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May autonomous vehicles transform freight and logistics

Communication at the 99th Annual Meeting of the Transportation Research Board 2020

Washington DC, USA

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Abstract

The objective is to study the impact the deployment of autonomous vehicles may have on freight and logistics from an economic point of view. We focus on interurban transport operations made by road and propose quantitative estimations of the outcomes of two scenarios where the automation technology is sufficiently efficient to remove the need of a driver during the whole or a significant part of the operations. To do so, we build a modeling chain which links consist of a series of theoretical microeconomical models and econometrical estimations. This chain is used on the one hand to describe theoretically and empirically carriers and shippers behaviors and on the other to target precisely where and how AVs intervene in order to obtain accurate estimations of the two scenarios outcomes. The results show that partial automation won't have a significant impact whether in terms of switching from a heavy to a light shipping mode and vice versa, nor on the shipments' sizes, or even on the carriers Total Logistical Costs. By contrast, full automation would have a much more significant impact : an increase of Full Truckload operations share; and a significant decrease of shipment sizes, transport costs and Total Logistical Costs.

1 Introduction

Freight and logistics sectors play an important role in the economy. The latter is still very physical, the flows of goods are worldwide constantly increasing (Organization for Economic Co-operation and Development – International Transport Forum, 2017a), and the share of the two sectors in total GDP is estimated at 10% in the developed countries and can reach 18% in the developing ones (Rushton, Croucher & Baker, 2014).

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Like many fields where mobility is primordial, freight is likely to be significantly impacted by the deployment of autonomous vehicles (AV). Two strong arguments suggest this. Firstly, drivers are responsible of a significant share of the overall cost incurred by the carriers (about 1/3 in intercity freight). Secondly, the necessity of a human operator to drive the vehicles generates numerous operating constraints : some are related to the regulation of working, driving and rest times, and some others to the design of the vehicles as these are conceived in a way to host a human operator while their original purpose is to ship goods.

From the perspective of supply chains, the consequences would be indirect but very important. A big change of the carriers constraints will very likely have an impact on the prices of the services they provide. And as the shipment of commodities is only one of the numerous decisions shippers must take while managing their supply chain, a change of the price of transport would lead them to modify their practices to a large extent. BAUMOL and VINOD (1970) theorizes the mechanism linking transport prices to shippers behavior in terms of shipment frequency and inventory management decisions. The mechanism is quite simple : more frequent shipments lead to higher freight costs but allow shippers to reduce their inventory related costs. Regarding this mechanism, the deployment of AVs may lead shippers to revise their trade-off between shipment frequency and the quantity of merchandise to store. The consequences of the new trade-off may be a transformation of the shipper behavior, and consequently a change of their transport and total logistical costs (TLC).

The objective of the present paper is to study the impact the deployment of AVs may have on freight and logistics from an economic point of view. Three difficulties make such an analysis particularly complex. The first is the great heterogeneity of freight sector, the second is that AVs can intervene in different ways and at different levels during a transport operation (The high diversity of the prototypes tested so far is showing this); and the third is that the economical and technical characteristics of the future AVs are not well known yet.

In this paper, we focus on interurban transport operations made by road. We propose quantitative estimations of the outcomes of two scenarios where the automation technology is sufficiently efficient to remove the need of a driver during the whole or a significant part of the operations. To do so, we build a modeling chain which links consist of a series of theoretical microeconomical models and econometrical estimations. This chain is used on the one hand to describe theoretically and empirically carriers and shippers behaviors and on the other to target precisely where and how AVs intervene in order to obtain accurate estimations of the two scenarios outcomes.

The modeling chain can be divided into two big blocks : the first deals with the supply side of the transport market (carriers) and the second with its demand side (shippers).

Concerning supply side, the objective is to measure the impact of AVs on the costs supported by the carriers and how this would be reflected on the prices of the services they provide. To do so, this block is of two sub-blocks :

1. The first consists of a microeconomical model that describes the structure of the costs incurred by the carriers. It links the used resources to the transport services produced. The resources can be grouped in two categories : ones for which the

needed quantities depend on the distance between the senders and the recipients (fuel, highway toll ...), and ones for which the needed quantities depend on the operations durations (presence of a vehicle, driver...).

The model distinguishes two types of shipping modes : large consignments sent without transshipment, and small consignments shipped with break bulk. This distinction allows to consider finely the two shipment family modes operating constraints (vehicles capacity, round organisation, logistics platform ...).

2. The second sub-block consists of regressing econometrical models that give estimations of the transport operation prices regarding a chosen shipping mode and a large set of parameters. Additionally to the classical weight and distance variables, the models take account, among other parameters, of packaging (bulk, palletes...) and handling (danger, fragility ...) constraints. These control variables allow to better target the parameters of the price equations that are likely to be impacted by AVs. Also, it is worth noting that we make use here of estimation techniques that corrects for heteroskedasticity, namely weighted least squares.

Concerning the demand side, the objective is to determine whether the outcome of the trade-off led by the shippers would be significantly impacted by AVs, and, therefore, whether they would switch from a shipping mode to another, and whether their transport and TLC would significantly change. To do so, the block related to demand is also of two sub-blocks :

1. The first consists of building a series of TLC theoretical background inspired models that consider a shipper who leads a trade-off between the shipment frequency and the mode the consignments must be sent. Once built, the models cannot be directly calibrated. For this, some assumptions must be made and a specific exploitation of data must be conducted. Once the calibration completed, the models can be used to simulate the reaction of the shippers to the economic conditions caused by AVs.
2. The second sub-block is the output of an econometric estimation of a discrete choice model that explains how shippers decide between a shipment operation with or without break bulk. More precisely, we estimate a logit Model à la Ben-Akiva and Lerman (1985) where the latent variables are TLCs calculated thanks to the 3 previous sub-blocks results.

Once the modeling chain shaped, AV scenarios impacts on freight and logistics are simulated; the simulations are patterned around the modeling chain links. AVs will impact some of the cost equations parameters. The corresponding parameters of price equations will change on their turn. Faced with the price changes, shippers will lead a new trade-off. The outcome can be a change of shipment size, shipping mode, shipment frequency, and TLC.

Combining microeconomical modeling and econometrical techniques can be justified in two points. Firstly, the microeconomical approach is essential because the data used for econometrical regressions don't contain enough information concerning the way the transport operations have been completed. Consequently, computing directly

AVs impact using data is impossible. In fact, the database lacks some accounting elements that we need to build; the microeconomical modeling meets this need. On the other hand, the microeconomical model is not sufficient for the whole analysis. Indeed, it cannot take account of the great diversity of the observed operations and prices. Furthermore, an analysis based only on microeconomical models cannot take account of intra-sectorial heterogeneity and wouldn't give an estimation of AVs impact for each industrial sector and on each shipper.

The data we use come from surveys conducted on French shippers by the French Institute of Science and Technology for Transport, Development and Networks (FICTTDN). These surveys are similar to the "Commodity Flow Surveys" conducted in the USA. Data is described above.

The results show that partial automation won't have a significant impact on shippers behavior, organisation and costs. Full automation would however lead the shares of shipping modes to significantly change, the shipment size to decrease on average by 460 kg (45% in terms of percentage), and the transport and the TLC to decrease on average by 48%. Furthermore, Full automation would generate more "small sized" shipments on the roads; which is likely to generate new land use and urban planning issues.

2 Microeconomical cost models and AVs scenarios

We build here analytical microeconomical models representing explicitly the carriers resources and constraints. This allows to develop sufficiently detailed and contrasting AVs scenarios.

Before embarking on modeling, a simplified description of the way transport operations can be conducted is needed. For simplicity, transport operations can be placed in two categories shown in Figure (1). The first concerns the operations that are conducted without any load break and in which a "big size" shipment that fills the trailer is sent alone. We call these operations here Full Truckload (FTL). There is also the case of Partial Truckload which consists of grouping a few shipments in a vehicle. Modeling FTL and PTL is similar. The second category concerns the operations requiring at least one load break. They are typical of couriers and parcels and are characterized by the need of unloading, sorting and reloading the sent commodities (That are generally of small size) in different vehicles. This kind of operations is called here Less Than Truckload (LTL).

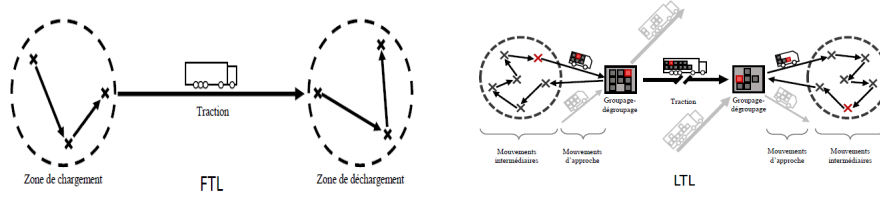


Figure 1: FTL Vs LTL

2.1 FTL related cost models

The model presented here is inspired by Combes (2018). It is at the same time very simple and very flexible. We start by presenting it then we proceed to its calibration.

2.1.1 Theoretical model

We consider the transport of a shipment which size is s from a given loading zone at a starting area to a given unloading zone at destination. Each operation generates an approach movement and a traction. The approach average distance and speed are respectively d_a and v_a , and (un)loading the commodities requires on average a duration t_l . The traction covers a distance d at an average speed v_t .

We distinguish two categories of cost items:

- Costs that depend on distance : fuel, maintenance, toll etc... These costs are grouped in c_d , a coefficient which unit is *Euro/km*.
- Costs that depend on duration : full drivers' related costs, vehicle related capital costs, and structure fixed costs. They are grouped in two coefficients $c_{h,a}$ and $c_{h,t}$ (depending on the scenario, they may differ in approach and traction).

Furthermore, it is necessary to consider the vehicle's capacity constraint K , the loading rate when the vehicle is loaded λ_s^{FTL} , and the vehicle load factor λ_e (assumed common to LTL and FTL models). Shipment dimensions and the vehicle capacity constraint are measured in tons.

The approach movement and loading duration is $\left(\frac{d_a}{v_a} + t_l\right)$. There is an approach movement and a (un)loading operation at origin and destination. The cost of these operations is specific to each shipment, and is assumed to be independent of its size. This cost is :

$$b_{FTL} = 2 \left(\frac{d_a}{v_a} + t_l \right) c_{h,a} + 2d_a c_d$$

The traction duration is $\frac{d}{v_t}$. Its cost is therefore $\left(\frac{c_{h,t}}{v_t} t + c_d\right) d$. By hypothesis, this cost must be corrected by vehicle capacity, loading rate, and load factor coefficients.

Thus, the traction cost for a shipment of size s over a distance d is

$$c_{FTL}sd$$

where :

$$c_{FTL} = \frac{1}{\lambda_e \lambda_s^{FTL} K} \left(\frac{c_{h,t}^{FTL}}{v_t} + c_d \right) \quad (1)$$

Thus, the total cost of a transport operation for a shipment of size s over a distance d is :

$$C_{FTL}(s) = b_{FTL} + c_{FTL}ds \quad (2)$$

$C_{FTL}(s)$ contains an element that is proportional to the ton-kilometers shipped and a fixed cost that is independent of the distance and the shipment size. The intuition is simple: transporting large quantities over large distances will involve more resources, and therefore be more expensive than transporting small quantities over small distances. However, if a large trailer makes a detour and stops for an hour to load a shipment of a few tens of kilograms, this generates a cost that is related to the existence of such an operation, and which is not correlated with the characteristics of the consignment.

2.1.2 Calibration

Calibrating the model is difficult because no accessible database allows to directly estimate the parameters of the obtained specification. The approach proposed here involves thus a degree of uncertainty; nevertheless we use the values of the French National Road Committee (FNRC) whenever possible and choose realistic orders of magnitude when necessary. The values obtained for all the parameters are shown in Table (1). The calibrated model is :

$$C_{FTL}(s) = b_{FTL} + c_{FTL}ds$$

$$b_{FTL} = 94.2 \text{ Euro}$$

$$c_{FTL} = 0.045 \text{ Euro/tkm}$$

2.2 LTL related cost model

LTL operations are in fact very diversified: shipments which unit is the palette, others for which it is the big box, or the small package... All these shipments present very similar constraints and organisations.

2.2.1 Theoretical model

We suppose that sending a shipment of size s over a distance d requires 5 steps :

- Collecting the shipment using a small vehicle that picks up many other shipments.
- Unloading the shipment in a first logistics platform and loading it in a trailer after sorting.
- Traction to a second logistics platform.
- Unloading the shipment in the second logistics platform and loading it in a small vehicle after sorting.
- Delivering the shipment at destination using a small vehicle that delivers other packages.

Modeling traction is not problematic, nor the cost of passing by the logistics platform. The main challenge results from the rounds at origin and destination. Note that traction hourly cost of LTL is different from FTL's. The reason is that the operations are made by night and / or with transshipment, which leads to higher labor costs.

We consider a round consisting of n stops where the average distance and speed between two stops are d^l and v^l , and the delivering or loading average duration is t_l^l .

The rounds are completed using a light vehicle which hourly and per kilometer costs are respectively c_h^l and c_d^l .

We consider also that the round contains an approach movement between the warehouse and the delivery area which distance and average speed are respectively d_a^l and v_a^l .

Regarding these elements, the average cost generated by a shipment in a round is :

$$c_a^l = \left(\frac{d^l}{v^l} + t_l^l \right) c_h^l + c_d^l d^l + \frac{2}{n_l} \left(\frac{d_a^l}{v_a^l} c_h^l + d_a^l c_d^l \right)$$

The cost related to the passage by the consolidation platform is proportional to the shipment size. This marginal cost is c_X .

The traction cost between the two platforms is given by equation (1).

Thus, the total cost of an LTL operation is :

$$\begin{aligned} C_{LTL}(s) &= b_{LTL} + c_{LTL} \\ b_{LTL} &= 2c_a^l + 2c_X \\ c_{LTL} &= \frac{1}{\lambda_e \lambda_s^{LTL} K} \left(\frac{c_{c,t}^{LTL}}{v_t} + c_d \right) \end{aligned}$$

2.2.2 Calibration

Calibrating LTL model is much more difficult than FTL's for two reasons : the first is that there is no FRNC equivalent figures, and the second is the great heterogeneity of LTL operations.

The first task is to calibrate all c_a^l related terms in order to have a platform allowing contrasted AVs scenarios. As there are no available statistics, we lead discussions with different operators. According to some of them the overall cost of a round is between 200 and 400 euros and according to some others the costs for delivering a package is between 1.5 and 3.5 euros. The cost is much higher for bigger shipments.

The calibration here is based on medium sized shipments typical of the courier (order of magnitude around 100 Kg). Only one microeconomical model will be proposed. The econometric model presented below proposes several control variables.

Characteristics of the round Assuming that the useful part of the round lasts 6 hours and that 25 operations are performed, we obtain 15 minutes per operation on average. If the delivery itself lasts on average 5 minutes, then the journey between two operations lasts 10 minutes on average. Assuming an inter-stop distance of about 2.5 km traveled at 15 km/h, we have a total tour length of about 60 km, excluding access and return distances. For approach movements, an average distance of 20 km traveled at an average speed of 20 km/h seems acceptable. The total length of the round would then be about 80km.

Hourly cost The driver works 5 days a week and performs 20 tours per month. To reach an income of 1500 euros net monthly, it is necessary to achieve a gross margin of around 2500 euros over the same period. The cost of the driver is then approximately 16 euros/hour.

Concerning the vehicle ownership related cost, FNRC estimates it for a heavy truck carrier at 13% of the replacement value. The ratio is not available for light commercial vehicles, so we keep this ratio. Assuming that a new vehicle is worth 40000 euros, the annual cost is 5200. To this must be added insurance which is difficult to quantify. We assume insurance fees to reach 1000 euros/year (against 1852 for a carrier.). Assuming 230 workdays and 8 hours per round, we obtain an hourly cost of 19 euros/hour.

Cost per kilometer Fuel consumption in congested urban areas is about 0.15 L/km, fuel costs about 1 euro/L and there are no urban tolls. Concerning maintenance, we can only make a fragile extrapolation from the case of heavy vehicles. According to FNRC, the traveled distance is 74000 km/year, and maintenance and tire costs represent 10% of vehicle's value. There is no good way to pass from heavy vehicles to light vehicles related costs; however, we assume 3000euro/year for maintenance and an annual travel distance of 15000 km. The total cost per kilometer obtained is then 0.35 euro/km.

Full calibration We still need to decide for the value of c_X and the traction cost . A usual price range for the passage of a pallet in a logistics platform is 3 to 5 euros. We Have reasons to believe that for the shipment we consider the price is rather 3 euros.

Concerning the traction, the parameters values are the same as the ones of FTL.

Table (1) contains all the LTL related values. The calibrated cost model is thus :

$$C_{LTL}(s) = b_{LTL} + c_{LTL}ds$$

$$b_{LTL} = 20.05 \text{ euro}$$

$$c_{LTL} = 0.083\text{euro/tkm}$$

2.3 AV scenarios

Scenario 1 : partial automation outside urban areas: This scenario is a possible representation of a situation where AVs can circulate on the main network in open country but where the urban environment remains too complex for the technology.

We assume here that origin and destination areas are such as automation is impossible. Thus, a human operator is needed to achieve the approach movements but not the traction.

For FTL operations, the same vehicle must operate during the approach movement and the traction. Thus, the equipment needed by the driver are kept in addition to all those added for automation. Consequently, the vehicle is more expensive and its maintenance costs are higher. We assume here that per kilometer costs related to the vehicle raise by 25%.

Concerning LTL operations, the round is not modified and the traction is achieved without any driver.

Scenario 2 : full automation : This scenario corresponds to a possible configuration where humans are no longer required to lead the whole transport operation. In this scenario labor costs disappear totally and vehicles have higher capacities as all the equipment needed for a human operator are suppressed. Consequently, the vehicles acquisition and maintenance costs are lower. We assume a 25% vehicle related cost decrease.

Concerning LTL operations, relaxing the rounds time constraint allows more operations per round (We assume 8 hours round instead of 6) and thus a lower cost by shipment.

Summary LTL and FTL related parameters reference values as well as the AVs scenarios consequences are summarized in Table (1).

Variable	Symbol	Ref	PLA1	PLA2	Unit
Traction hourly cost	$c_{h,t}^{FTL}$	30	10	6	<i>Euro/h</i>
Approach movement hourly cost	$c_{h,a}$	30	32	6	<i>Euro/h</i>
Cost per kilometer	c_d	0,51	0.53	0.49	<i>Euro/Km</i>
Traction average speed	v_t	70			<i>Km/h</i>
Approach average speed	v_a	25			<i>Km/h</i>
Approach distance	d_a	10			<i>Km</i>
Loading duration	t_l	1			<i>h</i>
FTL Loading rate	λ_s^{FTL}	0,9			1
Load Factor	λ_e	0,86			1
Capacity	K	27		30	<i>t</i>
Distance between two operation	d^l	2.5			<i>km</i>
Round average speed	v^l	15			<i>km/h</i>
Round loading time	t_l^l	0.0833			<i>h</i>
Approach distance	d_a^l	20			<i>km</i>
Approach average speed	v_a^l	20			<i>km/h</i>
Round hourly cost	c_h^l	19.4		2.5	<i>euro/h</i>
Round per kilometer cost	c_d^l	0.35		0.26	<i>euro/km</i>
Operations per round	n_l	25		33	-
Round unit cost for a shipment	c_a^l	7.03		1.63	<i>euro/shipment</i>
Round cost	-	175		54	<i>euro/round</i>
Logistics platform cost	c_x	3			<i>euro/shipment</i>
LTL Traction hourly cost	$c_{h,t}^{LTL}$	35	10	6	<i>euro/h</i>
LTL Loading rate	λ_s^{LTL}	0,5			1
	Δb_{FTL}		+6.4%	-71.8%	
	ΔC_{FTL}		-28.3%	-44.8%	
	Δb_{LTL}		=	-53.8%	
	ΔC_{LTL}		-35.3%	-48.7%	

Table 1: Reference and AV scenarios

3 Price models regressions

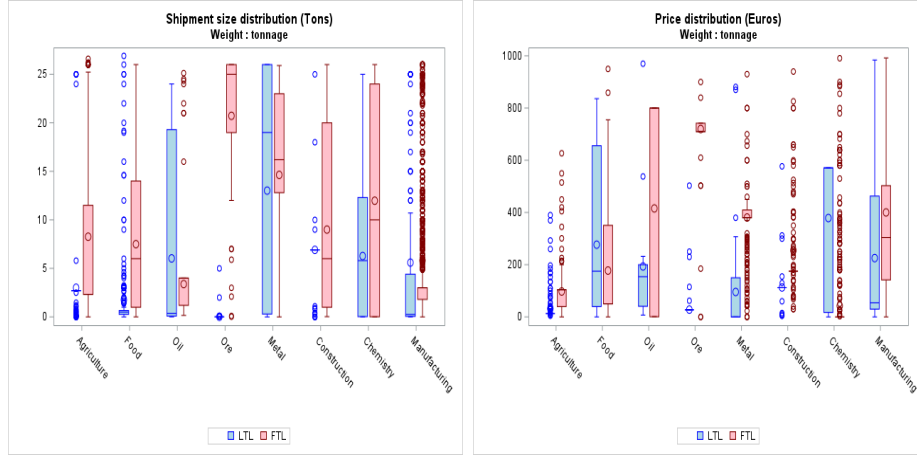
3.1 Data

The FICTTDN conducted surveys in 1988, 2004-2005 and on more regular basis but on reduced form since 2017. For each survey, a set of firms located in France are sampled and three of their last twenty shipments are randomly selected. For each of these shipments, the survey examines its characteristics (nature, weight, packaging, value ...), the manner in which it was transported (mode, sequence of operations, price, fill rate), the sender characteristics (economic activity, turnover, location...), and the sender-recipient relationship (including the annual flow between them).

For the econometrical estimations, we use the data obtained thanks to 2004-2005 survey. This data is quite old but remains the most exhaustive and precise available. This database contains 10462 observations among which 8366 are related to shipments

made by road. Detailed descriptive statistics are available from the authors. Figure (2) shows the distributions of shipments weights and prices, broken down by sector and shipment mode, and weighted by tonnage.

We can see that FTL shipments are globally heavier than LTL ones and that the prices are very scattered whatever the sector and the shipment mode. Rather than providing a summary view, the main interest of these graphs is to show the clear difference between FTL and LTL shipments (More accurate ANOVA tests are available from the authors). This is in line with the fact that each mode meets specific needs and particular demand, which justifies leading econometric regressions broken down by mode.



(a) Weights distribution by Sector and shipping mode (b) Shipment price distribution by sector and shipping mode

Figure 2: Shipments weights and prices distribution

3.2 Specification and estimation results

We estimate here linear models using a Weighted Least Square (WLS) approach. WLS is preferred to Ordinary Least Squares method because it corrects for heteroskedasticity. Many specifications have been tested. We select the following for both FTL and LTL shipments :

$$p_i = \beta_0 + \beta_d d_i + \beta_s s_i + \beta_{sd} s_i d_i + \sum_{j \in J_c} (\beta_{c_{jd}} X_{C_j} d_i + \beta_{c_{js}} X_{C_j} s_i) + \sum_{j \in J_o} \beta_{O_j} X_{O_j} d_i + \varepsilon_i \quad (3)$$

Index i corresponds to the observation. X variables take 1 when the corresponding characteristic is present, 0 otherwise. The equation terms are:

- p_i : the transport operation price
- d_i : the distance as the crow flies between the sender and the recipient

- X_{C_j} : handling constraints (volume - refrigeration - fragile - dangerous) - J_c is the set of these constraints
- X_{O_j} : packaging constraint (palette - container - loose - other) and destination (France - Europe) - J_O is the set of these constraints
- ε_i : error term

The estimation results are presented in Table (2) :

	FTL		LTL	
	Estimator	Significance	Estimator	Significance
Intercept	139,79	***	73,77	***
Distance (Km)	0,31	***	0,048	***
Weight (t)	3,1	***	4,73	**
Weight*Distance (tkm)	0,0278	***	0,058	***
Distance*Volume constraint	0,4	***	0,14	***
Distance*Refrigeration constraint	-0,25	**	-0,036	
Distance*Fragile constraint	-0,097		-0,016	
Distance*Danger constraint	-0,075		-0,045	
Weight*Volume constraint	-3,47	**	15,61	***
Weight*Refrigeration constraint	8,7	**	90,94	***
Weight*Fragile constraint	0,56		1,11	
Weight*Danger constraint	9,56	**	59,49	***
Packaging				
Loose	-3,34		-2,95	
Container	87,17	*	26,48	
Other	-83,69	***	-52,75	***
Pallet		Ref		Ref
Europe	55,18	**	44,32	***
R ²		0.53		0.39
Homoskedasticity		Yes		Yes
Observation		1006		1071

Table 2: Price model regression results using WLS

By examining the significant coefficients, we can see that the signs are as expected for the “interest” variables. There is a positive effect of distance, weight, and their product on price. Handling constraints variables have the expected effects (higher price for the dangerous materials in interaction with weight) or effects that are more difficult to explain (positive effect of the volume constraint in interaction with distance but negative in interaction with weight, negative effect of the temperature constraint in interaction with distance, but positive in interaction with weight.). Shipments in bags or parcels are cheaper than pallet shipments. Finally, a shipment to Europe is more expensive than a shipment to France; this reflects both specific operational or administrative constraints.

By comparing LTL and FTL related results, we can see that LTL intercept and distance coefficients are smaller and that weight and weight*distance coefficients are higher. This is in lines with expectations. LTL transport services are cheaper for small shipments; but the heavier the shipment, the less competitive LTL is compared to FTL. Concerning distance, it is a major factor while establishing the price for FTL shipments but not for LTL ones because the latter are supported by a hierarchical network of platforms connected by regular pulls. This fact is poorly represented by the theoretical model presented before and can explain the weaker influence of distance on price in LTL.

3.3 Applying AV scenarios

The scenarios developed in the previous section are based on a microeconomical model that can be written as follows :

$$p = b + csd$$

However, the econometrical specifications are as follows :

$$p = \beta_0 + \beta_d d + \beta_s s + \beta_{sd} sd + \sum_x \beta_x X_x \quad (4)$$

As the coefficient b corresponds to the marginal costs generated by launching the transport operation and the coefficient c to the marginal costs that depend on the characteristics of the consignment, we assign the expected variations of b and c to the different coefficients of the econometric model as follows :

$$\begin{cases} \Delta\beta_0 = \Delta b \\ \Delta\beta_s = \Delta b \\ \Delta\beta_x = \Delta b, \forall x \\ \Delta\beta_d = \Delta c \\ \Delta\beta_{sd} = \Delta c \end{cases}$$

4 Shipping mode and shipment size decisions

In business relationships based on the sale of commodities, a central question is that of the frequency and thus the size of the shipments. Should the shippers send small quantities on very regular basis or big quantities less often? The first alternative allows lower immobilization costs but higher unit transportation costs, and the second leads to the opposite. To determine the optimal shipment size, the one that minimizes the TLC, we use an approach inspired by Harris (1913) and Baumol and VINOD (1970).

4.1 Theory

We consider a shipper sending an annual flow of commodities Q and who must determine the optimal shipment size s . We suppose that the commodity is produced

continuously and that the stock is increasing on a linear basis until reaching s . In this context, the average quantity in the inventory is $\frac{s}{2}$.

If we note a_w and a respectively the storage cost and the opportunity cost of immobilizing the commodity per unit of time and commodity, the inventory cost at origin and destination is $(a_w + a) \frac{s}{2}$. The total inventory cost is thus :

$$C_I = (a + a_w)s \quad (5)$$

The cost entailed by a shipper for transporting a package which size is given by equation (4). The annual number of shipment is $\frac{Q}{s}$. Thus, the annual transport cost is

$$C_t = (\beta_0 + \beta_d d) \frac{Q}{s} + (\beta_s + \beta_{sd} d) Q \quad (6)$$

The third cost item is the pipeline inventory cost. For a trip which duration is t , this cost is :

$$C_p = atQ \quad (7)$$

The TLC is the sum of the three cost items :

$$TLC = C_I + C_t + C_p$$

$$TLC = (a + a_w)s + (\beta_0 + \beta_d d) \frac{Q}{s} + (\beta_s + \beta_{sd} d) Q + atQ \quad (8)$$

The optimal shipment size meets the following First Order condition :

$$\frac{\partial TLC}{\partial s}(s^*) = 0$$

So :

$$s^* = \sqrt{\frac{Q(\beta_0 + \beta_d d)}{a + a_w}} \quad (9)$$

And :

$$TLC^* = 2\sqrt{(\beta_0 + \beta_d d)(a + a_w)} + (\beta_s + \beta_{sd} d + at) Q \quad (10)$$

The theoretical approach presented here has been empirically checked by many studies. The ones using FICTTDN data are Combes (2012), Lloret-Batlle and Combes (2013), Combes and Tavasszy (2016), and Koning et al. (2018).

We consider now a shipper that has to make a choice between FTL and LTL. As seen in the previous section, β coefficients are very significantly different between the two modes. Furthermore, if we consider the observed values of s to be close to the optimal ones, we can see, as shown in Figure (3) that the opportunity cost of immobilizing the commodity is much higher for the commodities sent by LTL. And last but not least, the trip duration is very different between the two modes (statistics are available among the authors). In this context, each mode has its ‘‘area of relevance’’: FTL is likely to be the best solution when Q is high and $a + a_w$ is low and LTL is the solution to choose otherwise.

Regarding these elements, shipping mode and shipment size decisions appear clearly to be simultaneous. The role of the shippers is to take these simultaneous decisions regarding the transport and the inventory costs entailed by each mode. The decision to be taken is the one that minimizes the TLC.

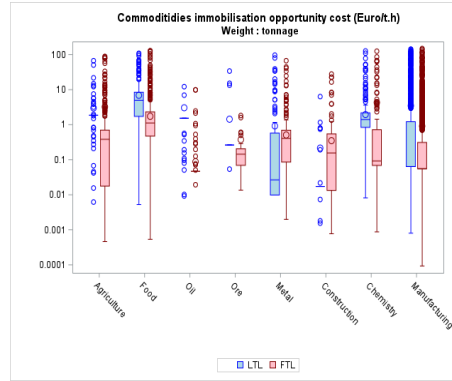


Figure 3: Immobilization opportunity cost

4.2 Calibration

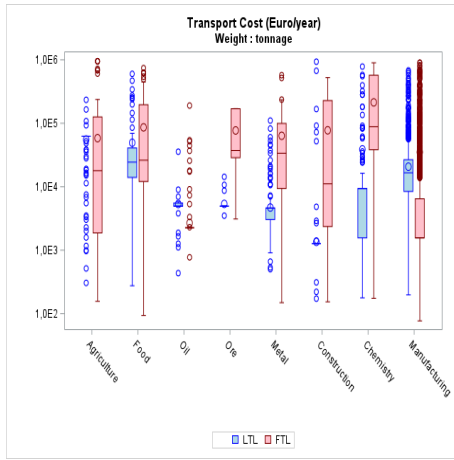
To model how shippers react to a change in the transport supply conditions, functions (9) and (10) need to be known. Q and the control variables can directly be observed in the dataset and the other parameters have been estimated previously. The only missing information is t . We estimate it using the following proxy :

$$\tilde{t} = \begin{cases} \frac{d}{65}/8760 & \text{if FTL} \\ \left(\frac{d}{65} + 12 * (\text{Number of trips})\right) / 8760 & \text{if LTL} \end{cases}$$

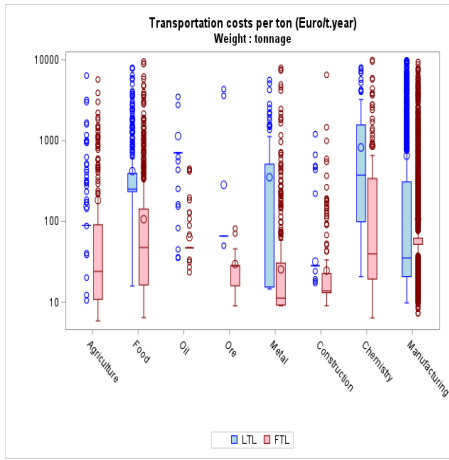
We are aware this proxy is not fully reliable. However, C_p is exogenous in our framework and is not likely to evolve considerably after automation. Furthermore, the discrete choice model FTL vs LTL we regress below tackles the problems this approximation may cause to a large extent.

Figure (4) shows the distributions of Transport costs, Inventory costs and TLC; and Transport costs, Inventory costs and TLC per ton, broken down by sector and by shipping mode. We can see that :

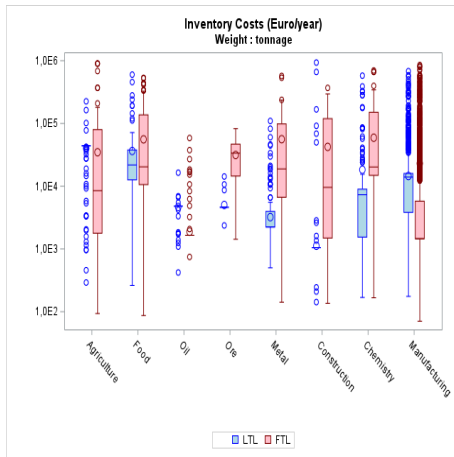
- TLC per ton is very significantly different depending on the industrial sector
- TLC is globally higher for FTL but TLC per ton is globally lower for this shipment mode
- The ratio of transport costs to inventory costs is favorable to the first in FTL and to the second in LTL. This is consistent with the theory described above, although the comparison is not here all the other things being equal.



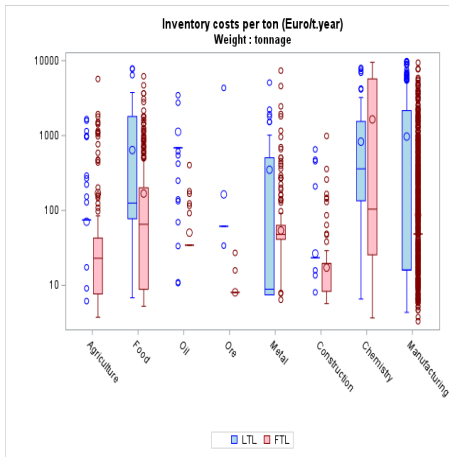
(a) Transport cost distribution



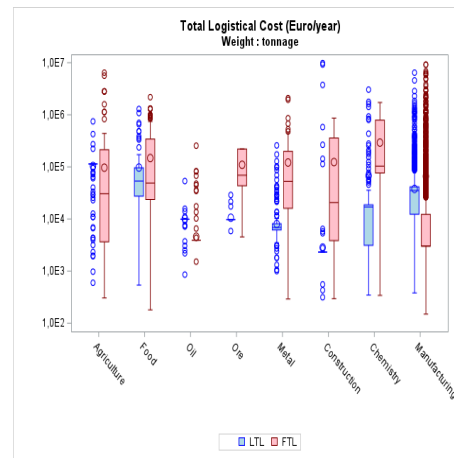
(b) Transport cost per ton distribution



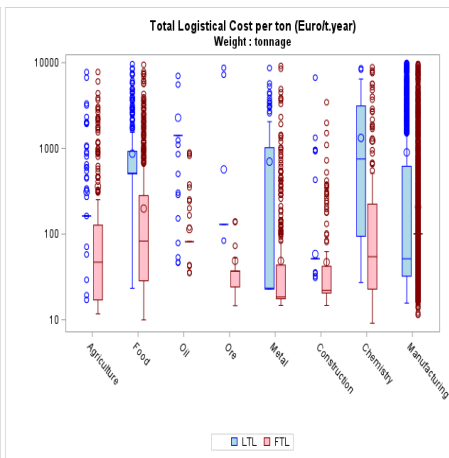
(c) Inventory cost distribution



(d) Inventory cost distribution



(e) TLC distribution



(f) TLC per ton distribution

Figure 4: Total Logistical Cost components distributions

4.3 FTL vs LTL discrete choice model estimation

When they have to choose between FTL and LTL, shippers are expected to choose the option that minimizes the TLC per unit of commodity. However, the TLC generated by each option is not directly observable. We can nevertheless estimate them, with a precision that is lower for the option that has not been chosen.

Furthermore, the disadvantage of each transport organisation is not restricted to the monetary TLC it generates. Each organisation has its own drawbacks, for example : less flexibility and higher difficulty to deal with stock-outs for FTL and more administration and higher difficulty to control for risks for LTL. Hence, the disadvantages of FTL and LTL related equations are respectively :

$$D_{FTL} = C_{FTL} + \beta_{FTL} \frac{\widetilde{TLC}_{FTL}}{Q} + \varepsilon_{FTL}$$

$$D_{LTL} = C_{LTL} + \beta_{LTL} \frac{\widetilde{TLC}_{LTL}}{Q} + \varepsilon_{LTL}$$

Where C_X and \widetilde{TLC}_X are respectively the specific drawback and the estimated TLC for option X. ε_X is a random realization drawn from a Gumbel distribution whose parameters are 0 and 1.

If we note FTL a dummy variable that takes the value 1 when FTL is chosen and 0 otherwise, the probability of choosing FTL is as follows :

$$\begin{aligned} \Pr(FTL = 1) &= \Pr\left(C_{FTL} + \beta_{FTL} \frac{\widetilde{TLC}_{FTL}}{Q} + \varepsilon_{FTL} < C_{LTL} + \beta_{LTL} \frac{\widetilde{TLC}_{LTL}}{Q} + \varepsilon_{LTL}\right) \\ &= \Pr\left(\varepsilon_{FTL} - \varepsilon_{LTL} < C_{LTL} - C_{FTL} + \beta_{LTL} \frac{\widetilde{TLC}_{LTL}}{Q} - \beta_{FTL} \frac{\widetilde{TLC}_{FTL}}{Q}\right) \end{aligned}$$

$\varepsilon_{FTL} - \varepsilon_{LTL}$ follows the logistical distribution. So if we note $\gamma = C_{LTL} - C_{FTL}$, we have :

$$\Pr(FTL = 1) = \frac{\exp\left(\gamma + \beta_{LTL} \frac{\widetilde{TLC}_{LTL}}{Q} - \beta_{FTL} \frac{\widetilde{TLC}_{FTL}}{Q}\right)}{1 + \exp\left(\gamma + \beta_{LTL} \frac{\widetilde{TLC}_{LTL}}{Q} - \beta_{FTL} \frac{\widetilde{TLC}_{FTL}}{Q}\right)} \quad (11)$$

The estimation results of the Logit model are presented in Table (3) :

	Estimator	Significance	
γ	0,5585	***	
TLC_{FTL}/Q	-0,0516	***	
TLC_{LTL}/Q	0,0104	***	
Concordant percentage	77,5	D of Somers	0,55
Discordant Percentage	22,5	Gamma	0,55
		AUC	0,776
		AIC	264591561
Test	khi-2	DDL	Pr > khi-2
Likelihood ratio	24679735	2	<.0001
Nb of obs	2642		

Table 3: Discrete choice model estimation results

We can see that AUC is very close to 0.8 which means that the predictive quality of the model is very good. Furthermore, the β coefficients are very significant and have the expected signs : the probability of choosing FTL decreases when the TLC related to this option increases, and it increases when the TLC related to LTL option increases. And last but not least, γ is significantly positive and β_{LTL} is much lower than β_{FTL} in terms of absolute value. This shows the shippers strong preference for FTL when LTL monetary related costs are not much lower.

5 AV impact

Now that all the modeling chain links are forged, we can estimate the impact of AVs.

Switches from a mode to another :

Figure (5) shows the share of shipments that would switch from a shipping mode to another.

Scenario 1 (Partial automation): The share of FTL would remain the same after automation : around 90% of the overall tonnage. However by looking more in details on the statistics (available among the authors), we can see that 66% of the tonnage shipped using LTL would switch to FTL, while only 8% of the tonnage shipped using FTL would switch to LTL. The switching proportions from a mode to another are different from a sector to another. However, whatever the sector, the switch from LTL to FTL would be much more frequent.

Scenario 2 (Full automation): The share of FTL would increases from 90% to 94%, 77% of the tonnage shipped using LTL would be shipped using FTL, while only 4% of the tonnage shipped by FTL would switch to LTL. And whatever the sector, the switch from LTL to FTL would be much more frequent.

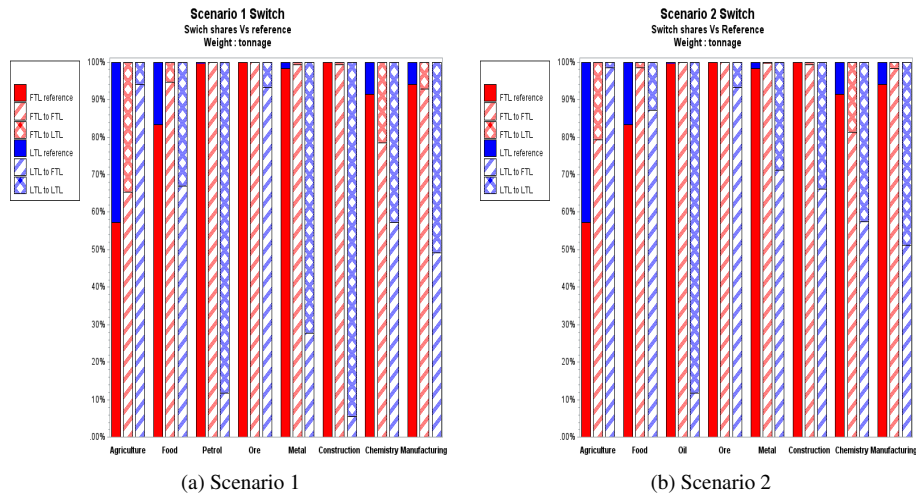


Figure 5: Switches from a shipping mode to another

Shipment size : Figures (6a) and (6b) show AVs impacts on shipment size. The changes to be generated by the first scenario would be very different from those that would be generated by the second. In the first scenario, shipment size would decrease on average by 50 kg, the median change would be -20 kg, and for many shippers this scenario would lead to an increase of the shipment size. Concerning the second scenario, the size would decrease for all the shippers and the decrease would be much more spectacular. In terms of weigh, the average decrease would be 420 kg and the median change -460 kg. In percentage terms, scenario 2 would lead to mean and median decreases near 45%.

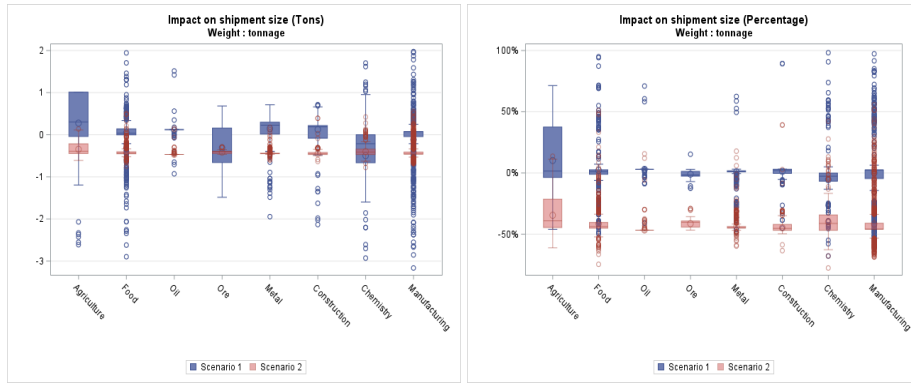
Furthermore, Figure (6c) shows that scenario 2 would lead to a very significant increase of the share of smaller packages while scenario 1 won't lead to a much different situation from reference.

Note that the changes of inventory costs in terms of percentage are similar to the changes of shipment size.

Transport cost : Figure (6d) shows the impact of the two scenarios on transport costs. The mean and median transport costs changes generated by Scenario 1 in terms of percentage would respectively be -3% and -4% . For many shippers, this scenario would lead to a significant increase of annual transport costs. Concerning Scenario 2, transport costs would decrease massively for almost all the shippers whatever the industrial sector. The average and median changes would respectively be -48% and -50% .

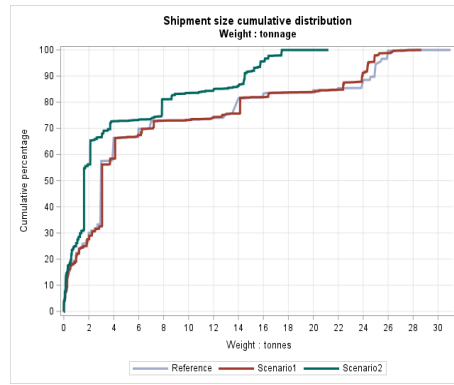
Total Logistical Cost : Figure (6e) shows the impact of the two scenarios on TLC. The contrast between the two scenarios would be also very clear. The first scenario would lead to respectively the following mean and median changes in terms of percentage : -7.18% and $-14,92\%$ with a significant increase for many shippers. Concerning

the second scenario, the decrease would be very clear and spectacular for almost all the shippers. The mean and median changes generated by Scenario 2 would respectively be -48% and -52% .

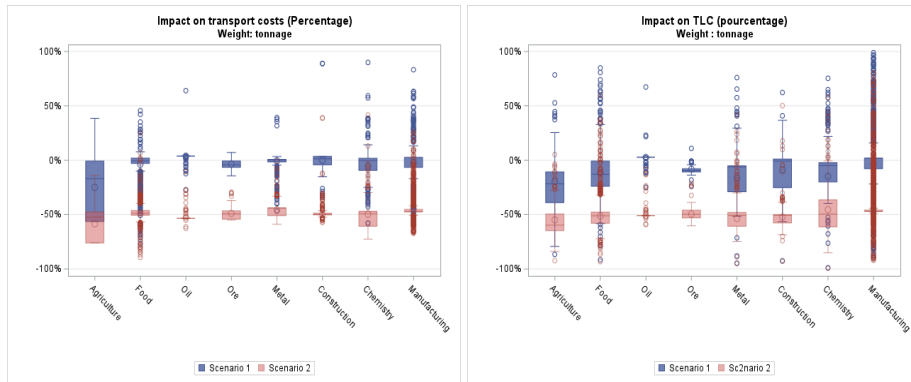


(a) AV impact on shipment size (Tons)

(b) AV impact on shipment size (Percentage)



(c) Impact on shipment size distribution



(d) Impact on transport cost

(e) Impact on TLC

Figure 6: AV Impact

6 Conclusion

The objective of this paper is to propose a quantitative estimation of the impact the deployment of the autonomous vehicle technology would have on freight and logistics sectors. To do so, we adopt a two stages methodology : the first consists of building a modeling chain describing the shippers and the carriers behavior thanks to a series of microeconomical models and econometrical estimations, and the second consists of imagining two different AV scenarios, calculating the impact of each one on the right supply related parameters and estimating how the shippers react to the change of the transport supply generated by each scenario.

In the first scenario technology is not advanced enough to ensure a full automation of transport operations and in the second its level is high enough to make full automation possible.

The results show that the first scenario won't have a significant impact whether in terms of switching from one shipping mode to another, on shipments' sizes, or even on the shippers TLC. By contrast, the second scenario would have a much more significant impact : an increase of FTL operations share, and a significant decrease of shipment sizes, transport costs and TLC. The contrast between the scenarios can be explained by the need of a human operator during a significant part of the operation in the first while no human intervention is needed in the second.

Regarding these results, one can say that autonomous vehicles won't have a significant impact on freight and logistics as long as a human operator is needed. If technology allows full automation, new land use and urban planning issues will emerge.

To conclude, it is worth noting that this work suffers from many limitations. The first is the lack of information concerning the technical and economical characteristics of the autonomous vehicles to come. The second is the lack of suitable data to lead precise statistical and econometrical analysis. Even if the data we use here is of good quality, it lacks however information concerning the vehicles, the shippers, the carriers etc.... so we can not deal with all endogeneity issues as we would have liked. Nonetheless, we believe that we pushed the data to its maximum. And last, we didn't study the impact of AVs on the overall demand for goods nor on the labor market of truck drivers. To deal with such questions, a broader framework is to build and much more data is needed.

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