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IMPACT OF LOGISTICAL CHOICES ON FREIGHT TRANSPORT CARBON EFFICIENCY

CHRISTOPHE RIZET, UNIVERSITY PARIS EST, IFSTTAR (FRENCH INSTITUTE OF SCIENCE AND TECHNOLOGY FOR TRANSPORT, DEVELOPMENT AND NETWORKS) – DEST (DEPARTMENT OF ECONOMY AND SOCIOLOGY OF TRANSPORTS), 2 RUE DE LA BUTTE VERTE, F-93166 NOISY-LE-GRAND CEDEX FRANCE. CORRESPONDING AUTHOR: CHRISTOPHE.RIZET@IFSTTAR.FR

CECILIA CRUZ, UNIVERSITY PARIS EST, IFSTTAR-DEST, 2 RUE DE LA BUTTE VERTE, F-93166 NOISY-LE-GRAND CEDEX FRANCE. MAIL : CECILIA.CRUZ@IFSTTAR.FR

MATTHIEU DE LAPPARENT UNIVERSITY PARIS EST, IFSTTAR-DEST, 2 RUE DE LA BUTTE VERTE, F- 93166 NOISY-LE-GRAND CEDEX FRANCE. MAIL : MATTHIEU.DE-LAPPARENT@IFSTTAR.FR

This is an abridged version of the paper presented at the conference. The full version is being submitted elsewhere. Details on the full paper can be obtained from the author.

ISBN: 978-85-285-0232-9

13th World Conference on Transport Research

www.wctr2013rio.com

15-18 JULY 2013 Rio de Janeiro, Brazil

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Christophe RIZET, University Paris Est, Ifsttar (French institute of science and technology for transport, development and networks) – DEST (Department of Economy and Sociology of Transports), 2 rue de la Butte Verte, F-93166 Noisy-le-Grand Cedex France. Corresponding author: christophe.rizet@ifsttar.fr

Cecilia CRUZ, University Paris Est, Ifsttar-DEST, 2 rue de la Butte Verte, F-93166 Noisy-le-Grand Cedex France. Mail : cecilia.cruz@ifsttar.fr

Matthieu DE LAPPARENT University Paris Est, Ifsttar-DEST, 2 rue de la Butte Verte, F-93166 Noisy-le-Grand Cedex France. Mail : matthieu.de-lapparent@ifsttar.fr

ABSTRACT

What are the characteristics of freight transport which have an impact on CO_2 emissions? Among those characteristics, what is the importance of the shipper's logistical choices on CO_2 emissions? To answer this question we use the 2004 French shipper survey. This survey describes the characteristics of 3 000 shippers, of 10 000 shipments, and of 20 000 different legs of the transport chains. We computed the energy consumption and CO_2 emissions of each shipment, leg by leg and then summed it on the transport chain, per shipment. This CO_2 emission, when related to the tonne-kilometres, gives the carbon intensity of the shipment, in grams of CO_2 per tonne-kilometre. We find that there is a very high variability of carbon intensity per shipment: from less than 0.01 to more than 100 kgCO2/tkm.
We then analyse this carbon intensity per shipment according to two types of shipment characteristics: the shippers' logistical choices (shipment frequency and mode choice) on the one hand and, on the other hand, transport demand characteristics independent of the logistical choices (distance as the crow fly and yearly tonnage shipped to the same client). Using a log log model, where carbon intensity is a function of these characteristics, we find that the shippers' logistical choices have at least as much impact on carbon intensity as transport demand characteristics.

Keywords: Green-House Gas, freight transport, logistics

1. CONTEXT AND OBJECTIVE

Over one quarter of greenhouse gas (GHG) emissions in France comes from the transport sector and this share is growing. Furthermore, the share of emissions from freight activity is growing and there is neither sign of saturation of energy use nor GHG emissions. Therefore, in order to reach our target of dividing per 4 the anthropological GHG emissions, deep changes are necessary, either through carbon efficiency improvements or by means of reduction of transport demand.

Carbon efficiency of freight transport and also the determinants of freight transport demand are not well understood. We claim that an in-depth knowledge of the factors that influence firms in their logistical choices as well as the factors that influence carbon efficiency would make freight GHG mitigation much easier. This lack of knowledge is due to several factors, including the theoretical complexity of the problem, the insufficiency of resources that have been made available for freight compared with passenger transport, and the inadequacy of the existing data. The French shipper survey developed in 2004 is an attempt to fill this gap in data. The survey methodology is discussed in Rizet et al.(2002 and Guilbault & Gouvernal (2010) gives an overview of the results.

Our objective in this paper is, using this survey, to analyse at a disaggregate level the carbon efficiency of freight transport and to quantify the influence of logistical practices on transport energy consumption and CO_2 emissions. The main logistical characteristics that we consider in this paper are the number of shipments that will be sent in a year to the consignee to satisfy his yearly demand (frequency of the deliveries) on the one hand and the mode choice on the other hand.

After presenting the survey (section 2) and developping the way we estimated transport energy consumption and CO_2 emission per shipment (section 3), we analyse the relation between CO_2 and the main characteristics of the shipment (section 4) and then we focus on the impact of the logistical choices.

2. DATA : THE SURVEY AND THE VARIABLES WE USED

The methodology of the French shipper survey has been described in (Rizet et al. 2002). Two major characteristics of this survey are 1) the description of the shippers' organizational features influencing the transport choices and 2) the tracking of a selection of shipments from their departure from the plant up to their arrival to the consignee. In this survey, information is collected at three levels:

- Shipper establishment: after a few questions about the volume and structure of the company's ingoing and outgoing transport flows and its own fleet of vehicles, a face-to-face interview is administered to the logistics manager of the company. Questions regard what covers the economic characteristics of the firm: production, distribution, storage practices, relationships with its customers and suppliers, and the management and communications systems it uses. This description of the firm's industrial and logistical organization is supplemented by a "transport" section, which deals with the firm's relationships with carriers,

terms of access to the various types of infrastructure, and how responsibility for transport is shared between the firm and its partners.
- Consignment level: at the end of the establishment questionnaire, the last 20 consignments are listed, of which 3 are randomly selected and then surveyed until they reach their final consignee. The consignment questionnaires (which are filled in either with the manager mentioned above or with the manager in charge of dispatching) deal with the economic relationship between the shipper and the consignee and the terms of business between the two. This relationship between the shipper and his customer is described not only through the physical and economic characteristics of the shipment but also with questions on the quantity of goods sent to this client per year (yearly tonnage to this consignee), the yearly number of shipments to this consignee, the split of responsibilities with regard to transport organization and the contractual allocation of transport costs and associated services. The first information required in order to reconstruct transport chains is also collected at this level, with the identification of the consignee.
- Transport operator and journey link: for this part of the survey, questionnaires are administered by telephone. Questions deal with the economic characteristics of the operator, including the operator to whom it handed the shipment and with the characteristics of the transport leg: mode and vehicle type, load, etc. The next operator is in turn questioned up to the final consignee and the description of the whole transport chain. The transport chain is split into as many legs as there are changes to another vehicle.
The transport chain is therefore reconstructed throughout Western Europe and includes an interview with the consignees. For a shipment which travels beyond this limit, the transport chain is surveyed only until the first transfer point after the frontier of Western Europe.

Furthermore, the 2004 shipper survey has been adapted to enable the quantification of energy consumed and CO_2 emitted, and to relate them to the determinants of freight transport demand (Rizet et al., 2004). Primary and final energy consumption have been computed per leg, as the product of distance per vehicle energy intensity (litre per km), divided per the load and multiplied per the shipment weight; empty backhauling is estimated using the results of the French national freight vehicles survey. Energy consumption is converted in Grams of Oil Equivalent (goe) and shipment energy consumption is the sum of energy per leg. Both tank to wheel and Well to Wheel CO_2 emissions are then computed as the product of energy per an emission factor. Dividing energy and CO_2 per the tonne-kilometre of the shipment gives the energy and carbon intensity of the shipment, in goe/tkm and CO_2/tkm.

Among the numerous variables of the survey, in this paper we have used few variables for our analysis:
The shipment carbon intensity, in CO_2/tkm, is the variable we try to explain;
Two kinds of variables are used to explain this carbon intensity:

- The ‘transport characteristics’, which are supposed to be independant of the logistical choices:

  The shipment Straight Line DISTance (SLDIST) or distance as the crow flies, between origin and final destination, independently of the followed route,

  Yearly Tonnage sent to the Same Consignee (YTSC);
- And two variables characteristics of the shipper logistical choices:

- Yearly Number of Shipments sent to the Same Consignee (YNSSC) and
- Transport mode.

Note that shipment weight is not among our explanatory variables. This is because this shipment weight is neither fully a logistical choice (it is highly constrained by the total weight claimed by the client), nor fully independant of logistical choice. In this analysis, instead of the shipment weight, we use two variables: 'yearly tonnage' and 'yearly number of shipments' to the same consignee.

Table 1 below summarizes the distribution of the variables we used.

Table 1 - Distribution of the main variables used

Variable	**Min.**	**10th centile**	**25th cent.**	**Median**	**75th cent.**	**90th cent.**	**Max.**
Straight line distance, km	0	18.6	74.1	277	610	5 228	18 821
Yearly tonnage to the same consignee, tons	0.0010	0.150	1.10	17.0	350	3 300	630 000
Yearly shipment number to the same consignee.	1	3	11	40	128	312	21 700
Shipment weight, tonnes	0.0010	0.00500	0.0500	0.650	7.80	23.00	10 800
WW kg CO_2 / tkm	0.00074	0.0491	0.0717	0.202	0.661	1.632	43 94

The range of shipments is very broad:

- From less than 1 gram to more than 4 tons CO_2/tkm for the carbon intensity,
- from zero to nearly 20 000 km for the distance as the crow flies,
- from 1 kg to more than 600 000 t. for the yearly tonnage to the same consignee,
- from 1 to more than 21 000 for the yearly number shipments to the same consignee,
- from 1kg to more than 10 000 t. for the shipment weight,
- and from half an hour to more than 1 year for the delivery deadline.

We now turn to a more precise description of these variables.

Distance as the crow flies: Different modes have different distances for the same travel (same origin and same destination), according to their different networks. In order to compare their carbon efficiency, a straight line distance has been computed not to use the distance actually performed on the network. Figure 1 here under compares these 'distances as the crow flies' and 'network' distances on our sample of 10 000 shipments. Because of the large dispersion of the distances, the axes are in logarithm.

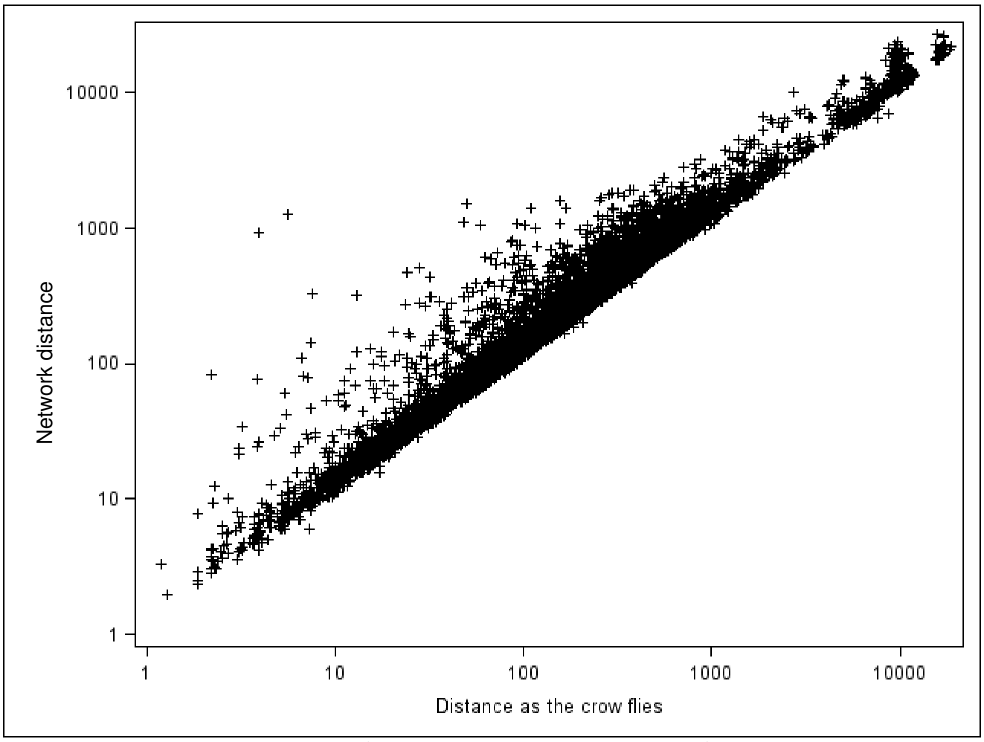

Figure 1– Distance as the crow flies versus network distances of the shipments (log log)

As expected, there is a strong correlation between the two distances; for each shipment the logarithm of network distance is generaly comprised between the log of straight line distance and 1.1 times this value. Nevertheless, it should be noted that this strong relation of the logarithmes corresponds to a weaker relation for the distance: if the distance is 1000 km, a ratio of 1.1 for the logarithmes means a ratio of nearly 2 for the distances, as shown in table 2 here under.

Table 2 – Impact of a variation of 10 % of the logarithm on the corresponding value of the distance

Distance (km)	log (distance)	1.1 *log (dist)	Corresponding distance
1	0.0	0.0	1.0
10	1.0	1.10	12.6
100	2.0	2.20	158.5
1000	3.0	3.30	1995.3
10000	4.0	4.40	25118.9

Shipment weight, yearly tonnage and yearly number of shipments sent to the same consignee.

For each shipment surveyed, the shipper was asked the yearly tonnage and yearly number of shipments sent to the same consignee, to understand its relation with this customer. So for each shipment we can calculate the weight of the ‘average shipment to this consignee’ as the ratio between the yearly tonnage and yearly number of shipments to this consignee.

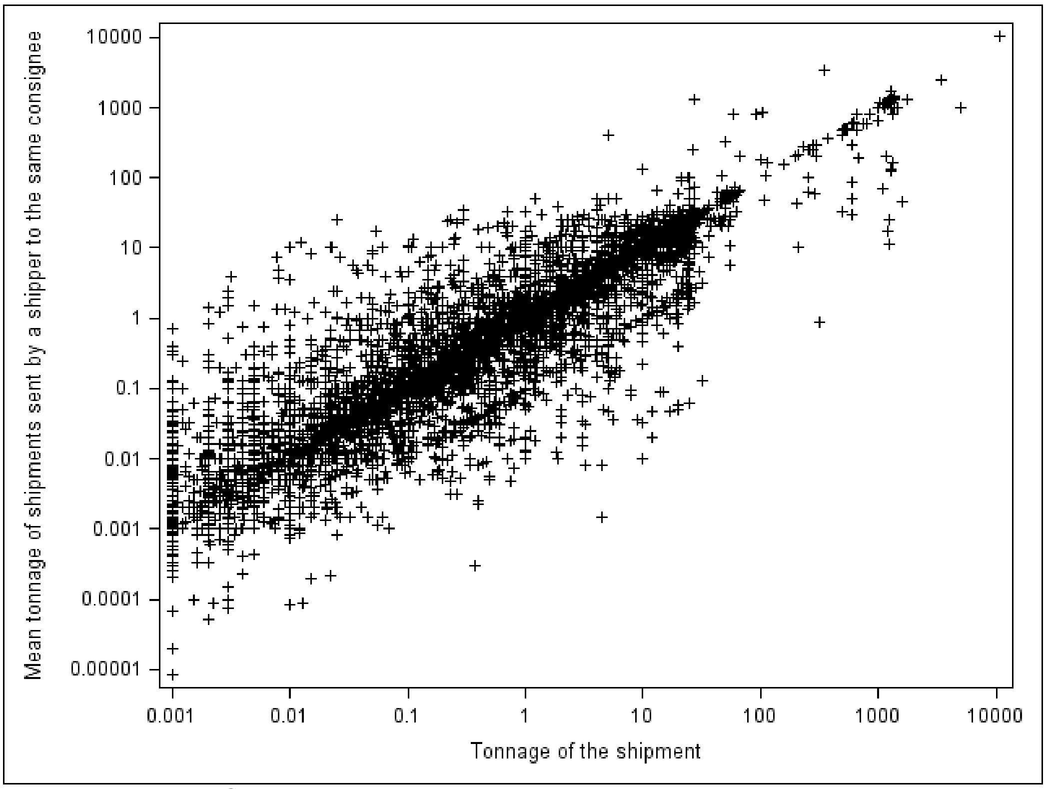

Figure 2 – Shipment weight versus average shipment weight to this consignee

There is a strong relation between the logarithm of the surveyed shipment weight and the logarithm of the average weight of shipments sent by this shipper to this consignee (computed as the yearly tonnage sent to this consignee, divided per the yearly shipment number to the same consignee), somewhat reflecting a kind of regularity in business relations. As in the previous graph, it should be noted that this strong relation of the logarithmes corresponds to a weaker relation for the tonnage values.

Scope of the survey: A comparison with the French Transport National Accounts.
All types of shippers are not covered by the French shipper survey: some activities like agriculture and the small shippers (less than 5 employees) are not surveyed. Table 3 here under enables to compare the result of the French Shipper Survey (FSS) with the results of the French Transport National Accounts (FTNA) which is the reference of freight transport GHG emissions for the Kyoto protocol.

Table 3 - Main results of the French Shipper Survey and comparison with French National Transport Accounts

	observ	tons(millions)		tkm (billions)		tep (thousands)		t CO_2 (millions)	
		FSS	FSS /FTNA	FSS	FSS /FTNA	FSS	FSS /FTNA	FSS	FSS /FTNA
Railways	369	81,4	0,88	32,0	0,95	168	0,86	0,12	nd
Waterways	54	9,4	0,22	1,3	0,22	14,7	0,25	0,05	0,28
Road	17299	1029	0,50	203	0,97	10 790	0,98	33,8	0,97
Total	17722	1120	0,51	236	0,95	10 973	0,97	34,0	0,95

Because of the scope, FSS severely underestimates the tonnages (51%). As this underestimation mainly comes from very short distance transport, traffic expressed in tkm is much less underestimated (95%); and so are energy (97%) and CO_2 emissions (95%).
For waterways, FSS has very few observations and dramatically underestimates not only in terms of tons, but also in terms of energy and CO_2.

3. CARBON INTENSITY PER SHIPMENT

A shipment is a group of goods sent by one shipper to a consignee. In the survey, it corresponds to a transport chain, i.e. a succession of transport legs. The number of transport legs per transport chain varies from 1 up to 8. Carbon intensity per shipment is expressed here in gCO_2/tkm and is considered as the indicator of the carbon efficiency: when carbon intensity is increasing, the efficiency is decreasing.
In table 4 here under, shipments have been classified according to the main transport mode declared by the shipper. We first describe the average characteristics of each type of transport chain, in order to compare their specificities.

3.1 The specificities of the type of transport chain

Table 4 - Average characteristics of the transport chains

	ROAD			SEA	AIR	RAIL	WATERW	ALL
	H&R	O A	All					
Number of shipments observed[1]	6 059	1 777	7 836	484	656	312	28	9 316
Average shipment weight (tons)	1.15	1.13	1.15	7.66	0.03	24.69	497	1.26
Average distance as the crow flies (km)	265	35	192	4 340	2 468	597	295	266
Yearly tonnage to same consignee (tons)	418	318	388	997	7	1 801	45 598	386
Average yearly shipment number to same consignee	153	504	274	91	60	114	26	267
Av. shipment weight to same consignee (tons)	1.5	1.5	1.5	7	0.07	17	517	1.53
Average delivery deadline for shipments in non-established program (in hours)	131	44.7	111	329	87.9	74.2	335	111
Average carbon intensity in gCO2/tkm	162	189	165	20	493	18	41	108

Among these characteristics of these transport chains, some are well known: road own account (OA) is mainly for very short distances (35 km) and for very frequent shipments. Air transport chains are for light shipments and long distances whereas sea transport chains are for long distances and medium weight shipments. Waterways are for heavy shipments. Among the characteristics which are new are the yearly relations between the shipper and its consignee, the delivery deadline required by the consignee and carbon efficiency.

[1] * In this paper, we are only using fully reported transport chains, thereby reducing the number of usable observations.

Yearly relations between the shipper and its consignee : this table also point out that average yearly shipment number to the same consignee is very important, mainly for road: 274 for all road transport chains, which means more than one shipment per working day to the same consignee. A previous research (Cruz, 2011) about own account transport emphasized the fact that shippers choose their main customers to deliver in own account transport.

Delivery deadline: In the survey, the question on delivery deadline claimed by the customer is only asked when the shipment is not part of a pre-established programm. For these shipments, average delivery deadline stands between 45 hours (less than two days) for road own account, 3 days for rail, 4 days for air, 5,5 days for H&R road and 14 days for water or sea transport chains. Given the distance, delivery time directly impact the minimum speed, and so, indirectly the mode choice and the grouping opportunities to get a full load.

Carbon efficiency is the last line of in table 4 in grams of CO_2/tkm per type of transport chain, as we computed it from the survey. Rail, sea and waterway transport chains are the most efficient ones with an average of respectively 18, 20 and 36 gCO_2/tkm. At the opposite, air chains are the most carbon intensive with 493 gCO_2/tkm. In between are road transport chains with an average 111 gCO_2/tkm. These average carbon efficiencies, computed for transport chains from the French Shippers Survey are coherent with the figures published by DEFRA for UK for transport modes, as shown in table 5 here under.

Table 5: a comparison of carbon intensity in France and UK in gCO2WW/tkm

	road	sea	air	rail
French transport chains computed from FSS	111	20	493	18
UK transport modes (Source Defra 2012)	165[2]	20[3]	773[4]	36[5]

[11] The figures for rail are difficult to compare

The last line of this table gives the average figure per mode for UK as published by DEFRA (2012). These DEFRA figures are per mode while our ECHO figures are per transport chains. Figures are not too different for road and sea transport. The difference for rail is mainly linked to the upstream emission of electricity production (mainly nuclear in France and carbon intensive in UK); for air, it could be linked to the type of planes.

For the sake of clarity and to better depict the relations between carbon intensity and the main variables of table 3, we now propose a series of scatter plots.

[2] Heavy Goods Vehicles only (excluding vans)
[3] Container 3000-7999 TEU
[4] Long haul international only
[5] Figures for rail are linked to electricity production

3.1 Carbon efficiency as function of shipment weight

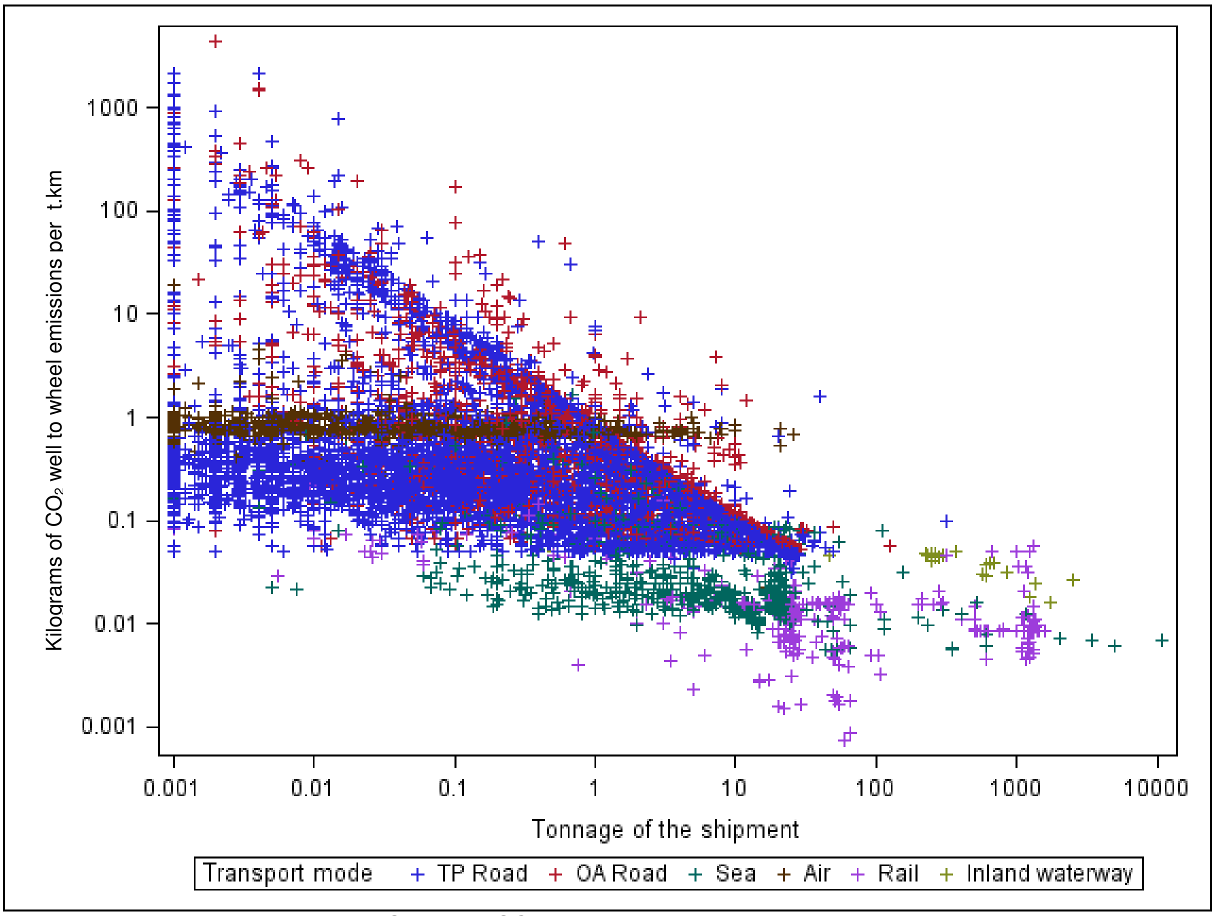

Figure 3 – Shipment CO_2 emission/tkm versus shipment weight

Figure 3 shows a clear relation between the shipment weight (tons, in abscissa axis) and carbon intensity (kgCO_2/tkm, in ordered). This relation is fairly straightforward to understand when the shipment comprises one single leg. For road, a 25 t. shipment has the minimum carbon intensity, under 50 g CO_2/tkm; for a smaller shipment carbon intensity does not change if the vehicle load is completed by consolidation but, if there is no consolidation, the carbon intensity may grow without limit as it is infinite for a shipment weight approaching zero. For air and rail, the load weight was often lacking, so we had to make assumptions on the load, according to other caracteristics of the shipment.

3.2 Carbon efficiency as function of distance

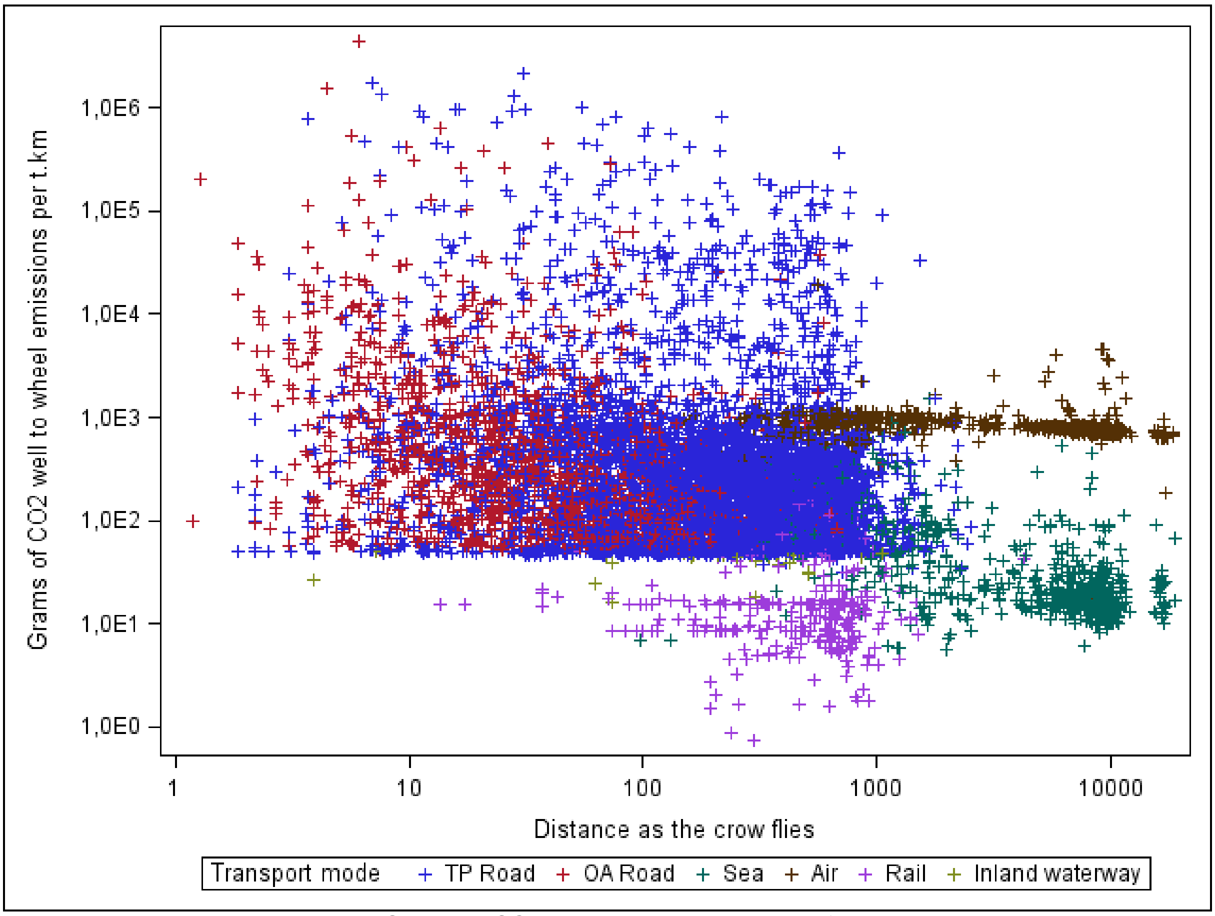

Figure 4 – Shipment CO_2 emission/tkm versus crow fly distance

In this graph, the link between carbon intensity and distance seems to be mainly due to the mode choice: sea or inland waterways vessels are carbon efficient and are mainly used on long or very long distances. For road, own account transport, which is generally less efficient than hire and reward, is also used for shorter distances on average. Only air transport which has high emissions for long distances is going against this trend. For road hire and reward, the link between carbon intensity and distance may also be explained by a better optimization of the load as the distance rises.

3.3 Carbon efficiency as function of the yearly tonnage shipped to one consignee

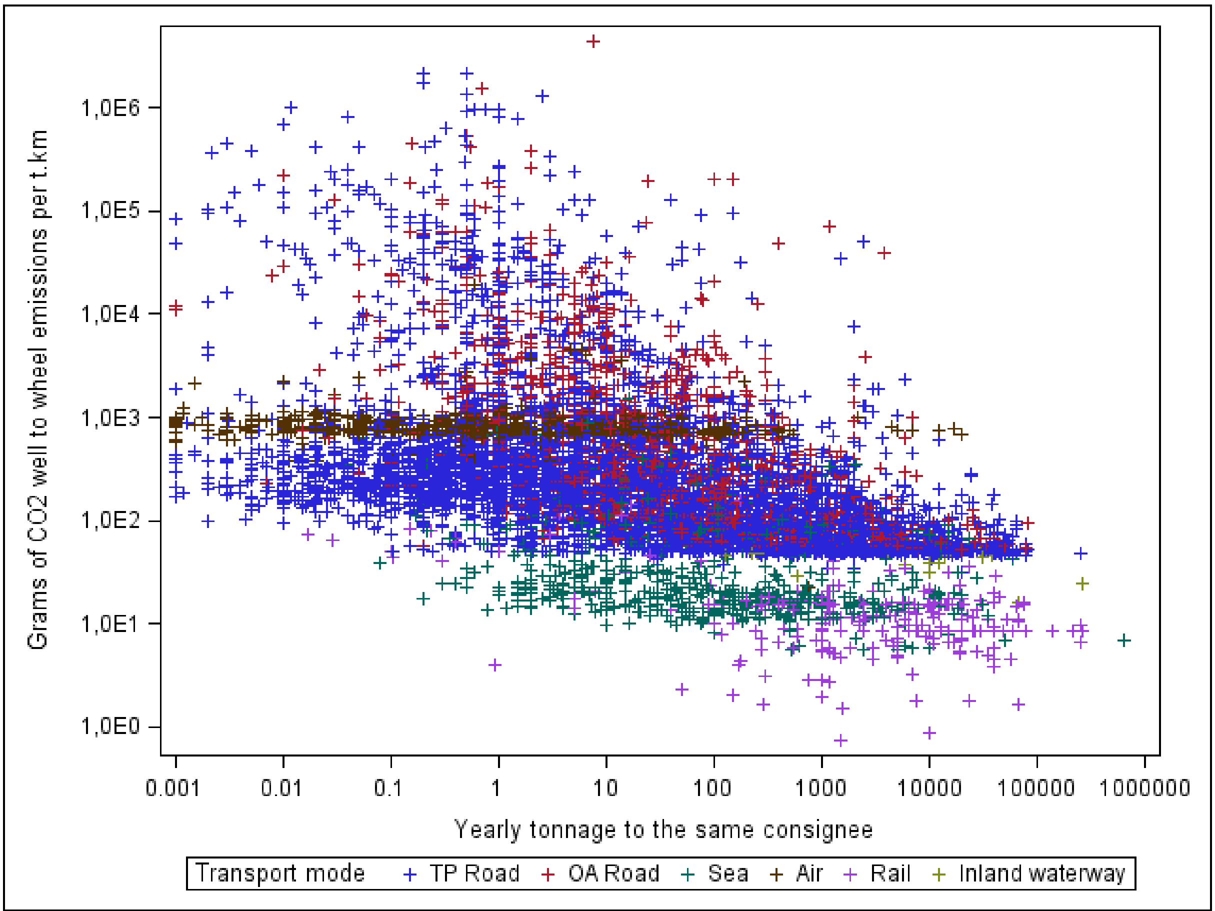

Figure 5 – Shipment CO_2 emission/tkm versus yearly tonnage to the same consignee

This variable measuring yearly tonnage shipped to the consignee is not independent of shipment weight seen in figure 3. The link between this variable and carbon efficiency in figure 5 appears as the result of both modal choice and load optimization:

- modal choice because efficient modes have a high capacity and are used for important yearly tonnages;
- load optimization because the higher the volume of flow, the more optimized the vehicle load and the lower the carbon intensity.

3.4 Carbon efficiency as function of the yearly number of shipments to one consignee

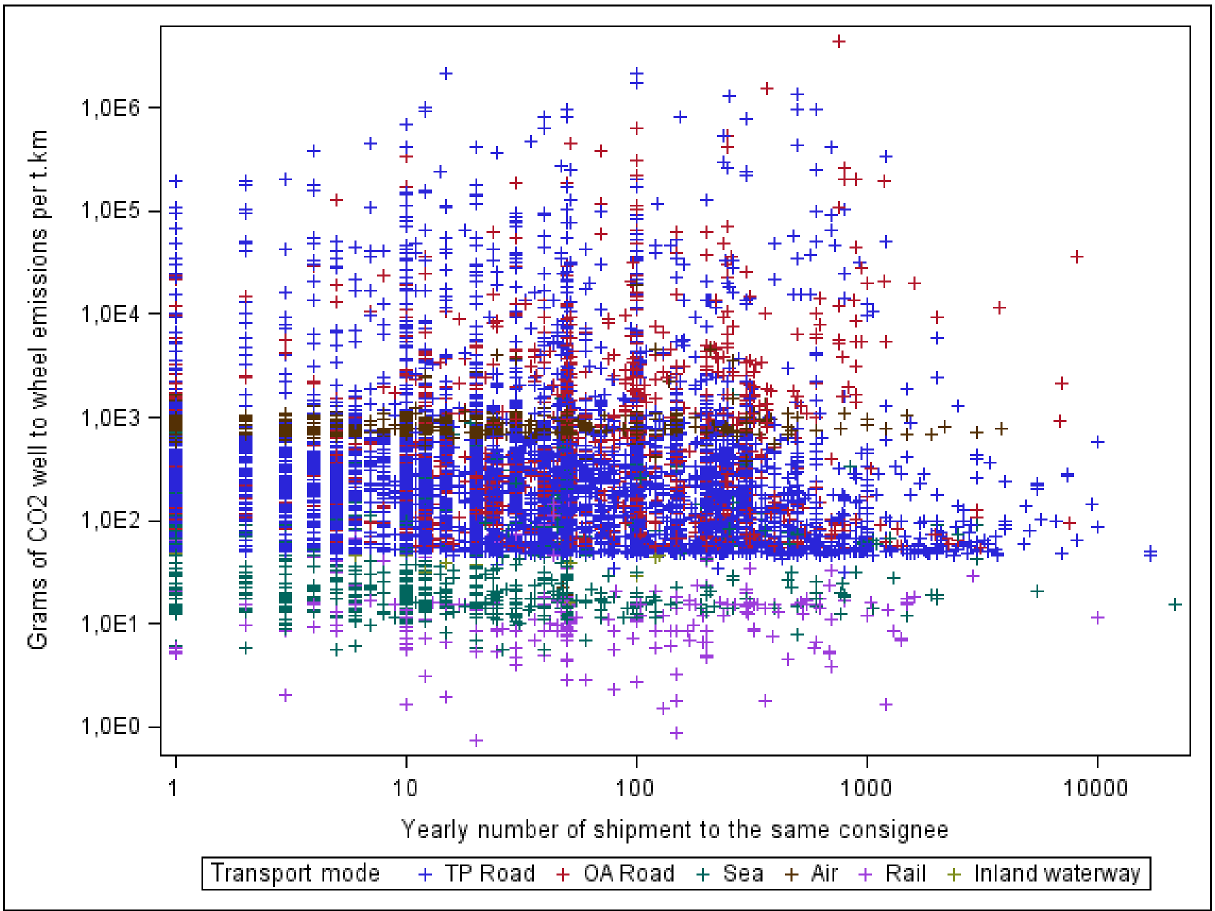

Figure 6 – Shipment CO_2 emission/tkm versus yearly number of shipment to the same consignee

In this figure, there is no clear link between carbon intensitys and the yearly number of shipments to the same consignee. We have seen in the average characteristics of transport chains (table 3) that own account transport has the most important average yearly number of deliveries to the consignee and that it is among the less carbon efficient. However, in figure 7, a high carbon intensity (for ex. > 100 gCO2/tkm) is rare for very frequent deliveries (> 500 shipments per year, which is over 1 shipment per day).

4. MODELING CARBON INTENSITY USING THE SHIPMENT CHARACTERISTICS AS EXPLANATORY VARIABLES

In order to analyze the influence of logistical characteristics of the shipment on its carbon intensity, we simulate in a first step the shipment carbon intensity as a function of the shipment non logistical characteristics: shipment Straight Line Distance (SLDIST) and Yearly Tonnage to the Same Consignee (YTSC); then we introduce two logistical characteristics as explanatory variables: Yearly Number of Shipment sent to the Same Consignee (YNSSC) by this shipper and the choice of transport mode.

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4.1 A simulation of carbon intensity a function of distance and yearly tonnage

We present here our best simulation of the carbon using these two variables. After different tests a log-log linear model was adopted to estimate the parameters in the following function:

Log (CO_2/tkm) = α*log (SLDIST) + β*log (YTSC) + intercept + error (model1)

where

CO_2/tkm is the carbon intensity of the shipment
SLDIST is the Straight Line distance of the shipment
YTSC is the Yearly Tonnage to the Same Consignee

The result of the estimation process is presented here under in Table 4.

Table 4 – Results of the simulation of model1: kg CO_2/tkm, with SLDIST and YTSC (non logistical variables)

R^2: 0.3684	adjusted R^2: 0.3682	σ^2=1.97857		
Parameter	**Estimate**	**Std. Err.**	**T**	**P > |t|**
Intercept	0.91376	0.04992	18.30	<.0001
SLDIST	-0.28981	0.00846	-34.25	<.0001
YTSC	-0.25889	0.00423	-61.16	<.0001

With these two 'non logistical' variables, SLDIST and YTSC (distance and Yearly Tonnage to the Same Consignee), this very simple model explains only 37% of the carbon intensity per shipment. The coefficients of these two variables are highly significant and, as expected, negative. When the shipment distance or the tonnage of goods to ship increase, carbon intensity decreases; in other words, the more important the transport to a consignee, in yearly tonnage or in distance, the more 'carbon optimized' it is.

4.2 Introducing logistical variables in the model

In this simple model 1, we now introduce variables that represent the shipper's main logistical choices: yearly number of shipments to the same consignee (YNSSC), which determines the shipment weight, and transport mode.

Transport modes have been introduced as dummy variables for each mode. Road transport is the 'reference' so there is no variable and waterway was taken out as non significant (we have only a very small number of observations for waterways).

Table 6 – Results of the simulation of model2: kg CO_2/tkm, using logistical variables (in log-log)

R^2: 0.4908 adjusted R^2: 0.4904		σ^2=1.60190		
Parameter	**Estimate**	**Std. Err.**	**T**	**P > |t|**
Intercept	0.02319	0.06187	0.37	0.7079
SLDIST	-0.28221	0.00947	-29.80	<.0001
YTSC	-0.29699	0.00520	-57.14	<.0001
YNSSC	0.26366	0.01055	24.99	<.0001
Maritime mode	-0.61642	0.07232	-8.52	<.0001
Air mode	1.24220	0.06483	19.16	<.0001
Rail mode	-1.53034	0.08404	-18.21	<.0001

This new model explains 49% of the CO_2/tkm: by introducing two logistical variables in our model we increase the R2 from 0.37 to 0.49.
Coefficients (elasticities) are negative for distance and YTSC, as in model 1, but also for maritime and rail modes: CO2/tkm decreases when sea or rail is chosen. On the contrary, it increases when the yearly number of shipments increases or when air transport is chosen. Here again, elasticities have the expected sign: carbon efficiency is better than average for sea and rail transport and lower for air; an increase in the yearly number of shipments for the same quantity to ship yearly (i.e. a reduction in the average shipment weight to this consignee) reduces carbon efficiency.

The next step is to estimate the impact of these logistical variables on carbon intensity and to compare them with the impact of 'demand variables' (yearly tonnage and distance). In the following table 7 we have computed, for each of these variables (demand and logistical), the variation of carbon intensity induced by the shift of its value, the other variables being fixed to their median value. For quantitative variables this shift is from the variable 25th centile up to the 75th centile and, for transport mode, from air transport (the high emission mode) to rail (low emission).

In such conditions, the variations of CO_2/tkm induced by the shift of logistical choices appear very important.

Table 7 – Impact of a variation of the transport characteristics on CO_2/tkm

Quantitative variables	25th centile	75 th centile	% variation
Distance	346	191	-45%
YTSC	538	97.2	-82%
YNSSC	170	324	91%
	Air	Rail	% variation
mode	826	51,7	-94%

An increase in the yearly number of shipments to the consignee, from the 25th to the 75th centile, has a + 91% impact on carbon intensity: everything else being unchanged including the yearly tonnage to this consignee, changing from a small number of shipment to a large one induces a 91% raise in carbon emission. And a shift from air to rail decreases carbon emission of 94%.

In this very simple model, these logistical variables seem to have more impact than the demand characteristics: a change in the distance from the 25^{th} to the 75^{th} centile ‘only has a -45% impact; and a shift in the yearly tonnage send to the consignee has a -82% impact on the unitary emission.

CONCLUSION

An important result of the ECHO survey is the very high diversity of all the shipment characteristics. This paper shows that this heterogeneity includes the shipment carbon intensity which vary from less than one g of CO_2/tkm up to more than 4 tonnes, according to the transport mode and (mainly) to the load weight.
To explain this very high variability of carbon intensity per shipment, a log logs disaggregate model has been used, with two types of explanatory variables: variables characteristic of the logistical choices (yearly number of shipments to the consignee and main transport mode) and variables characteristic of the client demand, which are independent of logistical choices (distance as the crow flies and yearly tonnage shipped to this consignee).
This simple model explains 49% of the carbon intensity with only 4 variables. Both characteristics of the client demand and characteristics of logistical choice have a high impact on carbon intensity.

There are large differences of energy and carbon efficiency between shipments. This has important consequences in terms of freight transport policies: the possibility to improve the less efficient shipments by logistical solutions and not only by technological ones.
In term of research implication a lot of work has to be done to analyse the richness of this data. This paper is based on an ongoing research program. The first result of this research program is introduction of energy and CO_2 in the ECHO shipment database. After the analysis of the shipment emissions presented in this paper we intend to analyse the plant emissions and the CO_2 per employee and the sensitiveness of employment to a transport carbon tax.

ACKOWLEDGMENT

The results presented here are part of an ongoing Ifsttar research program funded by the French Ministry of transport (DGITM); we have used the SAS software for data analysis and figures.

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