An Integrated Modeling Approach to Assess the Impact on Road Freight Transport Demand of Allowing Longer and Heavier Vehicles (LHVs) in Spain

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SUMMARY

The assessment on introducing Longer and Heavier Vehicles (LHVs) on the road freight transport demand is performed in this paper by applying an integrated modeling approach composed of a Random Utility-Based Multiregional Input-Output model (RUBMRIO) and a road transport network model. The approach strongly supports the concept that changes in transport costs derived from the LHVs allowance as well as the economic structure of regions have both direct and indirect effects on the road freight transport system. In addition, we estimate the magnitude and extent of demand changes in the road freight transportation system by using the commodity-based structure of the approach to identify the effect on traffic flows and on pollutant emissions over the whole network of Spain by considering a sensitivity analysis of the main parameters which determine the share of Heavy-Goods Vehicles (HGVs) and LHVs. The results show that the introduction of LHVs will strengthen the competitiveness of the road haulage sector by reducing costs, emissions, and the total freight vehicles required.

1. INTRODUCTION

Freight transportation has become an increasingly important player in national economies since it supports trade between producers and consumers. As of today, freight transportation systems throughout the world are facing key challenges to ensure a well-functioning system. For this reason, it is important to define regulations to better manage the freight transport system and which, in consequence will lead to a successful and sustainable transportation in the near future. In this sense, one of the possible measures that could be applied in the freight transportation system is to allow the circulation of Longer and Heavier Vehicles (LHVs).

The experience of introducing LHVs is valuable in Europe (i.e. Sweden, Finland, Denmark, Germany, and Netherlands), and in other countries such as the United States, Brazil, Canada, Mexico, New Zealand, South Africa and Australia. These experiences have demonstrated that LHVs vehicles have the potential to make freight transport more efficient and environmentally friendly (Nagl, 2007). However, there also exist well-known disadvantages from allowing those vehicles to drive on the infrastructure as Grislis (2010) pointed out: pavement and road damage, safety, and road design issues.

Spain as well as other European countries, follow the Directive (96/53/EC) which allows using standard Heavy Goods Vehicles (HGVs) for international road freight transport to guarantee the same conditions for interoperability and competition among EU members. However, this Directive has not set up common rules for domestic transport, and allows to each member state to set size and weight of freight vehicles freely within their national borders. Consequently, transport government related parties and carriers involved in the transport of goods of Spain have been engaged in the debate about the introduction of LHVs, and they have not reached an agreement yet.

Although in Spain LHVs assessments have been carried out by considering the relaxation of dimensions and weights limits for HGVs taking into account economic efficiency matters or by considering the suitability of the road network for the introduction of LHVs, there is no travel demand model assessment performed for Spain to determine the demand and traffic flows of HGVs and LHVs across the roads of the whole country.

Within this context, this paper applies an integrated modeling approach composed of a Random Utility Based Multiregional Input-Output (RUBMRIO) model and a road transportation network model to study the impact of LHVs in Spain on road freight transport demand and traffic flows. This integrated approach is highly suitable to assess transport policies of road freight transport because it has a commodity-based structure that traces the linkages of inter-industry purchases and sales that use road freight services within the country.

This paper is organized into five sections. The literature review on methodologies to estimate the impacts of the introduction of LHVs is described in section 2, right after the introduction. In section 3, we set out the methodology proposed, the solution, and its limitations to assess the introduction of LHVs on a selected road network. The detailed description of the case study is described in section 3. The following section 4 presents an analysis of results in terms of demand changes, and on the transportation system as well. Finally, in section 5 we share the most relevant conclusions and suggestions about the implementation of policies, and possible future developments.

2. LITERATURE REVIEW

Most of the existing LHVs assessments have been focused on economic efficiency based on national desk-based studies –see for example Ericson et al. (2010), Lukason et al. (2011), and Ortega and Vassallo (2012). These authors have generally used the Cost-Benefit Analysis (CBA) to establish potential cost savings of the relaxation of dimensions and weights limits for HGVs through costing functions. Most of these studies have analyzed how main assumptions on transport costs, cost of road damage, traffic safety cost, congestion, and environmental costs of LHV introduction scenarios are advantageous in comparison to a reference scenario. These of the alternative limits. Also, other technical aspects of LHVs have been evaluated –see more details in Leduc (2009).

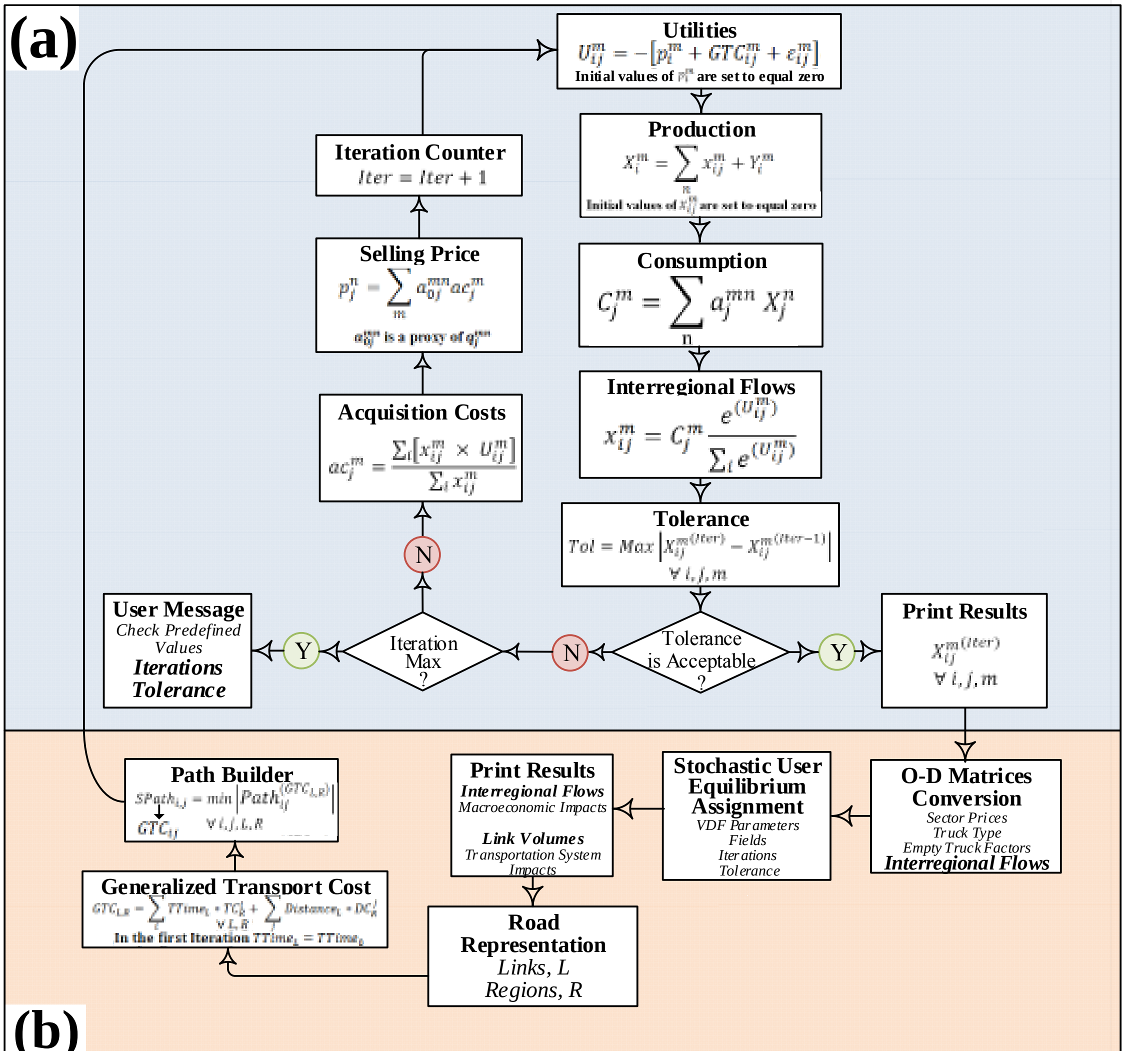
In addition, there also exist other relevant assessments of the hypothetical introduction of LHVs performed through demand and modal shift modeling approaches. These assessments have been developed with a long-term perspective considering economic approaches such as Input-Output relationships, System Dynamics Models (SDM), or by considering price elasticities for some specific corridors –see more details in De Ceuster et al. (2008), Doll et al. (2009), K+P and ISI (2011), and Vierth et al. (2008).

All these available studies conducted for the introduction of LHVs have taken into account an in-depth analysis on how main assumptions on LHVs are advantageous in comparison to a reference scenario. It is very clear that transportation costs are the main reasons behind the introduction of LHVs because of the reduction that would result in transport costs per tonne-km carried, and in fuel consumption, with the subsequent reduction of emissions that make road freight transport more sustainable and cleaner.

In any case, all these studies have widely reported the expected impacts of introducing LHVs. However, in the case of Spain, the available studies have not provide a comprehensive evidence of the demand changes derived from the allowance of LHVs on the road network. Our research aims at filling this gap by addressing the impact of LHVs on the road freight transport demand in Spain. To this end, we have looked at a varied range of key factors pertaining to Spain that will influence the successful introduction of such vehicles. In addition, we applied these factors through an integrated modeling approach composed of a Random Utility-Based Multiregional Input-Output Model (RUBMRIO), and a road transport network model to study the impact of introducing LHVs in a selected road transport network of Spain (9,799 kilometers, or 6,089 miles, in length). The results come from a comparison between the base-case scenario, and the case study.

3. A METHODOLOGY FOR ASSESSING THE INTRODUCTION OF LHVs ON THE ROAD TRANSPORT NETWORK

To assess the impact of a possible introduction of LHVs on the freight transportation demand over the whole network of a country such as Spain, we have considered a modeling approach capable of making more endogenous components such as transport costs by considering interactions between spatial economics –considering the technical structure of the industry and the requirements for trade– and transport system dynamics. The modeling approach analyzes both output-supply and input-demand relationships through trade flow patterns among regions using a road freight transportation system. The integrated approach is made up of a RUBMRIO approach (**Figure 1.a**), and a road network model (**Figure 1.b**).



Step 1) RUBMRIO input is generated from the road transport network model considering the free-flow time $TTime_0$ for the estimation of the Generalized Transport Cost among regions (GTC_{ij}).
Step 2) Estimation of the utility (U_{ij}^m) for origin region *i* of moving goods of sector *m* to be consumed in region *j*, considering the Generalized Transport Cost (GTC_{ij}^m). Initial values of the purchasing prices (p_i^m) in the origin region *i* are set to equal zero, and a random error term (ε_{ij}^m).
Step 3) Regional production of any given sector *m* in a producer region *i* (X_i^m) is evaluated including intermediate demand (x_{ij}^m - endogenous) and final demand (Y_i^m - exogenous). Initial values of interregional flow of goods and services x_{ij}^m are set to equal zero.
Step 4) Consumption of sector *m* in region *j* (C_j^m), is calculated considering the set of technical coefficients (a_j^{mn}) for the production process of all sectors considering region *j* and total production (X_j^n).
Step 5) Interregional flows (X_{ij}^m) are distributed considering utility variations.
Step 6) The tolerance criterion is evaluated. In the case of achievement the procedure stops, and these interregional flows are the inputs for the road network model.
Step 7) If tolerance was not achieved, acquisition costs (ac_j^m) are updated, to represents the average weighted cost of commodity *m* in region *j*.
Step 8) new prices (p_j^n) are computed considering technical coefficients without import considerations (a_{0j}^{mn}) as a proxy of the quantity of sector *n* needed for the production of one unit of sector *m* in region *j* (q_j^{mn}), and acquisition costs (ac_j^m). Sales price depends on the costs of purchasing raw materials, labor and necessary services form other producers. The new prices are used to run a new iteration until the equilibrium of interregional flow is achieved.
Step 9) Once the interregional flow is achieved; *OD* matrices per sector are prepared considering the interregional flows and conversion factors (e.g. prices, truck types, and empty truck factors).
Step 10) The route assignment is performed, and volumes of HGVs traffic is determined for each of the 17,422 links
Step 11) The results of the assignment are updated in the Generalized Transport Cost function $GTC_{L,R}$ considering the new travel time $TTime_L$.
Step 12) The new input for RUBMRIO is generated, and the process is repeated until convergence.

Fig. 1 – An Integrated Approach for Transportation Impact Assessment: (a). RUBMRIO Algorithm; (b) the Road Transport Network Model

3.1 The Random Utility-Based Multiregional Input-Output Model (RUBMRIO)

The Random Utility-Based Multiregional Input-Output (RUBMRIO) approach (**Figure 1.a**) replicates observed conditions of trade among regions through a Multiregional Input Output table (MRIO) by considering technical coefficients and trade coefficients. In fact, the MRIO table displays the economic relations among different production sectors, and among regions of a country instead of considering these relationships as spatially homogeneous (Duchin & Steenge, 2007). The MRIO table displays the economic relationships among different sectors by intersectional relationships of Input-Output coefficients or demand functions, and it is also capable of representing the spatial distribution of the flow of goods by using random utility-based models (Wegener, 2004).

As a result, the RUBMRIO model traces the linkages of inter-industry purchases and sales among regions within a given country by using transport, and in so doing it reproduces with more detail and realism freight transport services through a commodity-based structure rather than a trip-based or truck trip-based structure. Therefore, the RUBMRIO approach is able to show shifts between industries/sectors and regions supporting generative, redistributive, substitutability and complementarity effects through trade patterns.

RUBMRIO analyses have been conducted in well-known land-use models involving spatial economy e.g. MEPLAN, TRANUS, and PECAS (Echenique, 2004). In addition, RUBMRIO applications to transport cover different "*ex-ante*" topics such as: construction of transportation corridors, changes in travel times, infrastructure investment, operational cost variation, fuel taxes, road charging, trade pattern changes, and regional transport conditions—for more details see: Cascetta, Marzano, and Papola (2008), Du and Kockelman (2012), Guzman and Vassallo (2013), Huang and Kockelman (2010), Marzano and Papola (2008), and Zhao and Kockelman (2004). Most of these applications have found out important indirect effects of transport policies at the regional level on various macroeconomic aggregated indicators, but they do not evaluate the impact on the transportation system (e.g. congestion reduction, time savings, traffic flow deviation, pollution and reduction of emissions). Therefore, in our methodology we have included a transport network model in order to address these effects. More detailed discussion on the transport network model will be provided later on in this paper.

It is important to note that the practical application of the RUBMRIO approach is facilitated through the consideration of the supply prices of different sector products. The price at origin has been determined through an iterative single fixed-point algorithm that defines a sole spatial equilibrium solution —assumptions about the procedure are extensively described in Zhao and Kockelman (2004). Also, Marzano and Papola (2008) have proposed the RUBMRIO model solution through a double fixed-point formulation by considering the introduction of a new feedback in the model. However, the conditions for attaining a solution taking into account the uniqueness of the double fixed-point approach are still under development.

3.2 The Road Network Model

The road network is made up of a set of nodes and links. Links and nodes represent the physical structure over which traffic flow moves including attributes, such as: length, travel time, speed, number of lanes, traffic flow restrictions, origin and end-point of the roads, regional capitals, and larger municipalities or ports.

The road network model (**Figure 1.b**) should deal with the spatial representation of transport flows on a road network considering: 1) the conversion of interregional flows to vehicle flows so as to generate OD matrices; 2) an assignment procedure used to predict the traveler's choice of routes in the road transport network. For this purpose, the model considers the fact that link travel times are flow dependent through a volume-delay function (VDF) which reflect traffic behavior as is shown in Equation (1). This traditional formulation was proposed by the Bureau of Public Roads (BPR) in 1964, and has been used ever since to specify how sensitive the network times are to traffic congestion; and 3) determine possible routes between any two locations through a cost minimization criterion given by Equation (2).

$$TTime_L = TTime_o \times \left[1 + \alpha\left(\frac{v}{c}\right)^{\beta}\right] \qquad (1)$$

$$GTC_{L,R} = \sum_i TTime_L * TC_R^i + \sum_j Distance_L * DC_R^j \qquad (2)$$

$TTime_L$ is the travel time when the link L is reached. $TTime_o$ is the free-flow travel time. v is the traffic volume. c is the practical capacity is used to mean the maximum possible flow of vehicles that can be allowed in a road section per time period (usually one hour). In addition, the practical capacity might be reduced by the amount of roadway capacity that is utilized by the pre-load volumes —corresponding to trips performed by car, and bus. In addition, the practical capacity. However, it could also be used to reflect specific time periods by using time-of-day factors to distribute trips during the day in order to determine traffic behavior at the peak period. $\alpha,\ \beta$ are BPR parameters defined by link type (usually 0.15 and 4 correspondingly that facilitate the adoption of different functions for different kinds of links and for each class of traffic.

3.3 Model Integration and Solution

The integration is done on the basis of the algorithm shown in **Figure 1**. From the road transport network, the values of GTC_{ij} among regions are calculated considering $TTime_o$ according to Equation (2). These values are used to generate the RUBMRIO input. RUBMRIO algorithm is performed sequentially by using the single fixed-point algorithm implemented through a macro program based on Visual Basic for Applications (VBA) in Excel. This algorithm is executed until consecutive trade flows stabilize with an error lower than 1% defined by the tolerance criterion —see **Figure 1.a**. Afterwards, the road network model —see **Figure 1.b**— establishes OD matrices by transforming monetary values of the MRIO table into vehicles considering each economic sector, these matrices are assigned to the road transport network in order to update costs based on the updated $TTime_L$. The integrated approach is re-run, with the updated $GTC_{L,R}$ through an iterative feedback process until equilibrium is reached.

3.4 Limitations of the Integrated Approach

Although the integrated approach is sophisticated enough to obtain results of acceptable accuracy regarding economic matters and traffic flow impacts, the model still has limitations stemming from both the data and the methodology. The first set of limitations stems from the incomplete availability of Input-Output (IO) data regarding a fine level of spatial detail, information of exports and imports from other countries, and real transportation costs from confidential business data or negotiations among carriers to make the model more complete. The second set of limitations comes from the IO methodology since it does not permit us to: (i) answer questions concerning issues as innovation, technological progress, ownership structures, and other economic factors of industries; (ii) draw the effects of changes in an economy at a further particular point of time; (iii) combine at the same time various transport policy scenarios; and (iv) include passenger or freight logistic models.

4. CASE STUDY: THE INTRODUCTION OF LHVs ON THE ROAD TRANSPORT NETWORK OF SPAIN

4.1 Description

In 2007 Spain's road transport network for HGVs has more than 20,000 kilometers distributed in high-capacity roads, and conventional roads. In this sense, it is important to note that the Spanish road transport network has witnessed the development of a vast modern high-capacity road network —11,276 kilometers (7,007 miles) of tolled highways, free highways, and multilane highways— over the last two decades (see **Figure 2.a.**).

With regard to freight transport, it is important to highlight that the road mode is by far the prevailing mode in Spain. Official statistics given in the Permanent Survey of Transport of Goods by Road —MFOM (2011) states that in 2010, 1,567 million tonnes —98.7%— were transported by road. Rail freight transport, by contrast, amounted only for 21.44 million tons —1.3%— in 2010 (FFE, MFOM 2011).

We assume that the introduction of LHVs will affect only the road mode since freight by rail in Spain is already so very low (less than 2%), and there are no inland waterways. For this reason, no effects in the modal split were considered. The most suitable LHV configuration for Spain is made up of a tractor, semitrailer, and center-axle trailer (MFOM 2008a).

The selected road network adopted for the LHVs scenario is made up of high-capacity roads connecting the capitals of the regions (see **Figure 2.b.**). High capacity roads are suitable to handle LHVs vehicles while national roads do not. The length of the road network where LHVs could be introduced is 9,799 km —6,089 miles.

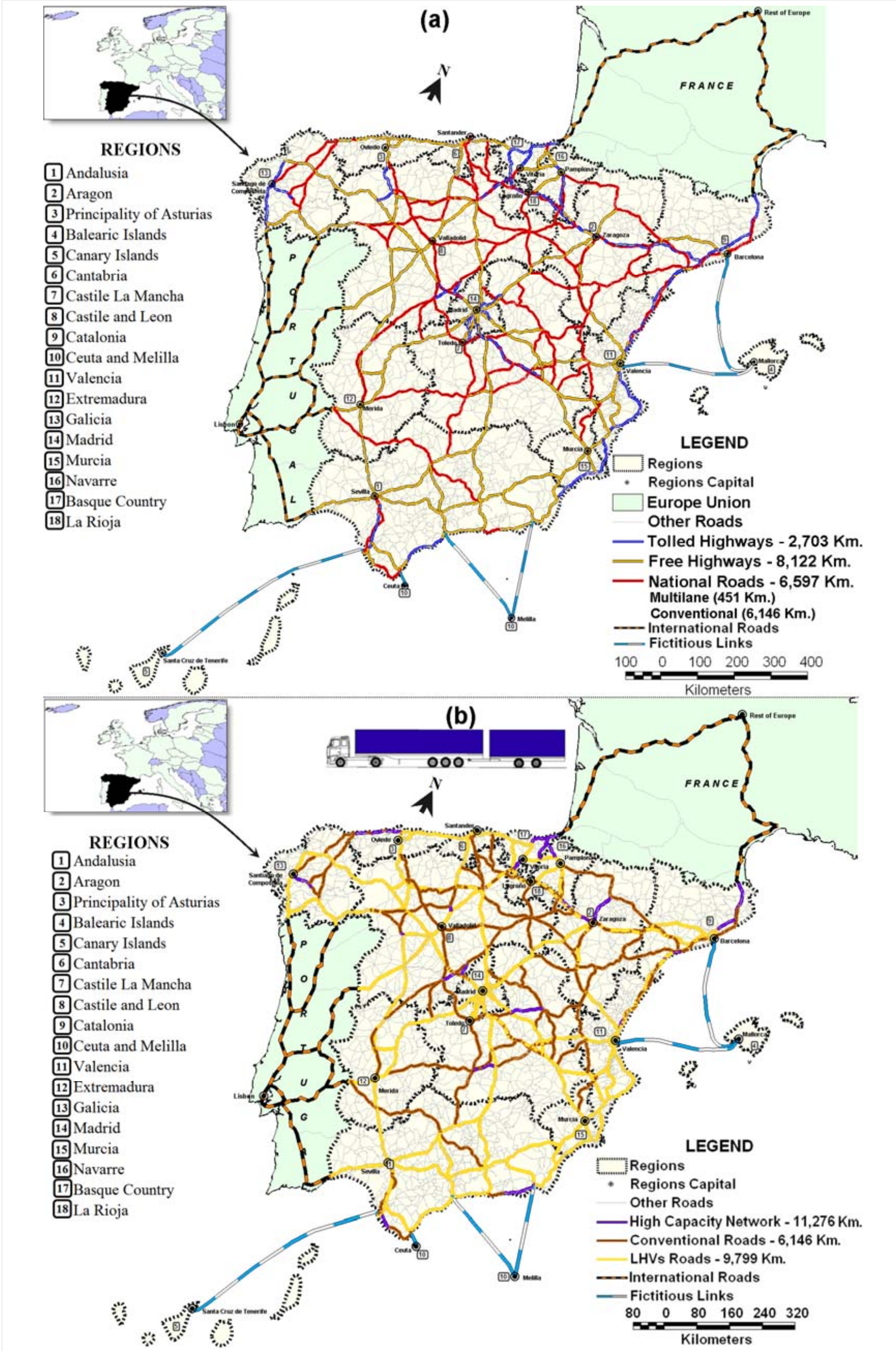


Fig. 2 – Road Network for Freight Transportation: (a) Base-Case; (b) LHVs Scenario.

4.2 Application of the Methodology to the Base-Case

4.2.1 The RUBMRIO Model Estimation

In order to construct the model for Spain, we used the existing interregional IO table developed by the DESTINO research project (Consortium DESTINO et al., 2011) for the year 2007. A simplifying procedure was developed to aggregate sectors identified as freight transport intensive sectors (MFOM 2008a) —see **Table 1**—, non-freight transport intensive sectors (e.g. Trade and Repairs of Vehicles, Finance and Real State, Tourism, Education, among others), and to discard multi-sector relationships among sectors (m to n) to build up a MRIO compatible with the transportation data available.

Sector			θ^m	λ^m	Likelihood Ratio Index McFadden Pseudo R2 (ρ^2)
Freight Transport Intensive	1	Agriculture, Fishing, Wood and Cork	-0.00370* (-1.791)	0.602	0.151
	2	Food and Kindred Products	-0.00221 (-1.618)	0.398	0.174
	3	Non-metal Minerals and Kindred Products	-0.00310** (-2.469)	1.212	0.174
	4	Energy, Petroleum and Petroleum Products	-0.00359* (-1.662)	0.286	0.101
	5	Mining	-0.00292** (-2.393)	0.999	0.328
	6	Metal minerals and Kindred Products	-0.00262* (-1.942)	0.759	0.123
	7	Construction	-0.00363** (-2.508)	1.730	0.365
	8	Chemical and Allied Products, Paper, Edition and Kindred Products, Rubber Materials	-0.00186* (-1.726)	0.534	0.166
	9	Textiles, Clothing, Leather and Shoes, Industrial Machinery and Equipment, Electric and Electronic Equipment, Transportation Equipment, and Other Manufacturing Industries	-0.00252* (-1.68)	0.417	0.144

( ) Wald statistical significance test
* $p<0.10$
** $p<0.05$

Table 1 – Input-Output Economic Sectors and Estimated Parameters for the Nested Logit Model

Concerning the utility function, we adopted a Nested Logit (NL) model representing the choice of regions in two relevant nests (within-region and outside-region), and four relevant alternatives (same, close, near and far) as it is presented in Equation (3). Though some utility models have included rail in the NL structure (Cascetta et al., 2008; Huang & Kockelman, 2010), we did not do the same because rail's market share is negligible in Spain. The NL structure was a way of overcoming problems detected in the single level multinomial logit formulation.

$$U_{ij}^{m} = -p_i^m + \lambda^m \ln\left[\sum_R exp(U_{ij,R}^{m})\right] \quad (3)$$

$$U_{ij,R}^{m} = \theta^m GTC_{ij,R}^{m} \quad (4)$$

U_{ij}^{m} shows the utility for region j of acquiring commodity m in region i. The systematic utility of the lower nest $U_{ij,R}^{m}$ is defined in Equation (4). p_i^m is the price of goods/services of sector m in region i. λ^m and θ^m are the logit model parameters. GTC_{ij}^{m} is the Generalized Transport Cost of sector m goods from production or origin region i to consumer region j. Total GTC between production and consumer regions was incorporated to avoid possible multicollinearity problems.

For the calculation of transport costs inside the same region (i.e. $i = j$), an average cost value was determined from the capital of the region to provinces of that same region by using the road transport network. Regions outside continental Spain were linked to the continental transport network by using fictitious links and attributing a larger share of the total costs to fixed costs in the transport network. This calculation assumes that transport costs increase with distance. The resulting GTC_{ij}^{m} combinations are computed through the road network model as it is described in detail in the following section.

The parameter estimates of the NL utility model —shown in **Table 1**— were obtained by using the NLOGIT with the maximum likelihood method. The estimated coefficients have the expected signs because costs have a negative effect on utility. Moreover, the Wald statistic (values in brackets) rejects the null hypothesis that the coefficient is zero with a level of 90% confidence —p-values for each parameter are reported. Also, it is convenient to measure goodness of fit analogous to those in linear statistical models. Indeed, the Likelihood Ratio Index —McFadden Pseudo R^2 (ρ^2)— provides a convenient basis for comparing different models when estimating more than one alternative. Pseudo R^2 values between 0.2 and 0.4 are fairly good reliable according to McFadden (1977).

Low values in these two tests could be explained by the lack of sufficient data at this point (Kockelman, 2008). This indicates that more data about flows of goods would be required in order to obtain more accurate results, but unfortunately these data are not available for the case of Spain.

4.2.1 The Road Network Model

The road network model was built using the software TransCAD. Capacity (vehicles/hour) and speed targets are defined by the government for each classification of roads by function. We have included these values as inputs for each link of the road network. In addition, the greater the slope of a road the greater the reduction, in both speed and capacity, of the traffic on that road. Therefore, we have reduced both speed and capacity by considering factors reflecting the slope of the road. We have used the traffic count data taken from (MFOM 2008b), sorted by type of vehicle, included for each link in order to validate the base-case year assignment model. We had to consider that in the model not only truck traffic —affected by the introduction of LHVs— but also cars and buses use the same road network. Therefore we treated these traffic flows as a pre-load volume, because we are not including them in our integrated modeling approach.

Conversion factors from the RUBMRIO model were applied so as to convert the measurement of the commodity trade in the transportation system from monetary units (Euros) to tonnes, and from tonnes to trucks per year, and finally, to trucks per day. This conversion used an average price per tonne for a specific commodity (€/tonne), the Heavy Goods Vehicles (HGVs) configuration of each sector, and a factor reflecting the percentage of trips of empty trucks. This procedure enabled us to obtain OD matrices per sector.

The percentage of empty HGVs was adopted from the Ministry of Transportation of Spain (MFOM 2008a), considering pickup/delivery truck operations in both directions of origin-destination pairs as a proxy since detailed information required to build up an empty trip model for Spain was not available. Additional information regarding external trips (imports and exports to/from other peripheral countries as Portugal, and elsewhere in Europe) were also incorporated (Gutiérrez, Condeço-Melhorado, Martin, & Román, 2012), since it was not included in the RUBMRIO.

A Multi-Modal Multi-Class Stochastic User Equilibrium assignment (SUE) procedure was conducted to assign the HGVs traffic of the resulting OD matrices as user classes and considering VDF functions for each functional classification class through TransCAD for the base-case scenario. These functions incorporated individual variations of generalized cost perceptions. We adopted a time period of 24 hours (one day) since detailed information about time periods was not available taking into account that daily capacity is calculated by multiplying the hourly capacity by a daily expansion factor.

The process of validation was conducted on the basis of comparisons between predicted and observed flows in all the links of the base-case scenario in order to determine whether the assignment model is loading HGV trips for each functional class in a reasonable way. VDF parameters and daily expansion factors changes were introduced in an iterative process intended to minimize deviations between assigned and observed traffic flows. The validation results depicted in **Table 2** show how recommended targets given in the guide (TMIP 2010) were met for each functional classification class. In addition, we have checked the model validation in each link considering the guide (TMIP 1997). We calculated percentages of deviation for daily volumes for individual links. The results show that 10% of the 3,874 links exceed the target values recommended in the guide. According to these results, we believe that the application of the model for the introduction of LHVs should produce reasonable results.

Functional Classification Class		Number of (Links) Km.	Average Traffic Count Data	Average Error	% Error	% RMSE	Recommended % RMSE*
1	Tolled Highways	(578) 2,703	5,576	-111.88	-3.65	29.92	43
2	Free Highways	(1,776) 8,122	8,562	129.39	3.57	21.91	37
3	National Road System	(1,520) 6,597	3,547	183.50	19.86	45.55	51
ALL		**(3,874) 17,422**	**8,523**	**114.62**	**4.62**	**27.95**	**37**

***** Recommended %RMSE targets for the average traffic count data considering guide (TMIP 2010)

Table 2 – Road Transport Network Model Validation by Functional Classification Class

4.2 Application of the Methodology to the LHV Scenario

The LHV scenario was developed by considering: (i) the road network ready to handle LHVs; (ii) the distance over which goods are transported; (iii) the characteristics of commodities transported; (iv) the potential market which might be relocated away from the existing ones; and (v) the expected cost reduction factor of LHVs compared to HGV.

With regard to the road network suitable for the LHVs scenario, it was shown in **Figure 2.b**. In addition, we have excluded intraregional OD pairs because LHVs are mostly favorable for longer distances (De Ceuster et al., 2008; K+P Transport Consultants & ISI Fraunhofer, 2011).

The characteristics of commodities as well as the potential market to be relocated in LHVs vehicles was defined by considering a sensitivity approach in the following way —see **Table 3**. First, loads transferred from HGVs to LHVs —column 3— were estimated based on the experience of other countries (De Ceuster et al., 2008; K+P Transport Consultants & ISI Fraunhofer, 2011; Vierth et al., 2008) and on the basis of their physical characteristics, such as the weight and/or volume for each commodity, and the ease of transferring them. We have considered a minimum and a maximum value.

Second, the potential market for LHVS —column 4— was defined on the basis of the willingness of current HGVs per sector to migrate to LHVs. This assumption takes into account, for instance, that trucks lighter than 20 tonnes will never migrate to LHVs because they could already have made the move to HGV trucks, but had not done so. On the basis of this assumption the maximum percentage of conventional trucks ready to migrate is adopted from (MFOM 2008a). In addition, we have set a minimum value expected for this variable. Third, deviation of each sector is calculated by multiplying the expected load transferred times the number of trucks that can potentially migrate to LHVs considering both minimum and maximum percentages. Fourth, we computed a cost reduction factor (CR) to show how far LHVs will reduce costs compared to HGVs by considering the unitary payload weight cost of Spain (Ortega & Vassallo, 2012) for both vehicles, and for both minimum and maximum possibilities.

These CR factors are included in the integrated approach to generate the RUBMBRIO input according to Equation (5). Other research works have established cost saving of LHVs varying from 10 to 25% against conventional HGVs due to greater loads (De Ceuster et al., 2008; Doll et al., 2009).

$$GTC_{ij}^{Scenario} = \frac{\left(\sum_{s=1}^{9} HGVs_s^{Base\ i,j} \times D_s^{LHVs} \times GTC_{ij}^{Base}(1-CR)\right) + \left(\sum_{s=1}^{9} HGVs_s^{Base\ i,j} \times (1-D_s^{LHVs}) \times GTC_{ij}^{Base}\right)}{\sum_{s=1}^{9} HGVs_s^{Base\ i,j}} \quad (5)$$

$$\forall\ i,j$$

$GTC_{ij}^{Scenario}$ is the weighted average GTC_{ij} among regions for the LHVs scenario. $HGVs_s^{Base\ i,j}$ are HGVs traffic flows from the base-case of the sector s and for the same OD pair. D_s^{LHVs} are deviation factors from HGVs to LHVs for each sector s. GTC_{ij}^{Base} is the generalized transport cost in the base-case scenario from production or origin region i to consumer region j. CR is the cost reduction factor of LHVs compared to HGVs defined in **Table 3**.

The assignment of the LHVs scenario was carried out in a way similar to that of the base-case one by adopting the calibrated assignment parameters of the base-case (VDF parameters, and empty trips of trucks per OD pair). The OD matrix included additional matrices of trips considering the new user class (LHVs) resulting from the deviation factors applied to the HGVs of each sector. Therefore, we have considered that LHVs will compete with other HGVs in the same road network. Also, for LHV trips the road links that cannot be used by these vehicles were specified. For both scenarios, transfer penalties for each functional classification of roads to prevent very short interchanges, convergence criterion value, and the maximum number of iterations to be performed were defined.

5. ANALYSIS OF RESULTS

The introduction of LHVs would mean lower transportation costs. This, in turn, would produce several effects on trade patterns and vehicle flows since it will make sales and purchases easier, and for that reason regions will be able to re-allocate goods to other regions, substitute production from other regions, and trade goods which previously were not being traded. All these changes will be reflected in the demand of freight services which in turn will be reflected on the road freight transport flows over the whole network.

The application of the model has assessed both scenarios separately. Initially, the model has allowed the estimate of 2007 data to be taken as the base-case considering the GTC_{ij}^{Base} for HGVs exclusively. Then, the $GTC_{ij}^{Scenario}$ for both the minimum and the maximum scenario was included in the integrated approach to determine the LHVs scenario results, which in comparison with the base-case shows the estimation of the various impacts on the transportation system.

	(1) Sector Description	(2) Articulated HGVs Type GVW - Payload (Tonnes)	(3) Expected Load Transferred (%)		(4) Potential Trucks Migration (%)		(5) Deviation (%)		(6) *GTC* Cost Reduction LHVs to HGVs	
			min	max	min	max	min	max	min	max
1	Agriculture, Fishing, Wood and Cork	Articulated Truck 40 - 25 Tonnes	30	60	16.8	33.5	5.0	20.1	5%	7%
2	Food and Kindred Products	Articulated Truck - Refrigerated 40 - 24 Tonnes	40	80	16.8	33.5	6.7	26.8	7%	9%
3	Non-metal Minerals and Kindred Products	Articulated Truck - Bulk Tanker 40 - 24 Tonnes	30	60	16.8	33.5	5.0	20.1	5%	7%
4	Energy, Petroleum and Petroleum Products	Articulated Truck - Fuel Tanker 40 - 27 Tonnes	0	0	16.8	33.5	0	0	0%	0%
5	Mining	Articulated Truck 40 - 24 Tonnes	30	60	16.8	33.5	5.0	20.1	5%	7%
6	Metal minerals and Kindred Products	Articulated Truck 40 - 24 Tonnes	30	60	16.8	33.5	5.0	20.1	5%	7%
7	Construction	Articulated Truck - Bulk Tanker 40 - 24 Tonnes	25	50	16.8	33.5	4.2	16.8	4%	6%
8	Chemical and Allied Products, Paper, Edition and Kindred Products, Rubber Materials	Articulated Truck - Fuel Tanker 40 - 27 Tonnes	0	0	16.8	33.5	0	0	0%	0%
9	Textiles, Clothing, Leather and Shoes, Industrial Machinery and Equipment, Electric and Electronic Equipment, Transportation Equipment, and Other Manufacturing Industries	Articulated Truck - Bulk Tanker 40 - 24 Tonnes	25	50	16.8	33.5	4.2	16.8	4%	6%

Table 3 – Sector Commodities Analysis, Cost Reduction and Sensitivity Analysis

5.1 Impact of Allowing LHVs on the Demand of the Road Freight Transportation System of Spain

Impact on the demand of the road freight transportation system have been focused on changes in flow volumes under both minimum and maximum scenario, as shown in **Table 4**. Overall, the results show a promising decreases of freight transport flows considering the Annual Average Daily Traffic – AADT (-0.90% in the minimum scenario and -3.60% in the maximum scenario). Furthermore, the detailed results sorted by type of road are worth analyzing.

The total AADT of the national road system experiences the greatest reduction in both scenarios compared to the remaining types of roads. The reason for this notable reduction is explained by the fact that LHVs are not allowed to travel on national roads. Taking into account the study of payload distance (tonne-km/day), it reveals that in the LHVs scenario both tolled and free highways will transport more tonnes using fewer vehicles than before. This will result from the greater carrying capacity of LHVs compared to HGVs, and the national road constraint.

One of the most important advantages of the introduction of LHVs is the reduction of emissions for different kinds of pollutants (CO_2, NO_x, and PM_{10}) in both scenarios. In **Table 4** we show the main results of the model in this respect. The expected reduction in the whole road network is less than 1% for each one of the three pollutants considered. However, considering the network where LHVs are not allowed –National roads, the reduction will much more significant. Although emission savings do not look substantial in the short term, they may have a greater impact in the long-term.

The comparison of both the minimum and the maximum scenario in relation with the base-case is shown in **Figure 3**. This figure displays the percentage change of both scenarios referred to the base-case scenario assumed as zero in each flow and emission comparison.

(a)

Functional Classification Class	**Number of (Links) Km**	**Total AADT Assigned HGVs/day (Millions)**			**HGVs-Km/day (Millions)**			**Payload-Distance (tonne-km/day) (Millions)**		
		Base-Case Scenario	**LHVs Scenario min Max**	**Change (%)**	**Base-Case Scenario**	**LHVs Scenario min Max**	**Change (%)**	**Base-Case Scenario**	**LHVs Scenario min Max**	**Change (%)**
1 Tolled Highways	(604)	1.78	1.77	-0.43	7.73	7.69	-0.41	92.77	95.13	2.54
	2,703		1.76	-1.39		7.61	-1.62		96.03	3.51
2 Free Highways	(1,739)	6.59	6.53	-0.98	29.28	29.00	-0.96	351.41	351.59	0.05
	8,122		6.34	-3.86		28.17	-3.79		352.10	0.20
3 National Road System	(1,531)	1.68	1.66	-1.26	6.91	6.83	-1.11	82.90	81.98	-1.11
	6,597		1.59	-4.95		6.57	-4.92		78.82	-4.92
ALL	**(3,874)**	**10.05**	**9.96**	**-0.93**	**43.92**	**43.53**	**-0.90**	**527.08**	**533.51**	**-0.01**
	17,422		**9.69**	**-3.60**		**42.35**	**-3.59**		**526.96**	**-0.02**

(b)

Functional Classification Class	**Number of (Links) Km**	**CO_2 Emissions (Tonnes/day)**			**NO_x Emissions (Tonnes/day)**			**PM_{10} Emissions (Tonnes/day)**		
		Base-Case Scenario	**LHVs Scenario min Max**	**Change (%)**	**Base-Case Scenario**	**LHVs Scenario min Max**	**Change (%)**	**Base-Case Scenario**	**LHVs Scenario min Max**	**Change (%)**
1 Tolled Highways	(604)	7,465	7,504	0.52	196.6	197.6	0.52	6.5	6.6	0.54
	2,703		7,648	2.45		201.4	2.45		6.7	2.51
2 Free Highways	(1,739)	28,277	28,227	-0.18	744.6	743.3	-0.18	24.7	24.7	-0.17
	8,122		28,098	-0.63		739.6	-0.63		24.6	-0.58
3 National Road System	(1,531)	6,671	6,597	-1.11	175.7	173.7	-1.11	5.8	5.77	-1.11
	6,597		6,343	-4.92		167.0	-4.92		5.54	-4.92
ALL	**(3,874)**	**42,413**	**42.328**	**-0.20**	**1,117**	**1,115**	**-0.20**	**37.1**	**37.0**	**-0.19**
	17,422		**42,174**	**-0.77**		**1,108**	**-0.77**		**36.8**	**-0.72**

Table 4 – Transportation System Impact: (a) Flow Volumes; (b) Emissions.

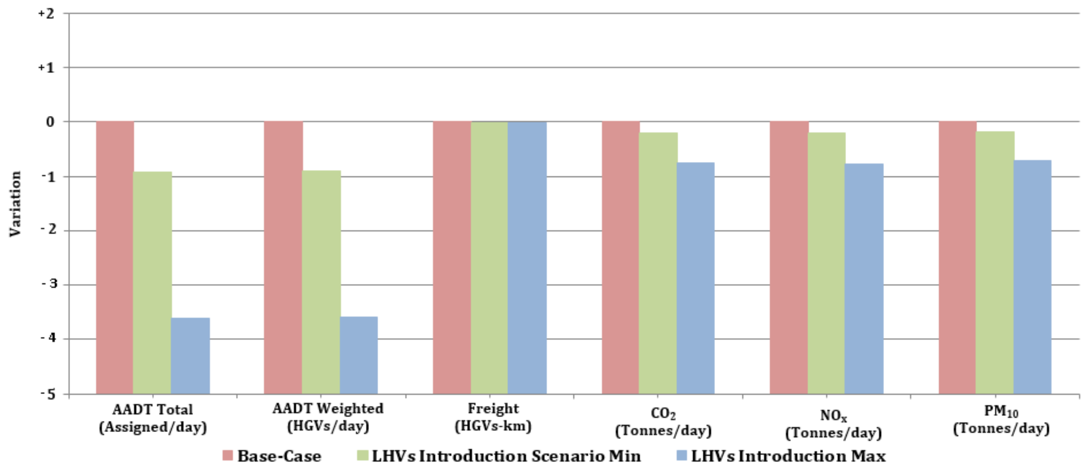


Fig. 3 – Transportation System Impact Comparison

In addition, the model has allowed for the calculation of the LHV traffic volumes for both minimum and maximum scenarios (see **Figure 4**). This figure shows the flow volumes of LHVs in each link. In the maximum scenario (**Figure 4.a.**), the LHV flow volume will be significant in the road network ready to handle LHVs. 71% of the roads – 6,938 Km – will have less than 500 LHVs per day, 27% – 2,699 – will have between 500 to 1,000 LHVs per day, and only 2% – 161 km – will have more than 1,000 LHVs per day. On the other hand, in the minimum scenario (**Figure 4.b.**), the road network will not exceed the 500 LHVs per day.

6. CONCLUSIONS

This paper provides an integrated approach to assess the nationwide impact of transport policy measures such as the introduction of LHVs. The results demonstrate that the model developed in this research is able to forecast freight transport demand changes — direct and indirect effects — produced on freight flows. In addition, the model designed provides a useful tool for policy makers, governments, and transportation authorities to evaluate the expected impacts on the road freight transport system of a country.

The first conclusion of this research is that introducing LHVs is good for the road system since it can offer traffic and pollution relief across the country, since LHVs will reduce the amount of truck-kilometers needed for transporting goods. These results are a consequence of bigger trucks that imply a need for fewer trucks to move the same amount of freight. Moreover, bigger trucks imply more trade because transport, and consequently exports to other regions and abroad, are subsequently cheaper. Finally, it is worth noting that there will be a deviation of traffic towards the corridors where LHVs are allowed to be used.

The second conclusion is that the flow of trucks in the network is expected to diminish slightly. In addition, there will be a noticeable deviation of freight traffic from conventional roads to high-capacity roads. This trend is favorable for the environment but might have a negative impact on those stretches of highway that exhibit congestion problems.

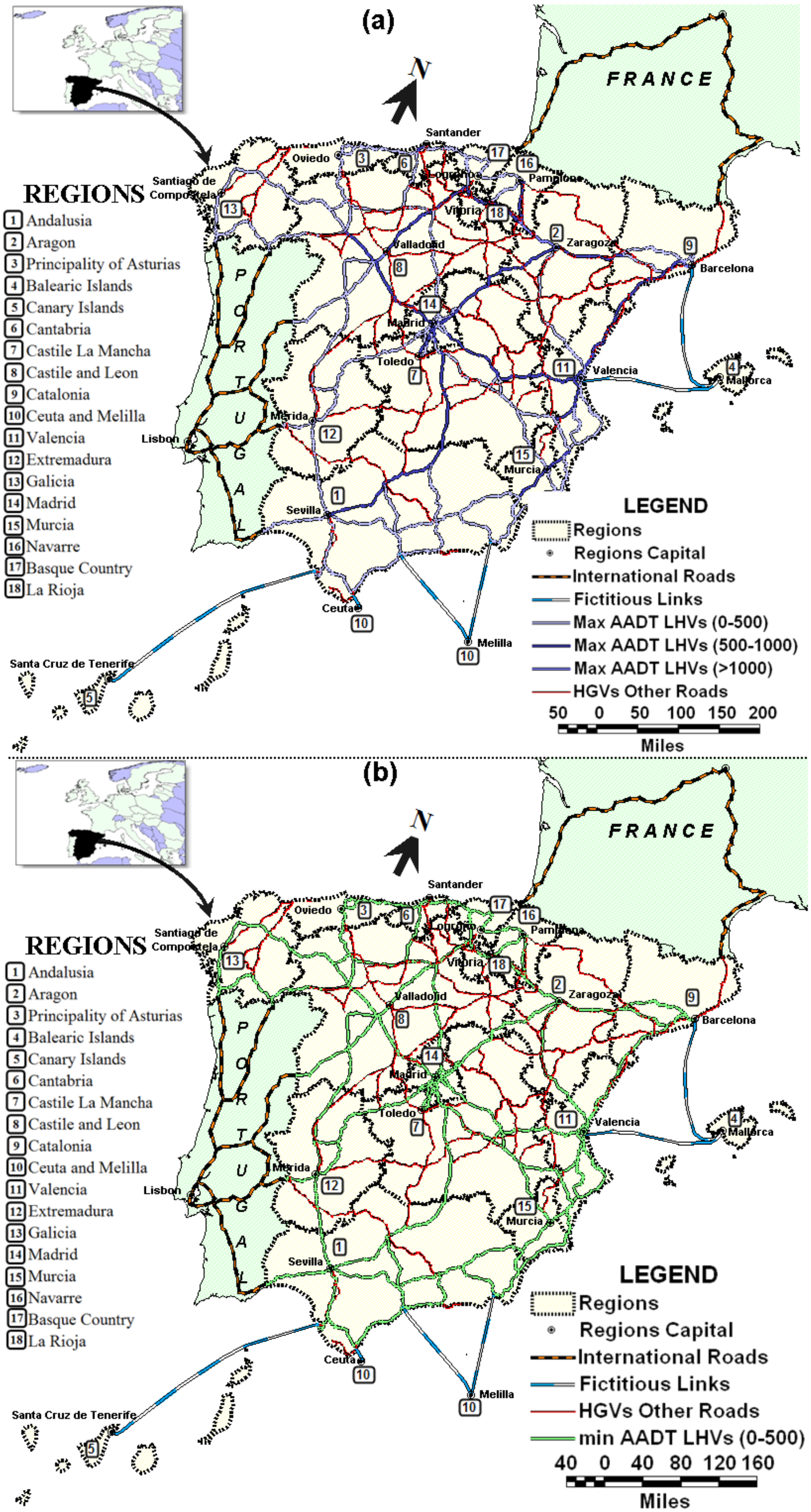


Fig. 4 – Annual Average Daily Traffic LHVs (LHVs/day) (a) Max; (b) min

The third conclusion is that national roads will experience the greatest decrease of traffic flows, and payload-distances (tonne-km). Fourth, introducing LHVs will lead to a certain reduction of emissions in the road transport network so it will overall be favorable for the environment. However, tolled highways will produce more emissions (CO_2, NO_x, and PM_{10}) since LHVs emissions factors per kilometer are greater than the emissions factors of HGVs.

Overall, the results have pointed out that our integrated modeling approach based on a commodity-based structure assesses the impact of transport policy measures on freight flows running on the road transportation network. This approach overcomes the undesirable limitations of models based on truck-trips. As a result, this research has proposed, and constructed, a comprehensive approach to better forecast transportation demand impacts, upon the introduction of new freight transport vehicles (in this case, LHVs) within a country like Spain. Moreover, the integrated modeling approach determines the flow volumes of both HGVs and LHVs vehicles in the road network of Spain.

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