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Sensitivity analysis of impact model for road freight by the increase in the use of larger trucks in Spain

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This study develops an impact model for road freight transport and aims to analyse the sensitivity of the results to the model parameters. Scenarios are simulated to study the effect of this model on road freight transport operations. The model and the methodology are applied to the sampling data from the permanent road freight survey of the Spanish Ministry of Transport. According to the results, the optimum parameter values or ranges are recommended, and the assumptions involved in the impact estimates are justified. Finally, the model is also proposed to apply and extended to a large logistic network.
Estimates and projections presented in this study are based on the level of shift of goods for the larger trucks, the modal shift from the railway, and the elasticity demand for road freight transport as a result of lower transport operation costs. The results of this study show that, considering the effects of induced truck traffic and the shift of goods from rail to road, increasing the weight limits for trucks produces slight benefits.

Keywords: *freight competition, mega trucks, modelling impacts, transport policies.*

1. Introduction

Increasing the maximum permissible gross vehicle weight (GVW) of trucks allows transport operators to consolidate loads, and therefore reduce the vehicle traffic required to collect and distribute a given amount of goods determined by the economic conditions of a country (Leonardi and Baumgartner, 2004; Oficemen, 2009). Under certain conditions, this can lead to economic, social, and environmental impacts (Christidis and Leduc, 2009). While there has always been an agreement on economic and social benefits involved in load consolidation, there has not been an agreement on the environmental implications. Scholars argue about the environmental impacts that lower operating costs of freight transport would induce an increase in road freight to detriment of rail transport (McKinnon, 2005). Specially, road freight transport has been in the discussion of shippers and managers about improving its energy efficiency, and it is estimated that freight transport accounts for approximately 8% of energy related to global CO_2 emissions (Kahn Ribeiro and Kobayashi, 2007); this amount is increasing at a faster rate than the energy consumed by passenger transport (McKinnon, 2010). In Spain the authorities are considering increasing the GVW of trucks from current 44 t to 60 t (Ortega et al., 2011).

Road freight transport in Spain is the dominant transport mode, accounting for 84% of total ton-kilometres (t-km) in 2008 (MFO, 2009). Between 1995 and 2008, road transport increased despite

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the maintenance of the average transport distance (115 km). On the other hand, rail freight transport has declined from 4.7% to 2.6% (MFO, 2010). Measures to reduce road transport operations and subsequent environmental impacts, use of clean vehicles and fuels, improvement of energy efficiency, reduction in transport intensity, consolidation of loads, and increase in the maximum weight of trucks can potentially produce greater environmental benefits than marginal changes in the transport modal share (EEA, 2009; CSC, 2010; PNI, 2009). The proportions of carbon dioxide (CO_2) and other air pollutant emissions directly associated with the transport of heavy-duty vehicles (HDVs >3.5 t) are significant (Table 1), and most of these measures are also aimed to reduce atmospheric emissions.

Key indicators, such as the transport content (production expressed in kilometres per ton), distance (logistic range in kilometres), and efficiency (specific organization in tons per vehicle and ratio between the distance and content) are strongly associated with environmental, economic, and social impacts of transport. Guidelines on developing key performance indicators and metrics for evaluating transportation sustainability are needed (Zheng et al., 2013). Thus, the content is a proxy for environmental impact and life cycle analysis (LCA) of transportation (Böge, 1995). Furthermore, the distance and efficiency are also linked to growth-related aspects of transport (Roth and Kaberger, 2002). The evolution of t-km differs from that of key indicators. The relationships between transport content, distance, efficiency, and t-km are highly influenced by the types of trip and goods (Pérez-Martínez, 2009).

The study starts reviewing and analysing the existing Spanish road freight transport system as well as the development of the Spanish legislation concerning maximum permissible loads. The study analyses the international experiences of load restrictions on trucks and compares the current Spanish situation with other studies on truck size and weight limits. The analysis studies the impacts of the potential increase in the GVW of vehicles to provide a basis for future decision-making and implementation of new legislation to control the use of larger trucks. The study includes forecasts of the impacts to be estimated from increasing the GVW based on modelling and scenario analyses. The model is applied and extended to a large freight road transport network connected to the major ports in Spain. The findings of the study assess the relevance of the impacts of larger trucks on the Spanish road freight market.

Table 1. Contribution of HDVs to the Spanish atmospheric emissions (2007)

Species	% of the emissions over the transport sector total	% of the emissions over the national total
Particle matter (PM_{10})[1]	20.9	4.5
Nitrogen oxides (NO_x)	38.9	12.2
Carbon dioxide (CO_2)	34.2	9.1

[1] Particle matter of 10 micrometre or less. Source: MFO, 2009; MMA, 2008.

2. Larger trucks and freight data

The legislation regarding the maximum number of axles and maximum weight allowed for trucks has constantly changed over the last years in Spain. The most two important changes took place during the years 1967 and 1997 (Table 2). In 1967, a decree allowed the traffic of 18 m and up to 38 t trucks. The new decree in 1997 allowed the use of 6 axles up to 44 t trucks, and increased the maximum permissible sizes to 18.75 m length and 2.55 m wide. The only size that has not been altered over the years is the gauge, which remains in 4 m. Meanwhile, the Nordic countries have allowed bigger sizes and truck tonnages. Sweden adopted the use of longer and heavier vehicles (LHV) from 1995 onwards, resulting in some positive impacts (Backman and Nordstrom, 2002). Fuel consumption and subsequent CO_2 emissions fell on average by 14.3%. Therefore, the emissions of NO_x would have reduced by 14,000 t/year (25% over the freight sector total). The results in Finland showed similar impacts, and joint studies demonstrated energy savings above 20%. Despite the experiences of Nordic European countries, not all European countries decided to implement similar policies (Table 3). Although there are countries that have conducted pilot studies using larger trucks, other countries have tested only trucks up to 44 t or have not done any type of pilot project.

2.1 Larger trucks

The effects of increasing the maximum weights and dimensions for road freight transport trucks in the world are usually expressed as expected impacts (Table 4): accidents, operation costs, externalities, maintenance, modal shift, congestion time, empty back hauls, and induced demand. These effects are based on various factors and parameters such as loading capacity, travel time, and emission levels. In general, the effects of road freight transport caused by larger trucks reflect a combination of positive impacts, such as reduction in transportation cost (Bergqvist and Behrends, 2011; Woodrooffe et al., 2010), and negative ones, such as increase in the severity of accidents (Knight et al., 2010) and maintenance of infrastructures (Table 4). The use of larger vehicle fosters the inter-modality and reduced transport operating costs per t-km (BRR, 2007). From the review, it seems that the negative effects, such as an increase in the back hauls (McKinnon 2005; Ortega et al., 2011) - and associated fuel consumption and emissions -, the modal shift from rail, and induced demand (Nealer et al., 2012; Santos et al., 2010; Eom et al., 2012) could offset the positive effects such as the reduction in the operation and travel time costs (Proost et al., 2002; Pérez-Martínez and Vassallo, 2013). According to the studies of the project ARCADIS (2006) and Vierth et al. (2008), capacity increases in trucking show major safety problems.

Different larger trucks have different infrastructure maintenance and conservation costs depending on the distance between axles and the sizes of trailer and semitrailer (UIC, 2007). Costs are related to special aspects of the trucks that can influence the infrastructure pavement maintenance and conservation (Table 5). In this study, 60 t GVW trucks are referred to the term mega-truck (*MT*): *LDS*, MST_{23}, and MST_{33} vehicles. According to García et al. (2013), road freight transport by larger trucks consumes energy levels per ton-kilometre that are similar to diesel rail freight transport only for manufactured commodities. Electric rail is by far the most efficient mode under certain transport profiles, commodities, and vehicle and fuel technologies. Therefore, it is very difficult to determine the impacts of modal shift in terms of impacts related to energy consumption and emissions, which are avoided.

This literature review highlights the discrepancies between different studies and the need to standardize environmental data and methodologies for estimating impacts. In general, the review of recent research and developments indicates the need of a structured analysis, based on the variability of the concluding impacts of using larger trucks. This study proposes a model to analyse the implications of recent research and developments on the use of larger trucks. The negative impacts give a fair judgment on future planning and transport policies on trucking weight and dimension increases and justify why European Governments, except those from the Nordic countries, have been contrary to them (Table 3). The level of analysis is not changing from experiences in Spain compared to other countries (from the Organization for Economic Co-operation and Development, OECD, and the International Energy Agency, IEA), and results available at international level (Woodrooffe et al., 2010; Knight et al., 2010; Eom et al., 2012) do not differ from the ones obtained in Spain (Ortega et al., 2011; Pérez-Martínez and Vassallo, 2013).

Table 2. Evolution of the Spanish legislation regarding maximum GVW

Year	Axles (n)	GVW (t)	Size (m) Length	Wide	Gauge
1962	> 3	32	16.50	2.50	4
1967	> 3	38	18.00	2.50	4
1986	6	44	18.00	2.50	4
1991-1996	6	44	18.35	2.50	4
1997-2004	6	44	18.75	2.55	4

Source: Ortega et al., 2011 and this study.

Table 3. European regulations related to longer and heavier vehicles (LHV)

Country	Length (m)	GVW (t)	Remark
Sweden	25.25	60	Allowed
Finland	25.25	60	Allowed
Norway	25.25	60	In pilot test
Denmark	25.25	60	Only in pilot test for some routes
Holland	25.25	50	In pilot test for 60 t
Germany	25.25	40	In pilot test
Belgium, Spain	18.75	44	In pilot test
France	Not allowed		
Switzerland	Not allowed		
Austria	Not allowed		
United Kingdom	Not allowed after pilot test		
Portugal	Not allowed		

Table 4. Impacts of the use of larger trucks

Country and source	Expected impact	Trend of the impact	Effect on freight market
Sweden & ITF/OECD countries: (Bergqvist and Behrends, 2011; Woodrooffe et al., 2010)	Transportation cost	Reduction (↓)	Positive
European countries: (Knight et al., 2010)	Severity of accidents	Increase (↑)	Negative
United States, United Kingdom, IEA countries: (Nealer et al., 2012; Santos et al., 2010; Eom et al., 2012)	Shift from rail and induced demand	Increase (↑)	Negative
European countries: (Proost et al., 2002; Pérez-Martínez and Vassallo, 2013)	Kilometres driven, congestion, and time	Reduction (↓)	Positive
United Kingdom & Spain: (McKinnon 2005; Ortega et al., 2011)	Empty back-hauls, load weight, and volume constraints	Increase (↑)	Negative
United States & Spain: (Nealer et al., 2012; Pérez-Martínez and Vassallo 2013; García-Alvarez et al., 2013)	CO_2 and pollutant emissions	≈	Undefined
European countries: (Ortega A, Vassallo JM, Pérez-et al., 2011; Knight et al., 2010)	Infrastructure maintenance and investment	Increase (↑)	Negative

Table 5. Larger trucks and infrastructure costs

Vehicle type	Configuration	Length (m)	GVW (t)	Cost (€/km)	Cost[5] (€ct/vkm)	Extra (€/km)	Difference (%)
[1]MST_{33}		25.25	60	73,063	7.3	3,213	4.46%
[2]MST_{23}		25.25	60	78,054	7.8	8,114	11.60%
[3]LDS		25.25	60	72,830	7.2	2,890	4.13%
[4]Standard		16.50	40	69,940	6.9	_	_

[1] Motor vehicle (3 axles), semitrailer (3 axles), and trailer (2 axles); [2] Motor vehicle (2 axles), semitrailer (3 axles), and trailer (3 axles); [3] Lorry (3 axles), dolly (2 axles), and semitrailer (3 axles); [4] Motor vehicle (2 axles) and semitrailer (3 axles); [5] The update of the EU handbook of external costs predicts marginal infrastructure costs of 8.0 €ct/vkm for 5 axles 40 t trucks and 10.6 €ct/vkm for 8 axles 50-60 t trucks, respectively (TRT, 2014). Infrastructure costs were obtained by the Miner's law; the pavement was exhausted after 10^6 truck crossings of 13 t axles; the crossings were uniformly distributed from the tare weight to the maximum GVW. Source: BRR, 2007; UIC, 2007; Kraemer et al., 2004.

2.2 Freight data

During the 2002-2007 period, the increase in the truck-kilometres (12%), estimated by the Spanish Highway Administration (MFO, 2009) from the Annual Average Daily Traffic (AADT) at the measurement stations of the Spanish road network, was similar to the increase in the Gross Domestic Product GDP (12.5%) and double of the increase in the vehicle-fleet (6%). Other studies and sources also showed that Spanish truck volumes were increasing significantly before the economic crisis started in 2009. Thus, the travelled kilometres and the vehicle fleet estimated from the Permanent Road Freight Transport Survey (PRFTS) increased by 47% and 23%, respectively.

In 2004, AADT measurement stations estimated 6.03×10^3 million vehicle-kilometres (v-km) more than the truck traffic recorded by the PRFTS (based on registered transport carriers). This gap has been narrowed to almost match in 2008. In 2009, measurement stations account for 8% more truck-kilometres than PRFTS. The divergence between the two data sources may be due to the following reasons (Aparicio et al., 2005): exclusion of abroad registered trucks, underestimation of the distances travelled by carriers, and misclassification of the trucks in the vehicle classes. Transportation by foreign carriers in Spain, according to Eurostat cabotage estimates (Pasi, 2008), represents 0.34 10^3 million truck-kilometres in 2002 (1.4% of total transport). This amount accounts only for 6% of the difference between the two sources. In this regard, McKinnon and Piecyk (2009) identified some discrepancies between sources of up to 29% in the UK, in such a way that a difference of 8% appears to be more than acceptable in our case.

Figure 1 shows the distribution of v-km for the years 1997 and 2008 by vehicle type and maximum payload according to PRFTS (MFO, 2010). The share of articulated trucks, with load capacity over 26 t, increased by 4.3% over 1997 levels (3.8% laden v-km in 1997 vs. 8.1% in 2008) from rigid trucks over 20 t (3.9% laden v-km n 1997 vs. 0.7% in 2008) and from articulated trucks of 24.1-26 t (27.0% laden v-km in 1997 vs. 22.4% in 2008). According to PRFTS, manufactured and volume constrained products weighed 28% of transported v-km.

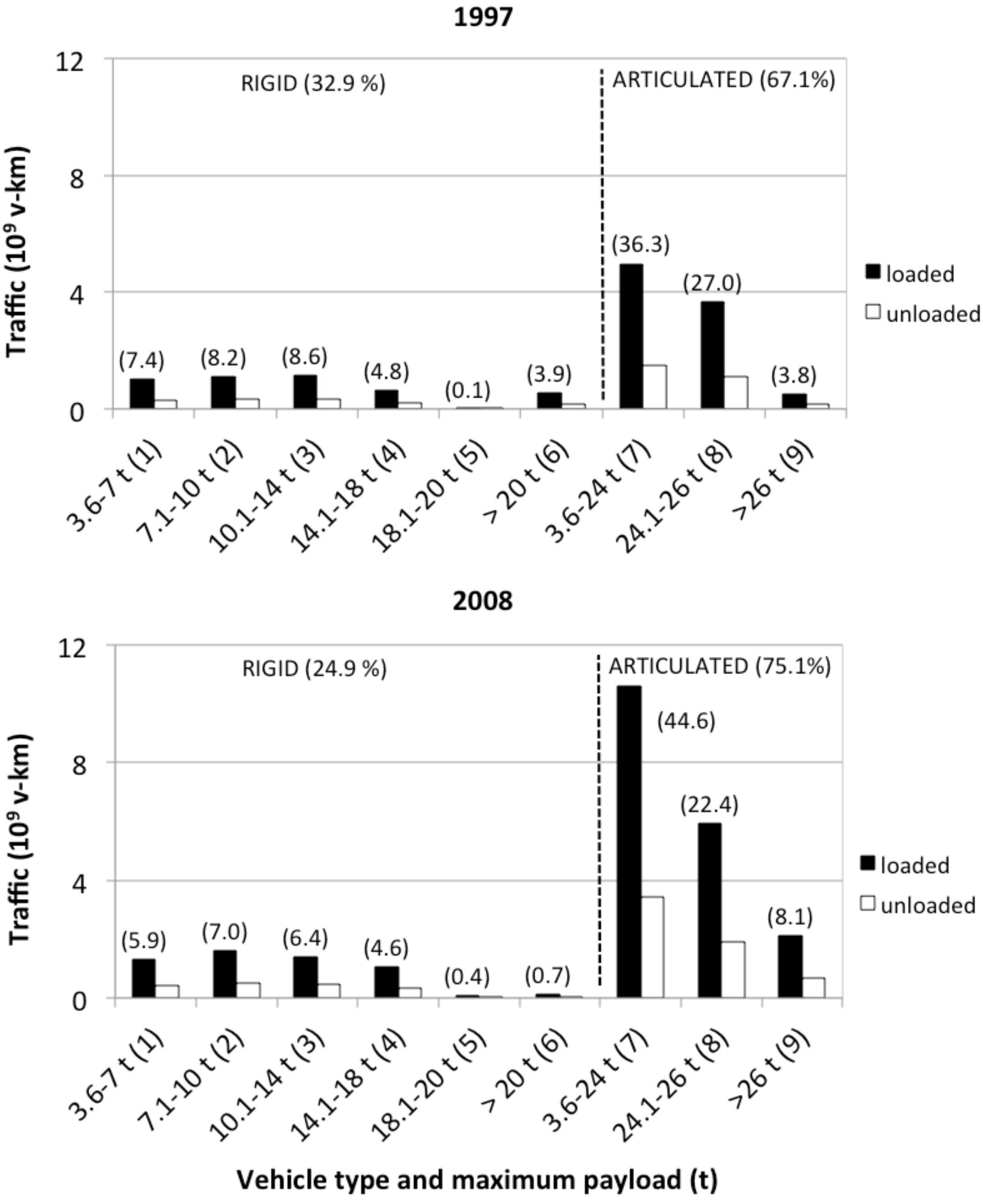

Figure 1. Distribution of v-km by type of vehicle and payload. Note: traffic shares of laden kilometres in brackets; [1]equivalent to <10 t Gross Vehicle Weight (GVW); [2]10-13.5 t; [3]14.1-18 t; [4]18-24 t; [5]24.1-26 t; [6] >26 t; [7]10-32 t (GVW); [8]32.1-38 t; [9]38.1-44 t; Source: (MFO, 2010).

3. Model

3.1 Notations

The following symbols and definitions are used in this analysis:

v: total annual laden vehicle kilometres (10^6 v-km);

MVLC: maximum loading vehicle capacity (t);

R: ratio between *MVLC* of high performance articulated trucks and *MVLC* of immediately smaller trucks (no units);

V: empty back hauls related to laden v-km savings (no units);

AADT: annual average daily traffic (AADT);
M: total annual laden v-km transferred to larger from smaller trucks (%);
W: proportion of load not subject to weight constraints (no units);
r: total annual laden v-km savings (10^6 v-km);
D: total annual laden v-km travelled by high performance trucks with load weight constraints (10^6 v-km);
η: elasticity of transport operation price related to transport distance (no units);
i: induced annual laden v-km (10^6 v-km);
t: ton-kilometres transferred from rail to high performance trucks (10^6 t-km);
f_c: loading factor of higher performance trucks in tons kilometre per laden vehicle kilometre (t-km/v-km);
f: total annual laden v-km transferred from rail to road (10^6 v-km);
r': total annual laden v-km savings, once deducted the induced and the transferred traffic (10^6 v-km);
c_o: unit operation cost (€/v-km);
c_m: unit maintenance and infrastructure conservation cost (€/v-km);
c_e: unit external cost (€/t-km);
c: reduced total costs (10^6 €);
LR: large rigid trucks of >20 t (maximum payload) and >26 t (GVW);
MA: medium articulated trucks of 24.1-26 t (maximum payload) and 32.1-38 t (GVW);
LA: large articulated trucks of >26 t (maximum payload) and 38.1-44 t (GVW, Table 5);
MT (MST_{33}, MST_{23}, LDS): large mega-trucks 41 t (maximum payload) and 60 t (GVW, Table 5);
BAU: business as usual scenario using current trucks;
Standard: substitution scenario using standard LA trucks;
MST_{33}: substitution scenario using MST_{33} trucks;
MST_{23}: substitution scenario using MST_{23} trucks;
LDS: substitution scenario using LDS trucks.

3.2 Principles

To calculate the v-km that have been transferred to large from small vehicles, the load weight ratio (*R*) between the maximum load capacities of larger vehicles regarding the vehicle capacity of smaller trucks must be calculated first; this ratio is multiplied by the average driving distance travelled by the smaller vehicles. This gives an estimate of the potential v-km savings that would take place by transferring all goods from smaller to larger trucks (assuming that all goods transported in smaller vehicles are limited by weight and benefit from increasing load capacity). However, many goods transported in smaller vehicles are limited by other physical constraints (i.e., volume) or time deliveries. For this reason, a scale factor must be applied to the potential v-km savings to take into account other loading restrictions.

The proposed model for estimating the impacts of increasing the maximum weight of trucks follows five steps (Figure 2):

1. The travelled truck-kilometres (*D*) by 38.1-44 t articulated trucks (Large Articulated, *LA*) and consequent t-km, transferred from 32.1-38 t articulated (Medium Articulated, *MA*) and over 26 t rigid trucks (Large Rigid, *LR*) with weight-restricted loads, are estimated from the road data of Figure 1. It is considered that 72% of the load is weight constrained (MFO, 2010).
2. A ratio (*R*) is calculated from the maximum loading vehicle capacity (*MLVC*) of vehicles. *MLVC* is expressed as the ratio between the *MLVC* of *LA* trucks (6 axles and 29 t), and the *MLVC* of *MA* trucks (5 axles and 26 t) and *LR* trucks (4 axles, 20 t). The ratio *R* of articulated trucks is 1.12.
3. The travelled v-km with weight-constrained loads (*D*) is multiplied by the former *MLCV* ratio to estimate potential savings in loaded v-km.

4. Potential empty back hauls (*V*) are discounted from the above savings in laden v-km. To simplify the modelling of impacts, it is assumed that the percentage of empty running kilometres in the *LA* trucks is similar to that in smaller trucks (studies of Table 4 foresee increases in empty back-hauls to replenish the cargo by using larger trucks as well as increases in load weight and volume constraints).

5. Net savings in v-km are converted into economic terms. This is done by considering an average transport operation cost of 1.12 € per vehicle kilometre (MFO, 2011). Costs per v-km are not intensive to the weight of the load (Pérez-Martínez, 2009). However, operation cost per t-km decreases with the transport distance (i.e., international vs. intra-municipal trips) and the weight of the load (i.e., heavier loads, such as bulk solid mineral fuels, result in lower cost per t-km than manufactured products). Environmental cost savings were estimated using monetary values provided by the study of the European Commission on transport external costs (Maibach et al., 2008). Environmental externalities, such as related climate change, air pollutant emissions, transport accidents, and congestion, were included. As an alternative to road haulage, rail estimates were made based on Class 66 locomotives use of good environmental performance (García-Alvarez et al., 2013). The environmental externalities were valued at 1.96 Euro cents per ton kilometre for trucks (19.0 € cents per v-km) and 0.83 € cents per t-km for rail (Vassallo et al., 2012). The input values used in this study fit well the estimates of the update of the EU handbook on external costs (TRT, 2014): 17.6 €ct/v-km for EURO III 30-40 t trucks running on motorways (1.8 accidents, 8.3 pollution, and 7.5 climate change) and 0.86 €ct/t-km for urban rail freight diesel (0.6 pollution and 0.26 climate change), respectively.

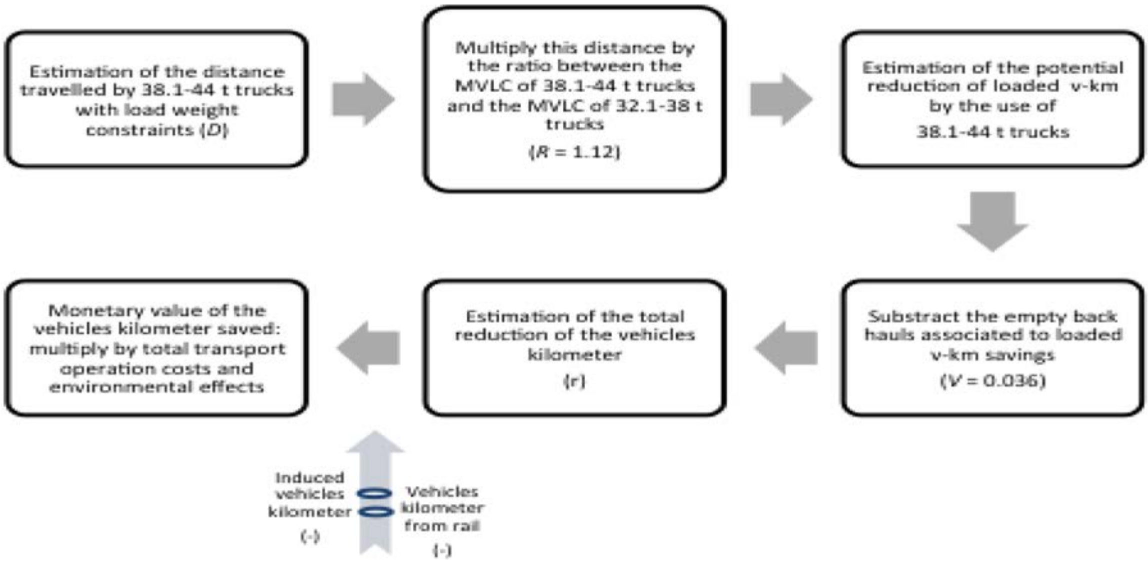

Figure 2. Analytical model used to estimate the benefits of increasing the maximum permissible gross vehicle weight (GVW) of the trucks. Note: MVLC is the maximum loading vehicle capacity (t). Source: McKinnon, 2005 and this study.

The analysis identifies the factors that are critical in the accuracy of the estimates, including:

1. Load migration (*M*) from smaller trucks immediately below *LA*.
2. Load factor (*R*) and empty running kilometres associated with larger vehicles (*V*).
3. Modal shift (*t*) and price elasticity (η) of road freight transport demand.
4. Statistics related to vehicle load constraints (*W*).

3.3 Equations

According to Figure 2, the final model for estimating the impact of the use of high productivity trucks would be represented by the following equation:

$$r\ (10^6\ \text{v}-\text{km}) = [1 \cdot (R-(1)-V)] \cdot [\frac{v \cdot M}{100 \cdot ((1)-W)}] \quad (1)$$

where R is the ratio between *MVLC* of larger trucks and *MVLC* of smaller trucks; V is the empty back hauls associated with the v-km savings expressed per unit; v is the total loaded travelled v-km, expressed in millions of v-km; M is the annual loaded v-km transferred to larger trucks, expressed as a percentage of v; $(1-W)$ is the percentage of load subject to weight constraints. The second part of equation 1 represents the distance travelled by larger trucks with load weight constraints (D).

Induced v-km i should be deducted in equation 1 as a result of lower unit prices of transport operation (in Euro/t-km). i is determined by the following expression:

$$i\ (10^6\ \text{v}-\text{km}) = \left[\frac{v \cdot M}{100 \cdot (1-W)}\right] \cdot \eta = D \cdot \eta \quad (2)$$

where, v, M, and W are the parameters shown in equation 1, and η is the elasticity of the average transport operation price related to the transport distance. v-km transferred from the railroad f should also be deducted in equation 1 as a direct result of increased weight limits of trucks and lower unit operation cost. f is determined by the following expression:

$$f\ (10^6\ \text{v}-\text{km}) = \frac{t}{f_c} \quad (3)$$

where t is the t-km transferred from rail to high performance trucks (in millions), and f_c is the loading factor of the higher performance truck. The reduction in v-km (r'), resulting from the increase in the maximum allowed weights for trucks, in million v-km per year, would be represented by the following equation:

$$\text{r}'\ \ (10^6\ \text{v}-\text{km}) = \text{r}-\text{i}-\text{f} \quad (4)$$

Finally, the truck-kilometres savings can be converted into reduced total costs - operation, maintenance, and conservation of transport infrastructure and consequent externalities - using the following expression:

$$\text{c}\left(10^6\ \text{€}\right) = \text{r}'\ \cdot (c_o + c_m + c_e \cdot f_c) \quad (5)$$

where c_o is the unit operation cost, expressed in € per vehicle kilometre; c_m is the unit cost of conservation and maintenance of transport infrastructure, expressed in € per vehicle kilometre; c_e is the unit cost of avoided externalities, expressed in € per ton kilometre, and f_c is the loading factor of the trucks.

3.4 Assumptions and application

In this is study the road freight input data used to test the model was not as important as the sensitivity of equations 1-5. Therefore, certain assumptions to the model presented in Figure 2 were considered to estimate the impacts of using larger trucks in Spain. Firstly, R took the value of 1.12 (29/26): ratio between *MVLC* of *LA* trucks (29 t) and *MVLC* of immediately smaller trucks (26 t); this ratio increased to 1.54 for *MT* trucks. V took the value of 0.04 and 0.07 for *LA* and *MT* trucks, respectively (MFO, 2010); the total volume of laden kilometres v was 25,487×10^6 v-km (MFO, 2010). Migration factors M, expressed as a percentage of v, were defined to determine total load transfers from smaller vehicles to *LA* and *MT*: 10%, 7.5%, and 5 %; the migration factors were 80% for *LR* and 20% for *MA* trucks, according to the Spanish road freight data during the period from 1997 to 2008 (Figure 1).

Secondly, another important assumption of using larger vehicles is the effect on the supply-chain operations. Thus, not all freight commodities can be consolidated in the same truck and the v-km reduction obtained from the methodology of Figure 2 could be overestimated. Likewise, it is also necessary to consider the types of commodities that are not limited by weight capacity, but volume capacity *W*. In this study, it was assumed that only manufactured products were not subject to weight constraints. The analysis considered the *W* factor equal to 0.28. This proportion will be increased, as the larger trucks will be used more intensively, decreasing v-km reductions. The *W* factor considered in the Spanish case study was similar to the proportion of load not subject to weight constraints applied by the Freight Transport Association of Carriers (FTA, 2004). This Association estimated the fraction of v-km not limited by the maximum weight by 0.29 (36.8% of loaded v-km travelled by British trucks under 38 t GVW were not restricted by weight and volume constraints, and 8.2% were not restricted by volume). The equation 1 used the complementary equation to the *W* factor, (*1-W*) ≈0.72, as a surrogate of the weight restricted goods, and used the factor as scale coefficient.

Thirdly, scenarios were defined as function of the annual loaded v-km transferred to larger trucks (*M*): 5 % low scenario (83% for *LR* and 21% for *MA* trucks), 7.5% medium scenario (90% from *LR*, and 40% from *MA* trucks), and 10% high scenario (95% from *LR* and 60% from *MA* trucks). The variation between scenario migration factors was due to the fact that the vehicle loading (for a loading capacity less than 29 t) can be subject to different constraints (i.e., volumetric, timing, and delivery). Scenarios also reflected the induced v-km (*i*), as a result of decreasing transport prices and the potential transfer of t-km from rail to road (*t*). The rail transport demand in Spain has fallen during the 1997-2008 period (-3%) from 11.488 to 11.116 10^6 t-km. Considering a loading factor f_c of 13.6 t-km per v-km of LA trucks (MFO, 2010), 24.5 10^6 v-km per year could have been transferred from rail to road (*f*). Therefore, transfer levels of t-km from rail to road (*t*) must be developed to estimate a reduction in v-km: low (3% of the t-km are transferred to road, lower loss scenario, 333 10^6 t-km-22.2 10^6 v-km), medium (6% of the t-km are transferred to the road, 667 10^6 t-km-44.5 10^6 v-km), and high (9% of the t-km are transferred to the road from the rail, higher loss scenario, 1,000 10^6 t-km 66.7 10^6 v-km).

Finally, the vehicle kilometres of the scenarios were transformed to monetary values using the unit costs operational (c_o), maintenance (c_m), and external costs (c_e), from the EU handbook optimized for Spain; in this study, c_o took the value of 1.12 (MFO, 2011); c_m took the value of 0.05,

Table 6. Summary table including parameters used in equations 1-5

			Traffic			
Notation	[1]v	[2]t				
Units	(10^6 v-km)	(10^6 t-km)				
Value	25,487	333-1,000				
Source	(MFO, 2010)	this study				
			Logistics			
Notation	[1]*MVLC*	[1]*R*	[2]*M*	[2]*W*	[2]*V*	[1]f_c
Units	(t)	(no units)	(%)	(no units)	(no units)	(t/v)
Value	[3]26-[4]41	[3]1.12-[4]1.54	5-7.5-10	0.28	[3]0.04-[4]0.07	[3]13.6-[4]15.0
Source	(MFO, 2010)	(MFO, 2010)	this study	(MFO, 2010; FTA, 2004)	(MFO, 2010)	(MFO, 2010)
			Costs			
Notation	[1]c_o	[1]c_m	[1,5]c_e	[2]η		
Units	(€/v-km)	(€/v-km)	(€ cents/t-km)	(no units)		
Value	[3]1.12-[4]1.15	[3,4]0.05	[3]1.96	0.12		
Source	(MFO, 2011; Vassallo et al., 2012)	(BRR, 2007; Vassallo et al., 2012)	(Maibach et al., 2008; Vassallo et al., 2012)	(McKinnon, 2005)		

[1] Input data; [2] assumptions; [3] corresponding to the *LA* trucks (Table 4); [4] corresponding to the *MT* trucks (Table 4); [5] in the presence of congestion, this cost is increased to 0.30 €/v-km (Maibach et al., 2008; Vassallo et al., 2012; TRT, 2014).

based on former studies (BRR, 2007; Vassallo et al., 2012), and c_e took the value of 1.96 (Vassallo et al., 2012). The induced demand (*i*) also depended on the elasticity of the transport operation cost related to the transport distance (η), which took the value of 0.12 in this study (McKinnon, 2005) and was equivalent to *i* equal to 16.4×10^6 v-km. The parameters used in the estimation of the impacts are summarized in Table 6. The parameters were grouped by traffic (*v* and *t*), logistic (*MVLC*, *R*, *M*, *W*, *V*, and f_c), and cost factors (c_o, c_m, and c_e).

4. Results

4.1 Vehicle-kilometres

The total loaded v-km saved by larger trucks (*r*) can be estimated using the Spanish road freight data, the model represented in Figure 2, and the parameters from Table 6. For instance, the total v-km in 2008 of Figure 1 (25,487×10^6) can be multiplied by the increasing percentage of loaded kilometres annually transferred to LA trucks from 1997 onwards (*M*=5%, low scenario). Not restricted weight loading should be deducted to this estimate (*W*=0.28). The estimation yielded 905.5×10^6 v-km (*D*). Considering a *MVLC* ratio of 1.12, total estimated v-km savings were 108.7×10^6 (*D**0.12). Empty back-hauls *V* associated with the v-km saved should be deducted from this amount: 3.6% more empty running kilometres as a result of analysing the difference between the percentages of empty running kilometres of *LA* trucks (27.4%) and *MA* trucks (23.8%). These percentages of empty mileages were similar to other markets and studies (20-40%) (FTA, 2004; McKinnon, 2005). Finally, 78.2×10^6 v-km per year could have been saved in 2008 (*r*). From this estimate, induced transport (*i*) and transfer from rail (*f*) should be deducted.

For different modal and loading shift levels, Figure 3 shows resulting v-km saved from increasing truckload. According to the mean estimate, based on average levels of modal shift from rail to truck (6%) and loading shift (*M*=7.5%), *r′* was reduced by 52.4 million v-km (once deducted the induced traffic *i*, 16.4 million v-km, and the transport transferred from rail *f*, 49 million v-km), roughly equivalent to a daily saving of 254 return trips between Barcelona and Madrid. Even in the worst-case scenario, a combination of lower level of loading shift and consolidation to *LA* trucks and higher modal shift from rail to road, the increased weight of trucks still had a positive effect on the reduction in kilometres (3.6 million v-km).

In the *MT* scenarios, estimates of v-km savings were increased 10 times compared to the base cases (360.5 to 816.3 million v-km). Therefore, the ratio between the maximum load of MT (41.1 t) and the maximum load of *MA* and *LA* trucks (26.8 t), *R*=1.54, was raised regarding the base case (37.6%), resulting in a significant increase in the saved v-km. As in the base case, empty back hauls *V* associated with the saved v-km were deducted. Empty back hauls were estimated to be doubled in the base case (*V*=0.067), based on the comparison of the *MR* and *LA* trucks in the base case. Initially, same laden v-km (*v*=25,487 10^6), loading transfer levels *M* to high performance trucks (5, 7.5 and 10%), and intermodal shift scenarios t from rail to truck (3, 6, and 9%) were considered. Also an increase in the loading factor f_c from 13.6 t per vehicle to 15 t was considered (Table 6). As in the case of standard trucks, the proportion of the load not subject to weight constraints *W* was 28.6%, and the operation cost related to transport distance elasticity η was equalled to 0.12 (equivalent to an induced demand *i* of 16.4 10^6 v-km).

According to the mean estimate, based on average levels of modal shift from rail to truck and loading shift from smaller trucks to mega-trucks, the annual transport demand of heavy vehicles was reduced by 584.4 million v-km (Figure 3), equivalent to a saving of 2,833 daily back trips between Barcelona and Madrid.

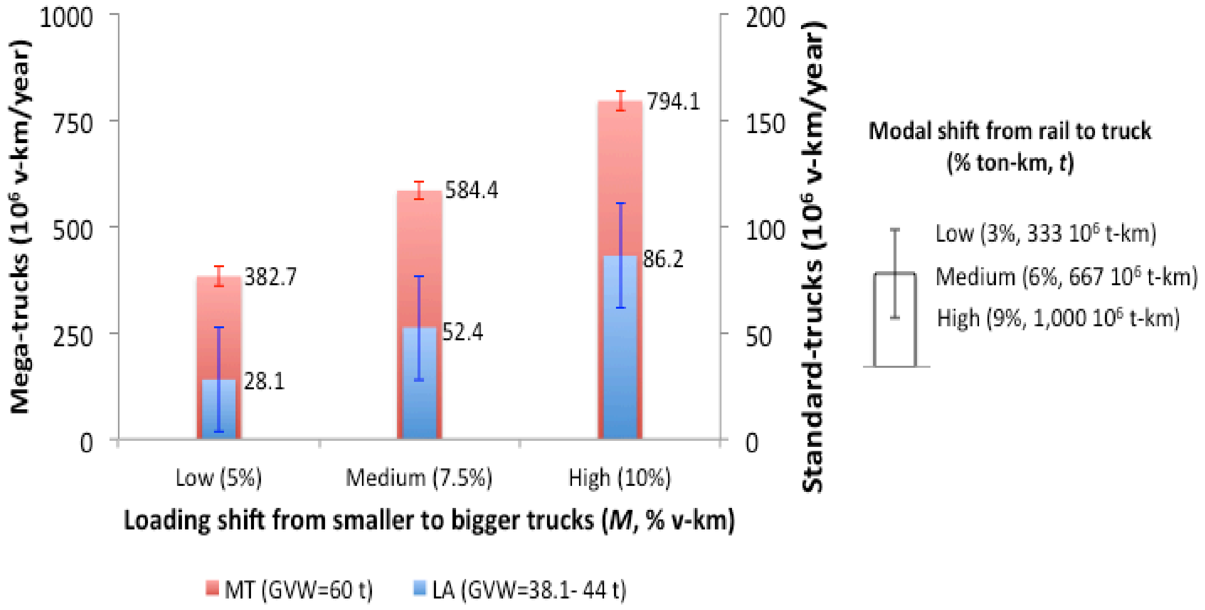

Figure 3. Estimates of vehicle kilometre reductions, resulting from the increase in the maximum allowable gross weight of trucks (in million v-km per year), by loading and modal shifts.

Notes: Mega (MT, GVW=60 t) and Standard (LA, GVW=38.1-44 t) trucks from Table 4 were used; error bars summarize the relative variability in vehicle kilometre reductions due to modal shift from rail to truck (% ton-km, t): High (9%, 1,000 10^6 t-km), Medium (6%, 667 10^6 t-km), and Low (3%, 333 10^6 t-km).

4.2 Costs

Figure 4a shows the balance between the current costs of road freight transport, called Business as Usual Scenario (*BAU*), and the costs of standard *LA* and each of *MT* vehicle scenarios (Table 4). The balance considered average levels of loading shift from road and rail (7.5% v-km migrated to bigger from smaller trucks and 6% t-km to road from rail). In the scenarios, 52.4 (0.2%) to 584.4 10^6 v-km (2.3%) were saved (Figure 3). These cost estimates were justified by previous studies (Christidis and Leduc, 2009; Pérez-Martínez et al., 2010; McKinnon, 2007; OECD-ITF, 2010) and considered scenarios contained in the logistic plan of the Spanish road freight transport (MFO, 2007).

The average unit operation cost according to the Spanish observatory of freight costs was 1.12 € per v-km for *BAU* and standard scenarios (MFO, 2011). This cost was increased in the case of *MT* scenarios up to 1.15 € (2.4%, Table 6 and Figure 4a), due to higher time and variable costs (MFO, 2011; Vassallo et al., 2012). Unit maintenance costs slightly varied when comparing *BAU*, standard, and *MT* scenarios (0.050 vs. 0.052 € per v-km, 0.4%). Unit road freight external cost accounted to 19 € cents per v-km (MFO, 2011), equivalent to 1.96 € cents per t-km (Pérez-Martínez and Vassallo, 2013), in the case of the *BAU* and standard scenarios. This cost was increased to 30 € cents per v-km considering congestion (Maibach et al., 2008).

Although in all the scenarios it was expected to relate the reduction in laden v-km (Figure 3) with the external costs, the reduction in v-km did not offset the higher specific fuel consumption and emissions of *MT* truck scenarios (Figure 4b). The external costs increased due to higher emission factors (EFs) of *MT* compared to *BAU* and *LA* scenarios, and also to the increase in grams of CO_2 and atmospheric pollutants per v-km of empty mega-trucks (García-Alvarez et al., 2013). Thus, *MT* consumed more fuel and emitted more pollutants than *BAU* and standard scenarios (Figure 4b), and the external cost per kilometre increased by 3.3%. Consequently, the use of *MT* increased the external costs in all the scenarios by 1%. In this estimation, the external costs associated with traffic congestion were not considered. Congestion costs were slightly lower in the *MT* scenarios, as a result of the reduction in v-km (0.110 vs. 0.109 € per v-km) (Pérez-Martínez et al., 2010). v-km savings also implied lower number of traffic accidents that offset the increase in road accidents caused by larger *MT* trucks: accident unit costs remain constant in all scenarios, around 0.03 €/v-km.

Finally, Figure 4a shows the balance of total costs regarding the *BAU* scenario. Only in the *LDS* scenario there was a significant cost saving of 65.2 M€. In the standard scenario, there was a small saving of 6.8 M€. Oppositely, the MS_{33} and MS_{23} scenarios produced extra costs of 43.6 and 12.4 M€ respectively. Considering congestion costs associated with v-km savings, there were positive impacts in the scenarios: 13.0 (standard), 25.4 (MS_{33}), 56.6 (MS_{23}), and 134.2 M€ (*LDS*). Figure 4a also divided total costs by operation, maintenance, and external costs. Thus, total operating costs fell by 0.3%, for the *LDS* scenario. In the other *MT* scenarios, total operation costs slightly changed. Maintenance costs decreased by 2.0% in the *MT* scenarios. Total operation costs had barely risen in the case of the standard scenario (0.02%), contrary to the maintenance and external costs, which fell by 0.2%. The total consumption increased by 0.7% in the *MT* scenarios as CO_2, NO_x, and PM_{10} emissions. In the case of the standard scenario, consumption and associated emissions decreased by 0.3%.

5. Road network

Technical constraints and the objectives of the intermodal transport infrastructure plans and policies determine the niche market of larger trucks in Spain (PEIT, 2004; SPIM, 2008; REPLICA, 2010). Although this study explores the impact of larger trucks, it does not deal with the last kilometre where only smaller trucks might be able to make delivers. Consequently, this analysis focuses mainly on main roads in Spain (Figure 5) and provides a geographical breakdown of the impacts of larger trucks on particular corridors. There is a South-North (SN) corridor that connects the seaports of Huelva and Cádiz with France, through the logistic nodes of Seville, Madrid, and Bilbao. In this corridor, there is one North alternative (N), which connects Bilbao with Santander and Oviedo. There is a Central North East (C-NE) corridor that connects Madrid and Barcelona with France. There is a Central East (CE) corridor that connects Madrid and Valencia, and an alternative South-North East (S-NE) corridor that connects Murcia with France. Table 7 shows the transport data from the main road freight corridors and logistics nodes in Spain (MFO, 2010). We recommend the use of larger trucks in high-capacity roads (AADT >13,000) and country-corridors as depicted in Table 7. In the Spanish high-capacity network (13,500 km), AADT from HDVs exceeds 2,000 vehicles per day and produces around 9,855 10^6 v-km per year (7,440×10^6 laden v-km, 29% of total). This traffic gives an estimate of the transport map and potential niche of larger trucks and other high productivity vehicles.

The potential for reducing t-km and the transport distance from the use of larger trucks is shown by the distribution and efficient relocation of the origin and destination pairs in the transport network in Figure 5. The 5 largest origins and destinations (O/D) pairs in Spain coincide with the provinces and the logistic nodes located at Barcelona, Madrid, Murcia, Seville, and Valencia. Only the goods included in these 25 O/D pairs account 22.9% (486×10^6) and 11.7% (28,455×10^6) of the total tons and t-km respectively (MFO, 2010). The presence of cross trading in these O/D pairs, activities which start and finish at different locations, represents opportunities to reduce transport by 11,881 10^6 t-km (4.9% of total) and the average transport distance from 58.4 to 34.1 km (-41.8%) respectively. For an energy intensity of 1.96 MJ/ton-km (Pérez-Martinez, 2010), the reduction on transport could decrease the total energy consumed at these O/D pairs from 55.8 Tera-joules (TJ = 10^{15} J) to 32.5 TJ (-4.5% of total energy related to road freight transport). Therefore, transport requirements and energy consumption could be reduced with appropriate measures of redistribution of goods and modal shift, meeting targets for ameliorating emissions (UNCCC, 2010).

International studies suggest that a small amount of goods can be diverted from alternative modes to larger trucks (Oum et al., 1990; Pickrell, 2000). A study in the UK estimated that GVW increased from 38 to 44 t could induce a shift of 5-20% of the t-km transported by rail to road depending on the taxes applied to trucks (CIT, 2000; DFT, 1998). Bergqvist and Behrends (2011) studied policies to allow for larger-trucks for pre-and post-haulage in connection to intermodal transport, not only for direct road shipments, in order to improve cost-efficiency of the door-to-door intermodal transport chain.

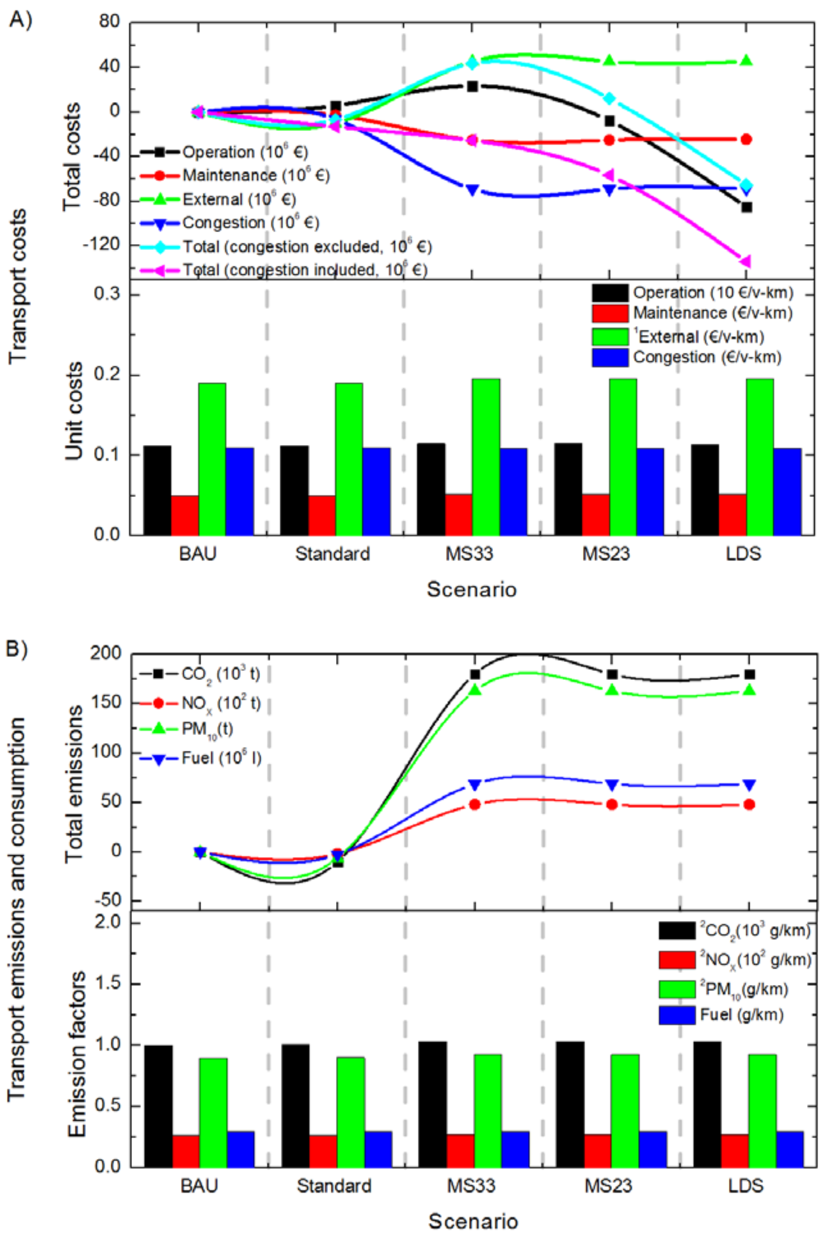

Figure 4. *Road freight transport costs and emissions.* ***A)*** *Operation, maintenance, external, and congestion cost balances of the aggregated freight road transport according to substitution scenarios (10^6 €, 2008 constant prices).* ***B)*** *CO_2 (10^3 t), NO_X (10^2 t), PM_{10} (t) emissions and fuel consumption (10^6 l).*

Notes: [1] External costs related to Carbon Dioxide (CO_2) and air pollutants (Nitrogen Oxides, NO_x, and Particle Matter smaller than 10 micrometres, PM_{10}) were estimated from the total emissions using the following unit prizes (MFO, 2010; Pérez-Martínez and Vassallo, 2013): 25 (€/ton of CO_2) 2,600 (€/ton of NO_x), 16,500 (€/ton of PM_{10}); [2] Consumption and emission factors coming from Ortega et al. (2011).

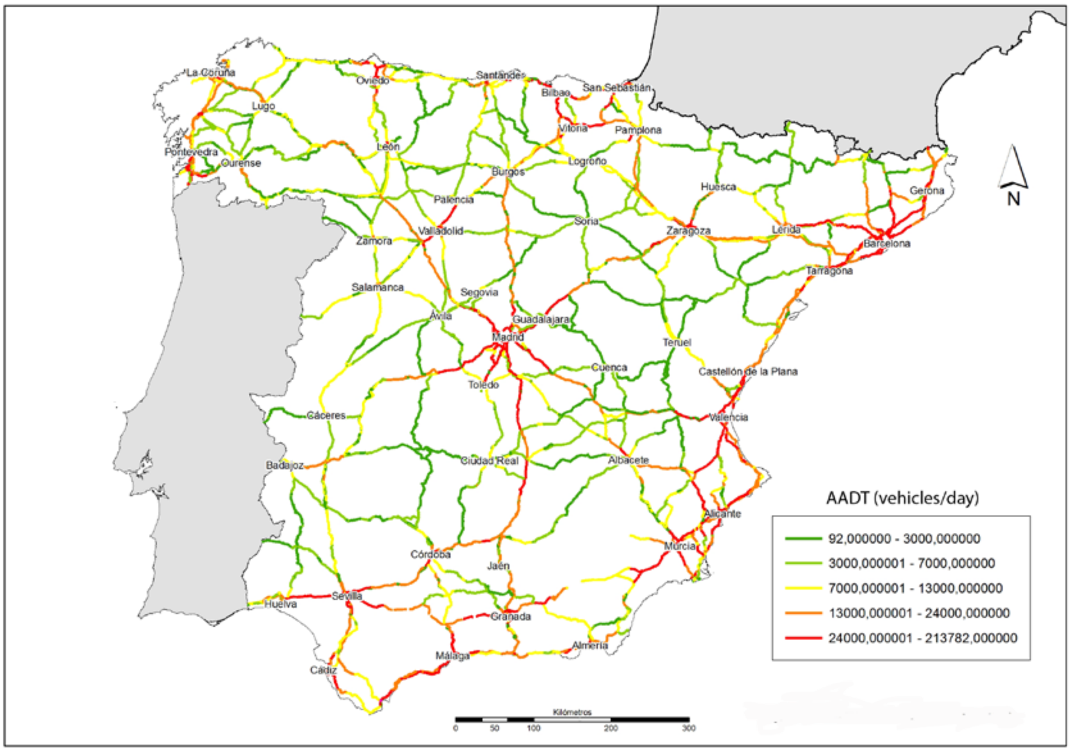

Figure 5. Road-network in Spain by AADT (vehicles/day). Source: MFO, 2009; and this study.

Table 7. Road freight transport and main highway corridors in Spain

Section/node Origin	Destination	AADT (veh/day)	Road type	HDV (%)	HDV (veh/day)	Demand (10^6 tkm/year)
S-N corridor						
Cádiz	Seville	>20,000	Toll	14.4	>2,880	n.d.
Huelva	Seville	>20,000	Free	16.1	>3,200	n.d.
Seville	Madrid	15,000	Free	16.1	2,415	[2](563+860)
Madrid	Irun	>20,000	Toll	14.4	>2,880	n.d.
N						
Oviedo/Gijon	Santander	15,000	[1]23 km	10.6	>2,000	n.d.
Santander	Bilbao	>20,000	Free	16.1	>3,200	n.d.
Bilbao	Irun	>20,000	Toll	14.4	>2,880	n.d.
C-NE						
Madrid	Zaragoza	>20,000	Free	16.1	>3,200	n.d.
Zaragoza	Lerida	15,000	Toll	14.4	2,160	n.d.
Lerida	Barcelona-Junquera	>20,000	Toll	14.4	>2,880	[3](1,476+1,776) [4](399+810)
C-E						
Madrid	Valencia-Murcia	>20,000	Free	16.1	1,610-3,220	[5](802+1,345) [6](280+398)
S-NE						
Murcia	Gerona	>20,000	Toll	14.4	>2,880	[7](786+629) [8](1,298+928) [9](594+645)

[1] Conventional road segment between Oviedo and Santander. [2] Seville-Madrid, [3] Madrid-Barcelona, [4] Seville-Barcelona, [5] Madrid-Valencia, [6] Murcia-Barcelona, [7] Valencia-Barcelona, [8] Murcia-Valencia, and [9] Madrid-Murcia round trips. These corridors represent 23.7% of the total Spanish high capacity network: 3.239 km. Source: Oficemen, 2009; MFO, 2009.

6. Sensitivity analysis

The results presented in this analysis represent special case studies and scenarios, and may be different in other cases. The most relevant contribution of this study is not the results per se, but equation 5 used to calculate them. This equation makes it possible to estimate the sensitivity of estimates based on the factors and parameters on which it depends to explain the differences between different types of vehicles and study scenarios. The sensitivity analysis also provides a measurement of the accuracy of the estimates, shown by the contribution to the variance and correlation coefficients (Table 8). The variance of the output of the model is decomposed into fractions, which can be attributed to the different parameters and factors of equation 5. For instance, 40% of the output variance is caused by the variance in the *MVLC* ratio (*R*), and 20% due to operation of standard-trucks. *R* and operation of standard-trucks are negatively correlated with total costs. On the other hand, operation costs related to larger trucks are positively correlated with total costs.

Table 8 shows that total costs are mainly influenced by the *MVLC* ratio (*R*). The increase in the *MVLC* ratio by 20%, using the load capacity of vehicles, decreases the total costs significantly by 412.1%. However, *MVLC* ratios are difficult to increase without increasing the maximum size of trucks, unlike the railway that can easily increase capacity by adding new wagons (García et al, 2013). Transport logistics also should be considered when trying to increase *MVLC* ratios. Operation costs are the second most important parameters. Increasing operation costs of standard vehicles and larger-trucks by 20% cause transport costs to decrease by -294.3% and increase by 278.3% respectively. The operation costs are related to consumption levels, which depend largely on the type of route profile (García et al, 2013). Increasing vehicle-km migrated to larger-trucks (*M*) by 20% causes transport costs to decrease by -238.2%.

The other parameters in equation 5, unit external costs, congestion costs, and t-km diverted from rail to road (*t*), have a smaller influence on total costs. In this study, it is estimated that a 20% increase and decrease in congestion costs involves an increase and reduction in total costs by 73.6% and -75.6%, in both standard vehicles and larger-trucks scenarios, respectively. Similarly, a 20% increase in t-km diverted to road involves an increase in total impact by 32.7%. Reductions in operation costs, resulting from increasing weight limits and use of larger trucks, can induce additional demand of freight transport and explain the migration of the goods to larger trucks.

Table 8. Sensitivity analyses for transport cost (M€) regarding parameter changes (equations 1-5 and Table 6)

Input factors and parameters (equations 1-5)	Variance contribution	Correlation range
Ratio MVLC mega truck/ MVLC standard truck	0.40	-0.58
Operation cost standard truck (€/v-km)	0.20	-0.41
Operation cost larger truck (€/v-km)	0.18	0.39
v-km migrated to larger trucks (10^6 v-km)	0.14	-0.35
External costs larger trucks (€/v-km)	0.04	0.19
Congestion cost standard truck (€/v-km)	0.02	-0.12
External costs standard truck (€/v-km)	0.01	-0.11
Transport volume diverted to road from rail (10^6 t-km)	0.01	0.09

7. Discussion and recommendations

Scenarios related to the use of larger-truck have lower unit transport costs, through the ratio *R* between the *MVLC*, and depend on the total diverted (*M*) and reduced (*r'*) v-km. On the other hand, the use of larger-trucks increases energy consumption and associated emissions, and induces more heavy traffic (*i*) and transfers goods from the railroad (*f*). This study is based on

PRFTS data from the 1997-2008 period. This period represents a time with increasing economy and transport activity. According to projections of scenarios resulting from potential use of larger trucks (MS_{33}, MS_{23}, and *LDS*), further consolidation of loads could have slightly positive economic impacts by reducing operating transport costs and congestion. Costs are connected with sustainability aspects of transportation. Connection between the trade-offs presented in this study and sustainable transportation goals and objectives are: slight decrease on transport operation costs and congestion times vs. increase on transport external costs (CO_2 and pollutant emissions and accidents), empty back hauls and induced demand.

New technologies and policies applied on trucks engines have reduced the CO_2 and PM_{10} emissions from transportation sector in EU after 2008. The results would likely change if the proposed larger-trucks were related to 25.25 m, but with the same weight-restrictions as the current *LA* truck systems. In this case, mostly manufactured and volume constrained products would be affected by transport policy measures.

The projections of the scenarios of this study are subject to the variability of the estimation parameters, especially regarding the environmental factors. Thus, induced road transport (*i*) involves greater environmental impacts that offset in part the decrease in operating costs. Sensitivity analysis can be used to evaluate the contributions of inputs to the variance of estimates. The results of the analysis show that inputs such as tons diverted from rail to road (*t*), v-km migrated to mega-trucks (*M*), and *MVLC* ratios have significant influences on the total costs. The total costs are more sensitive to the ratio between the maximum load of larger and standard trucks. Unit operation cost of standard vehicles is the second parameter with the highest influence on total impact.

From the methodology proposed in this analysis, we can make some recommendations for improving and applying the analysed approach in terms of data, location, and model assumptions. The first recommendation is that loads could be shifted to larger vehicles depending on the underlying O/D pairs and shipment sizes. The size increases with distance and is an important explanatory variable of freight modal choice (short distance shipments tend to be made in small sizes). As distance increases, the costs of transport and the shipment sizes increase as well (Figure 6). The variation in each field of Figure 6 is due to the different types of goods. The average elasticity for transport cost of 8 cents per ton kilometre is equal to -0.12, indicating that for 1% reduction in the transport cost the average transport distance, and thus increasing the quantity of goods carried (in t-km), could be increased by 0.12%. By increasing the GVW, the transport cost could be reduced (scale effect), making it possible to transport goods to longer distances (distance effect). The issue is that small shipments are not likely to use larger trucks or rail. Moreover, small shipments dominate the short range of distances. For that reason, aggregating all commodities flows and estimating the number of larger trucks is appropriate only for medium and long distance shipments (interstate and international trips over 300 km).

The second recommendation is related to the transport costs: in addition to the cost of operating the vehicles, transport companies compute the value of delays using the generalized travel costs (i.e., transfer times). These additional costs, when levied to shippers and consignees, could be important constraints to use larger trucks (reducing the number and frequency of deliveries). The third recommendation is related to the Miner's rule applied in Table 5, which could underestimate the infrastructure impacts of larger-trucks and explain the lack of sensitivity in infrastructure costs. In this sense, the Federal Highway Administration (FHA) produced a major technical report on heavy truck lanes and pavement health track reflecting more realistic values (FHA, 2010). The fourth recommendation coming from the study's approach is related to the back-haul assumptions and their influences in the modelling results. The assumptions are founded on the Spanish base case and in the back-haul distance comparison between *MR* and *LA* truck systems. In the future, it could be also expected that larger trucks would lead to better load factors and less empty back-haul distances because of higher costs per km that would motivate carriers to search for more contracts and return loads. This is the case of the Nordic countries where carriers using larger-trucks have now market shares of 17% (of total t-km) and empty running of around 15% lower than market averages (Backman and Nordstrom, 2002). The last recommendation is related to the other reasons for the current road trading patterns in Spain that are not considered here and would constrain attempts to redistribute and reduce goods flows in the future. This analysis does not deal with the last kilometre, and focuses mainly on main roads and particular corridors. These five recommendations could be an opportunity for future research.

The average vehicle taxes (689 € per vehicle per year) and the differentials between vehicle classes fell between 2001 and 2008, promoting the use of larger trucks (Oficemen, 2009). However, these taxes constitute a small percentage of total costs (CIT, 2000). Thus, operating costs decrease with increasing average transport distance, as a result of improved energy efficiency. Costs also vary for each type of goods, increasing with the energy intensity and in terms of the intrinsic value of the goods carried: high-value manufactured products (average transport and shipment values of 138 and 1,050 € per t, respectively) have energy intensities higher than 1.4 MJ per t –km (Figure 7). The variation in each field of Figure 6 - intra-municipal, national, and international - is due to the different types of goods transported: 0 agriculture products and livestock, 1 foodstuffs and animal feeds, 2 solid mineral fuels, 3 petroleum products, 4 ores and metal waste, 5 metals products, 6 crude and manufactured minerals, building materials, 7 fertilizers, 8 chemicals, and 9 other goods and manufactures.

The increase in maximum GVW could promote greater centralization of economic activity and greater dispersion of products, which generate greater movement of goods by road (Schipper et al., 1997; Pickrell and Lee, 1998). Between 1997 and 2008, laden v-km increased from 13,652 to 25,450×10^6 (5.8%/year), above the growth between 1980 and 1997 (less than 3%). Laden v-km travelled by larger trucks increased by 156×10^6 per year (14.2%), above the historical average (2.5%). In this study, 16.4×10^6 v-km of induced transport *i* (7% of current growth) have been estimated. Therefore, there is little evidence that the increase and use of larger vehicles can generate significant additional transport demand (CIT, 2000). Furthermore, the use of different types of vehicles would induce a different transport demand depending on mean operation price elasticity (η) in relation to transport distance. This elasticity was considered constant in all scenarios (-0.12) and was consistent with the elasticity found by other authors (CIT, 2000; Janic, 2007). However, the sensitivity analysis of this study shows that the elasticity value should be increased to -0.90 to eliminate the positive effect of v-km savings under the scenario conditions.

The study gives no information about the goods that have been shifted from the railway as a result of consolidation and reduction in transport operation costs. There has been a decrease in t-km transported by rail (-3.2%) from 11,488×10^6 t-km in 1997 to 11,116×10^6 in 2007. During this period, the modal share of rail has decreased from 10.5% to 4.3% (RENFE, 2008). This decrease compromises the rail business, and the impact of using larger trucks could only be corrected by lowering the prices of rail transport operations, offsetting the reduction in road taxes from LA trucks (Vassallo, 2010; DOT, 2000). The decrease in rail also compromises the Spanish infrastructure transport plan, which aims to promote rail freight growth to 80-100% (Monzón, 2010). This growth, based on high-density primary products, depends on the ability of the Spanish infrastructure administrator to compensate the sector by reducing the fee for track use. The reduction in rail freight between 1997 and 2007 was not due to the increase in efficiency in the trucking by higher capacities, but to the inadequate management of the rail freight transport itself. However, it is very difficult to account the effect of increasing the use of high productivity vehicles on rail, given the current situation and business management of the rail sector (Vassallo and Fagan, 2007)

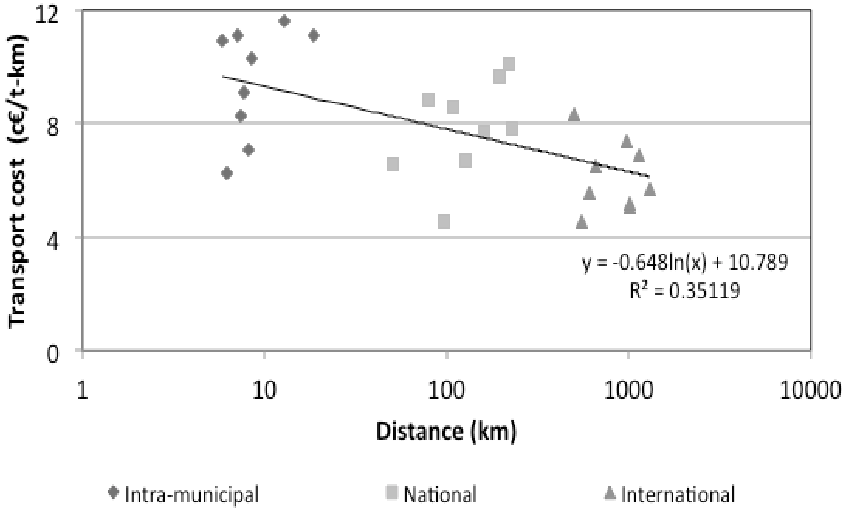

Figure 6. Operation cost and average transport distance on a logarithmic scale for Spain (2006).
Notes: the transport cost (X) elasticity regarding the average transport distance (Y) is calculated by the following expression $\eta_{x,y}$ = ∂Y/∂X*X/Y = -0.648/Y; the linear fit reported the square correlation coefficient, the slope, and the intercept. Source: MFO, 2009; and this study.

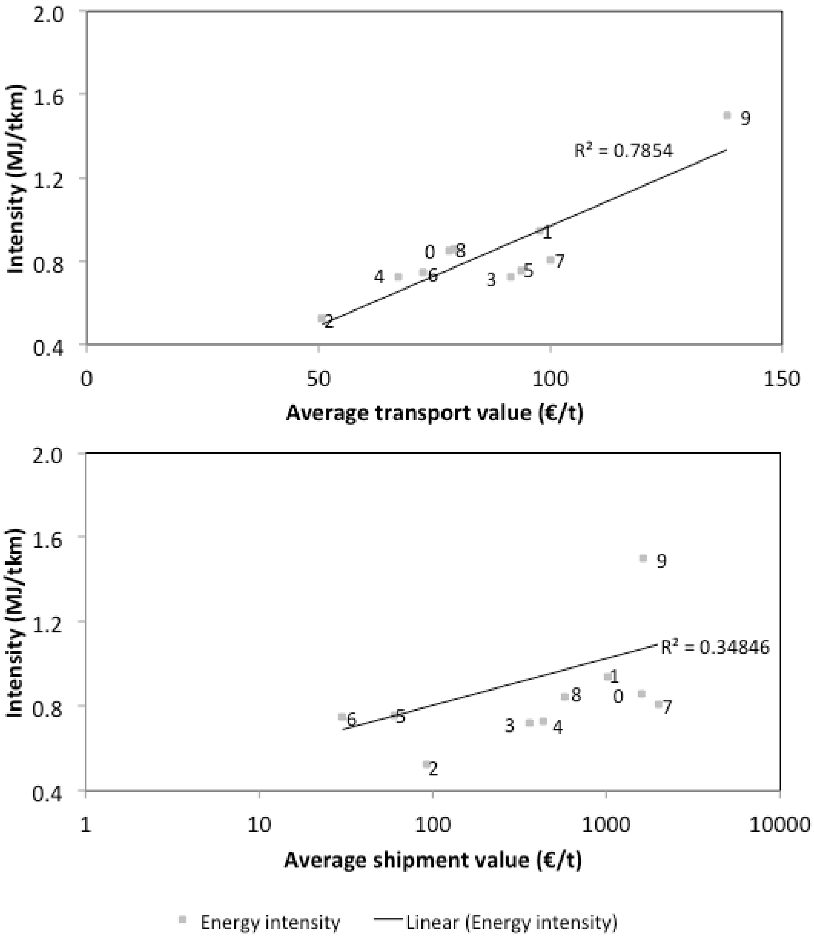

Figure 7. Energy intensity of road transport operations in Spain, average operation transport cost (€/t, upper graph), and average value of the shipment on a logarithmic scale (€/t, lower graph), 2006. The linear fits reported the square correlation coefficients. Source: MFO, 2009; and this study.

8. Conclusions

This study attempts to develop an impact model for road freight transport and conduct a sensitivity analysis on model parameters. The study presents a novel approach to defining impacts of road freight transport given different policies and measures. The model by itself is a good addition to estimate larger-truck impacts connected with sustainable transportation topics. The empirical results of this analysis reflect slight impacts related to the use of larger trucks: saving 52.4×10^6 v-km per year, 13.0 M€ per year (considering congestion), and avoiding 10.0×10^3 t of CO_2 (0.18×10^3 t NO_x and 6.2 t PM_{10}). Retrospective economic and environmental analysis of the estimated savings reflects that there has been a progressive saving increase since 1997, as road freight sector has been adjusted to maximum weights of 38.1-44 t. In 2008, approximately 78.0×10^6 v-km per year were saved, saving 86.1 M € per year (29.7×10^6 l fuel) and avoiding 78.6 10^3 t of CO_2 (2.07×10^3 t NO_x and 70.0 t PM_{10}).

The results of this study show that, considering the congestion avoided and taking into account both the effects of induced traffic and the transfer of goods from the rail, increasing the weight of the trucks could produce benefits of 25.4-134.2 M€ per year, depending on the mega-truck scenario. Only scenarios MS_{23} and *LDS* produce economic benefits as a result of operating cost savings (7.7 and 85.0 M€ per year respectively). Similarly, in the current scenario there is an external cost saving equals to 10.0 M€ per year. The mega-truck scenarios overrun 45.3 M€ per year external cost as a result of increasing fuel consumption (68.9 10^6 l) and associated emissions (180×10^3 t CO_2, 4.8×10^3 t NO_x, and 163.2 t PM_{10}). From the projections of this study, it can be concluded that increasing the maximum GVW results in economic benefits close to 74.2 M€ (average of the three mega-truck). However, the variability of the factors and parameters reflect a large variation in estimates (standard deviation of ± 696 M€). The large variation in the estimate overshadows the potential economic benefits of using larger trucks.

Migration of goods on larger trucks can continue as indicated by the fact that in 2008 only a migration rate of 5% was reached. Thus, the reduction in v-km per year could stabilize at around 125 million truck kilometres within 5-10 years (60% above current levels). Moreover, infrastructures in Spain are ready for more high performance truck traffic, standardized weight limits along key corridors, and maintenance of the existing security requirements.

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