense urban areas. Smaller vehicles are also more preferred by own account carriers and for transports from producer to distribution centres.

Table 3
Emission based charge by vehicle category (€/veh·km).

		Base policy Emission class		Extreme emission policy Emission class	
		High emission	Low emission	High emission	Low emission
Vehicle capacity:	3.5–12 T	0.144	0.086	0.288	0.00
	12–32 T	0.194	0.137	0.388	0.00
	> 32 T	0.199	0.141	0.398	0.00

Table 4
Impact of the emission based charges on vehicle kilometres by emission class.

	Reference (vkm)	Base policy (%)	Extreme policy (%)
Commodity group 1 (non-bulk)			
High emission class	31,313	−8%	−37%
Low emission class	609,020	1%	2%
Commodity group 2 (bulk)			
High emission class	35,780	−35%	−77%
Low emission class	275,689	4%	10%

5. Application

The model presented here was developed to analyse the impacts of emission and distance based road pricing charges for the Netherlands on vehicle type use. Therefore we analysed a policy scenario that is most likely for the Dutch policy. This base policy scenario is based on the level and dimensions of the emission based distance charge as implemented in Belgium (Viapass, 2018). This means the charge is vehicle size (carrying capacity) and emission class specific, varying between 8,6 ct/km for small and efficient vehicles and 19,9 ct/km for large and high emission vehicles. In our impact assessment we added the vehicle type specific charges to $c_{t,v}$: the unit time–cost prices per hour, see Eqs. (2) and (5). As a sensitivity analysis we implemented a second, more extreme scenario, where vehicles in high emissions classes are charged the double of the charge in the base scenario and vehicles in low emission classes don't pay any charge. Table 3 shows the charges by vehicle type, both for the base- and more extreme emission policy scenario.

We calculated the impact on vehicle kilometres by different vehicle types, emission classes and shipment sizes. The results are summarised in Table 4. Next, Fig. 1 illustrates the impact on absolute vehicle kilometres by different vehicle types and shipment size classes.

The overall results confirm a shift from vehicles with high emissions to low emissions: in the base policy the vehicle kilometres with

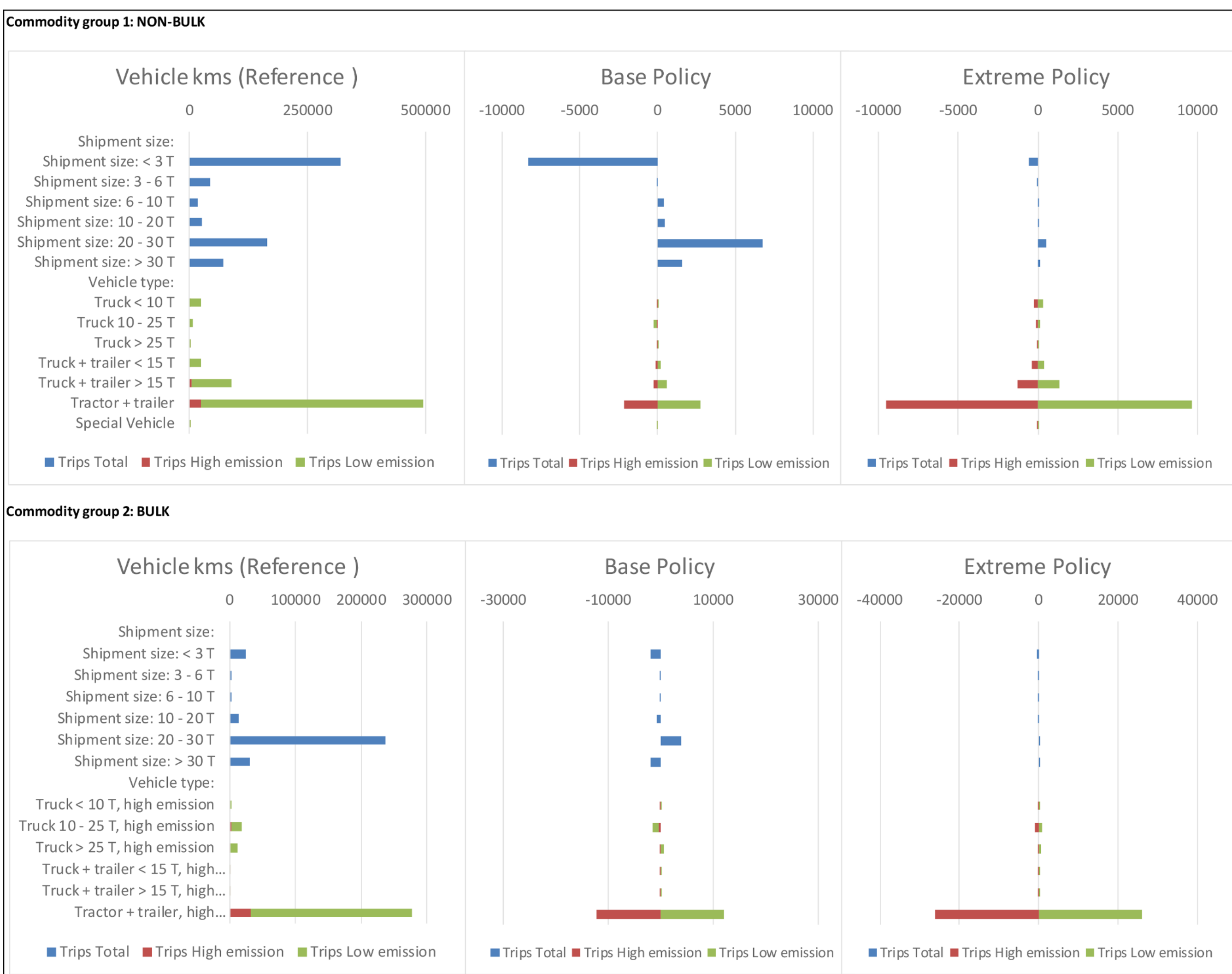

Fig. 1. Impact of the emission based charges on vehicle kilometres by different vehicle types and shipment size classes.

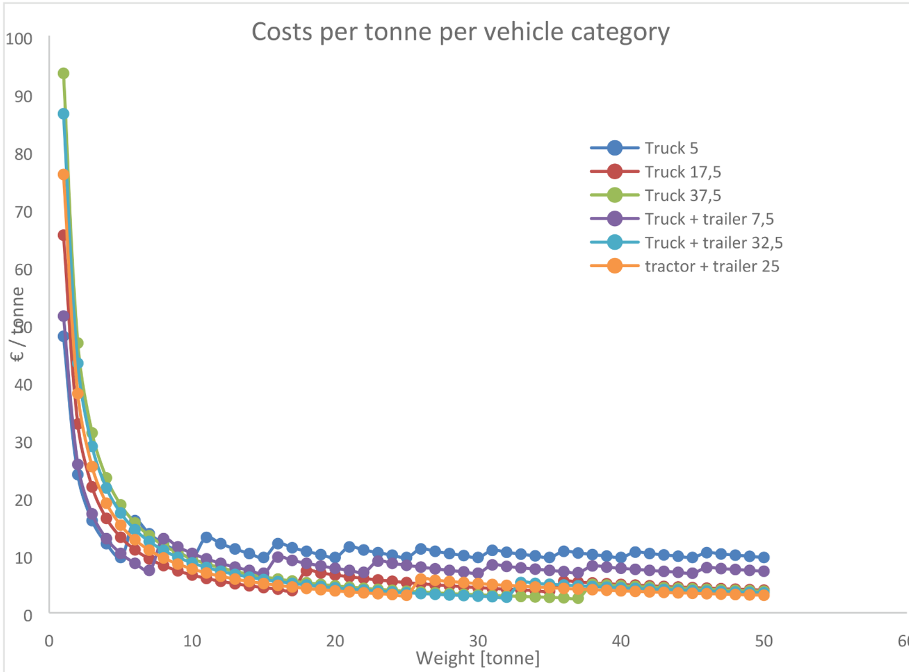

Fig. 2.

inefficient high emission vehicle reduce by 8% for non-bulk and by 35% for more cost-sensitive bulk commodities. The relative increase in vehicle kilometres for low emission vehicles is lower due to the large market share of these vehicles in the reference case. In the case of the extreme emission policy, the high emission vehicle kilometres are reduced even more strongly.

The results suggest that the truck charge will not lead to a significant increase of shipment sizes or substitution to other vehicle types. In the case of the base policy we observe a small shift to larger shipment sizes in commodity group 1 and for commodity group 2 we see a shift to the second largest shipment size class: 20–30 T. The explanation for this small shift in shipment size is the impact on warehousing costs in the total logistic costs. This emphasizes the need to include warehousing costs or shipments size in logistic costs function in ex-ante modelling studies, else studies might overestimate the shift to larger shipments sizes and heavier vehicles. Substitution can also take place from a larger to smaller vehicle: due to discrete shipment sizes and carrying capacity of the vehicles, the cost efficiency is not a continuous decreasing function (see Fig. 1A in Appendix A). As a result around 25 T a heavy truck becomes more cost efficient compared to Tractor + trailer combination. In the more extreme emission policy, low emission vehicles have zero charge, and are a likely substitute for the high emission vehicles: Fig. 2 shows most substitution from high emission to low emission vehicles, in particular tractor + trailer combination; the shipment size distribution is hardly affected.

The analysis shows that only small shifts occur between vehicle types, but most of the shift can be expected from high to low emission vehicles. The first explanation for a small shift, is the modest impact of the vehicle charge on total transport costs: the distance based transport costs have a relative small share compared to the time based transport costs. (This varies by vehicle type and transport distance, but for a transport by Tractor + trailer combination over 40 km distance and 1 h transport time, the distance based costs are < 30% of total transport costs). A second explanation is an inertia in how transport is organized: for some transports only one vehicle type is possible (e.g. containerized transport and tractor trailer combinations), but individual road freight trips are often also part of a supply chain that are conditional to the flexibility to adjust shipment sizes.

6. Conclusions

The analysis of a realistic emission based truck charge scenario shows that we should not expect dramatic changes in the road freight sector. We measure a minimal shift in shipment size choice and vehicle type distribution. This can be explained first of all by the modest impact of the vehicle charge on total transport costs. Secondly, shipment sizes also impact warehousing costs, which means less flexibility to change logistic operations to reduce transport costs. Many road freight transports are part of a longer supply chain, conditioning the flexibility to change shipments size or vehicle type used. This result points to a limited capability of supply chains to absorb transport cost increases by logistics re-organisation, and is in line with constraints to shifting identified in earlier work of Hensher et al. (2013).

The largest impact was seen not between the vehicle type but in a shift towards low emission vehicles. Therefore, we conclude that a distance- and emission class based truck charge can be an effective measure to reduce emissions for road freight transport. Since our study is based on RP data, we could only distinguish EURO class 6 as the most efficient vehicle type. Zero-emission vehicles are a relevant vehicle type that can help reducing emissions from road freight transport. However, since its recent introduction a minimal number of vehicles is available and in use, but observations are missing to include ZE-vehicle as a separate emission class in our analysis. The results from this study however, show that an emission class specific truck charge can lead to a significant shift towards low emission vehicles. Therefore we suggest that ZE vehicles should be a dimension in a differentiated vehicle charge. This way, an emission based distance charge can provide an effective incentive to accelerate the uptake of ZE vehicles. However, to design an empirical analysis, further research is required to estimate the behavioural response to new vehicle types. An interesting direction would be to extend the RP analysis presented in this article and combine it with a stated-preference study after the adoption of new ZE vehicles or other new efficient solutions under different pricing scenarios.

We emphasize that this ex-ante analysis only considers the impact on vehicle type and shipment size: impacts on modal split, spatial distribution of goods flow or route choice are not considered here. Policy studies with the Dutch national freight model, suggest a possible total impact of modal split and distribution effects of a distance based charge of 15 ct/km on the total network, and a decrease of 2% of total freight tonne-km's (MuConsult et al., 2018).

CRediT authorship contribution statement

Michiel Bok: Conceptualization, Methodology, Formal analysis, Writing - original draft, Writing - review & editing, Visualization. **Ivar Bal:** Conceptualization, Methodology, Data curation, Formal analysis. **Lóránt Tavasszy:** Conceptualization, Methodology, Writing - review & editing, Supervision. **Taede Tillema:** Investigation, Validation, Writing - review & editing.

Acknowledgements

The work reported in this paper follows from a collaboration project between Delft university of Technology and Statistics Netherlands. The authors are greatly thankful for the Central Bureau of Statistics for providing access to their transport statistics. Any interpretation or opinion expressed in this paper are those of the authors and do not necessarily reflect the view of Statistics Netherlands, nor the Netherlands Institute for Transport Policy Analysis. Also the authors are thankful for the useful feedback of prof. Gerard de Jong on the methodology, and the comments of two anonymous reviewers.

Appendix A. Cost per tonne by vehicle type and shipment size

The figure below illustrates the costs per tonne for the different vehicle classes are calculated. On the y-axis the cost per tonne are expressed and on the x-axis the total weight transported is shown. From this figure it can be seen that once the amount of weight to be transported increases, the costs per tonne decreases, but due to the carrying weight of vehicle type the functions are discontinuous.

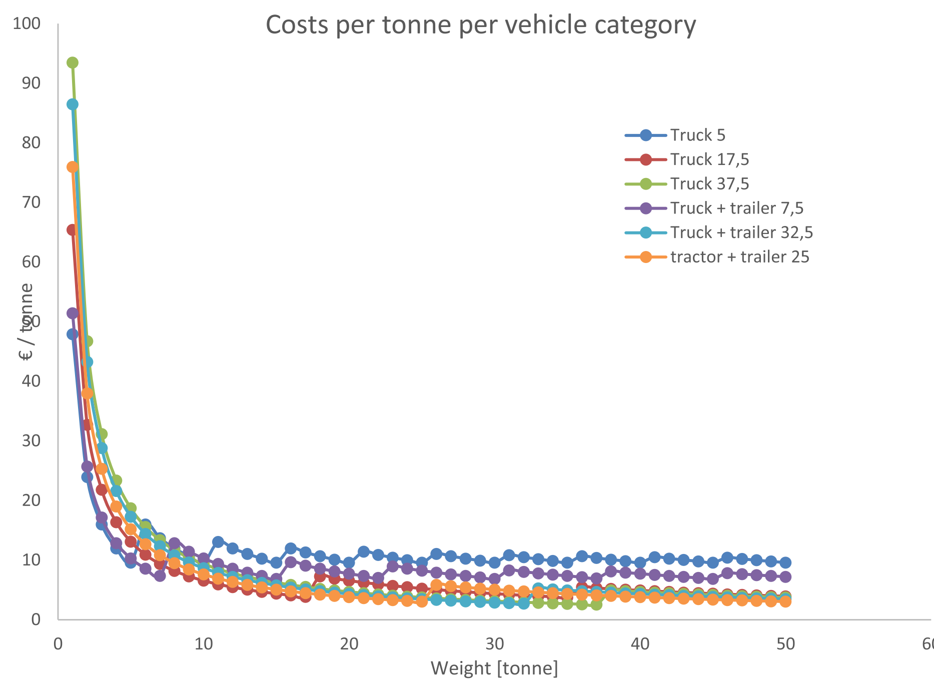

Fig. 1A. Unit transport costs per vehicle category, by shipment size.

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