Exploring the relationship between truck load capacity and traffic accidents in the European Union

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ABSTRACT

Applying econometric techniques to EU28 panel data and controlling for explanatory variables such as road types, we find that increased truck load capacity does not necessarily aggravate road traffic safety. Specifically, heavy trucks do not seem to be linked with greater numbers of traffic fatalities/accidents, medium trucks appear to be the worst performers in terms of fatalities, and light trucks seem to be the worst for accidents. In summary, our results clarify the complex relationship between truck load capacity and road safety, pointing to the existence of a negative correlation for accidents per capita and an inverse U-shaped curve for fatalities per capita.

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1. Introduction

Road freight traffic is a key part of the European common market. However, the external costs associated with motorized transportation have prompted the European Union (EU) to develop a more efficient, sustainable and safer transport system within a framework of liberalization and competition (e.g., Koliousis et al., 2013).

Additionally, as Sanches Rodrigues et al. (2015) explain, certain features of modern European supply chains (i.e., the high concentration of production seeking to exploit economies of scale, and large volumes of freight transported long distances across the continent) have led practitioners to call for an increase in truck dimensions. The fact that road freight transport seems to be a more flexible mode for door-to-door service has contributed to freight consolidation in larger and heavier vehicles (McKinnon, 2008).

However, from a road safety approach, the literature has generated unclear evidence as to the impact of large truck traffic (Carson, 2011). Therefore, the current article explores empirically how different truck configurations impact European road safety, with particular emphasis on the effect of heavy truck traffic compared to other truck categories.

Authors such as Stein and Jones (1988) consider that truck accident involvement may be affected by several factors (i.e., truck operating characteristics, such as load or size; truck driver characteristics, such as age or work conditions; weather and road conditions); while others, such as e.g., Jones et al. (1983) and Vallette et al. (1981), state that vehicle weight and loading variables are essential parameters for vehicle dynamics, roll stability and handling characteristics. Thus, we assess the safety

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differences between three different truck types on the basis of load capacity (i.e., light, medium and heavy trucks) in terms of traffic accidents and fatalities.

In general, the earlier literature has broadly shown that truck road accidents are a significant issue. According to Corsi et al. (2014), due to their economic and social costs, road traffic accidents involving trucks have caught the attention of governments, academicians and society in general. In recent years scientific papers have analyzed a vast array of issues. For example, Britto et al. (2010) and Cantor et al. (2008) have investigated the relationship between motor carrier safety and financial performance; Cantor et al. (2009, 2010), Hickman and Hanowski (2011), Mejza and Corsi (1999) and Mejza et al. (2003) have explored the effect of individual driver attributes, technologies and safety best practices on accident likelihood, while other authors have examined the impact of truck drivers' employment status (Cantor et al., 2013; Corsi et al., 2012). Further studies have tested the influence of external factors, such as infrastructure design (Chang and Chien, 2013); vehicle technologies and maneuvering capabilities (Mooren et al., 2014); environmental conditions (Choi et al., 2014), and specific safety policies (Castillo-Manzano et al., 2015a). Some studies have even analyzed the possibility of internalizing the externalities generated by truck accidents (Anderson and Auffhammer, 2014; Savage, 2011).

Less attention has been paid to research into the effects on traffic safety outcomes of trucks disaggregated by size, weight or configuration. Chang and Mannering (1999) explain that it can be difficult to isolate the significance of these effects due to the presence of confounding factors. In addition, Carson (2011) points out that this literature represents a mixture of statistical papers and institutional reports based on different sources, models and methodologies that provide contradictory conclusions. Moreover, since the well-known TRB study (1990), most of studies on the topic have referred to the U.S. (af Wåhlberg, 2008; Braver et al., 1997; Khorashadi et al., 2005; Welki and Zlatoper, 2009, among many others), or discuss the safety of only one truck size category, mainly large and heavy trucks (Anderson and Auffhammer, 2014; Lemp et al., 2011; Zhu and Srinivasan, 2011).

More precisely, the previous literature shows that the evidence regarding the relationships between load capacity-based truck categories and traffic accidents and their severity is fragmented or even inconclusive. In fact, the af Wåhlberg (2008) meta-analysis, possibly the broadest review published on this topic to date, states that research on this topic has been characterized by a geographic bias (most of the studies take the US as their case study) and detects certain methodological shortcomings that are basically the result of limited exposure data for holding the road type constant. Therefore, the author concludes that this issue has not been conclusively answered.

Our paper therefore attempts to shed light on this still unresolved issue by assessing the safety differences in terms of traffic accidents and fatalities between three different truck types categorized by load capacity (i.e., light, medium and heavy trucks). For this we use a comprehensive database of a large number of heterogeneous EU countries and for a broad recent timeframe, the 1999–2012 period. While the main variables of the empirical analysis are for different categories of truck load capacity, we control for several explanatory factors of safety outcomes, such as country attributes, proxies for the type of roads used by trucks and specific road safety policies. All this enables us to offer robust results on this relevant topic.

Specifically, our research aims to answer the following questions: How does truck weight – gauged by load capacity – affect European traffic safety? What differences in safety are there among different truck load capacity categories in the EU? Which truck load capacity category is the most hazardous for EU traffic safety? Are people more likely to be involved in fatal accidents in the EU as truck load capacity increases?

The main contribution of our investigation is that it is the first to examine EU road safety issues in relation to this specific breakdown of truck types using a broad set of control variables. We believe that our findings may serve as a starting point for the analysis of different truck types circulating on other geographic levels and in other areas; and, in a practical context, they may also be helpful to governments and policy makers by adding safety issues to the perspectives of sustainability and logistics to orient both logistics and road safety strategies. In this regard, our results could also serve as a guide to adapt technology efforts, regulation and enforcement strategies to different truck configurations.

The timeliness of our research is justified by recent EU and individual government initiatives to extend the use of higher capacity freight vehicles (see e.g., Bergqvist and Behrends, 2011; ITF, 2010; McKinnon, 2008; Sanches Rodrigues et al., 2015 for a more in depth analysis). The body of EU legislation that addresses standard regulations on maximum weights and dimensions for heavy goods vehicles, buses and coaches mainly conforms to Directive 96/53/EC (see http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:31996L0053). This norm ensures the unhindered movement in Member States[1] of vehicles within these limits. It also places restrictions on the cross-border movement of vehicles that are heavier, longer or higher than these standards, the so-called *Mega Trucks*, *Long and Heavy Vehicles (LHVs)*, and *EuroCombis* or *Gigaliners*.[2] The European Commission (EC) has attempted to legalize cross-border mega trucks traffic during recent years, but the initial Directive has recently been amended by Directive (EU) 2015/719 (accessible at: http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv%3AOJ.L_.2015.115.01.0001.01.ENG), which provides for derogations from the maximum lengths to improve the safety and environmental emissions of heavy goods vehicles (through improved aerodynamic performance) and also recommends that no modifications should be made to Directive 96/53/EC's

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[1] Today different EU countries have different national regulations regarding maximum dimensions. According to this Directive, the maximum permitted length is 16.50 m for semitrailers and 18.75 m for road trains with a total combined weight of 40 tonnes (the so-called Heavy Goods Vehicles, HGVs).

[2] Up to 25 m in length and 60 tonnes in weight.

restrictions on the cross-border movement of mega trucks.[3] A detailed analysis of the impact of mega trucks can be found in e.g., Ortega et al. (2014) and Steer et al. (2013).

Following this introduction, the remainder of the paper is organized as follows: Section 2 presents the theoretical background to our analysis and the research hypotheses; Section 3 describes the data, the variables and the model used; Section 4 analyzes and discusses the results, and Section 5 summarizes the main conclusions and implications for policy.

2. Theoretical background and hypotheses

Most of literature on the topic agrees that differences in truck weight affect road safety since, from a technical point of view, they lead to different designs, configurations and driving performance. Consequently, as truck traffic tends to change, there are also changes in risk exposure to accidents. A number of scholars, such as Abdel-Aty and Abdelwahab (2004), Bálint et al. (2013), Cantor et al. (2010), Carson (2011), Corsi et al. (2012, 2014), Dong et al. (2014) and Khorashadi et al. (2005), among others, have demonstrated this using a variety of approaches. Given that each truck configuration has its own specific problems, Kahane (2003) highlights physics and intuitive reasons (mass differences, speed differences and a range of other safety factors) that may explain why different weights can be expected to present different accident risks.

Nevertheless, from studies such as Braver et al. (1997) that do not find any relevant truck safety differences linked to weight in fatal accidents, the meta-analysis by af Wåhlberg (2008) (possibly the most comprehensive quantitative review published on the topic to date) deduces that this question has not been conclusively answered, as the relationship between truck weight and road safety is really a nonlinear correlation dependent upon the accident category considered.

We take as our starting point this relevant contribution by af Wåhlberg (2008), whose outcomes point to accident risk increasing in line with increasing truck weight up to a certain point, except in the case of fatal accidents. However, the author indicates that this finding may only be valid for North America and notes that there are several methodological issues with studies, mainly due to limited exposure data for holding the road type constant.

Further analysis of the literature on safety differences among the different truck categories could help to reveal the sign of this relationship.

A priori, the association between heavy trucks and road safety outcomes (re: light trucks) seems to be a complex issue because, as Milton et al. (2008) argue, there are two forces depending on the accident category. On the one hand, a higher number of heavy trucks can lead to a decrease in accident risk due to a variety of factors. For example, heavy trucks are mainly used for inter-urban trips (Kanaroglou and Buliung, 2008) and as af Wåhlberg (2008) highlights may have an advantage from circulating on better and safer roads (highways). Moreover, according to Cantor et al. (2008, 2009), Corsi et al. (2012, 2014), Huang et al. (2008) and Welki and Zlatoper (2009), the implementation of the latest safety technologies, specific safety regulations and performance measures for heavy vehicles means that they are more resistant, due to their superior dynamic stability and control. In addition, as Lemp et al. (2011) state, one heavy truck may replace several light trucks, meaning that if heavy trucks are used, fewer truck trips are required to haul any given volume of freight (lower risk exposure). Lastly, as Milton et al. (2008) argue, the presence of heavy trucks may have a slowing effect on traffic speed.

On the other hand, although their occupants may be better protected, heavy trucks may also be involved in more severe accidents than light trucks, mainly due to more dangerous maneuvers and as they are less flexible, because of the weight and speed differential (Carsten, 1987; Chang and Chien, 2013; Dong et al., 2014; Khorashadi et al., 2005; Qin et al., 2013; Zhu and Srinivasan, 2011).

Accidents specifically involving light trucks have also been explored, although findings have again differed depending on the road safety outcome considered. The accident risk of light trucks seems to be higher than that of heavy trucks, especially in urban settings. According to Kanaroglou and Buliung (2008) the reason for this is that freight distribution mostly requires goods to be transported over short distances by light trucks, especially in the case of the major medium and large European cities where, as Dablanc et al. (2013) state, typical urban morphologies (high traffic density, parking problems, commercial–leisure–tourist activities concentrated in the city center) influence mobility and place restrictions on freight pick-up and delivery by heavier goods vehicles. Friswell and Williamson (2013) state in this regard that the urban environment creates more hazardous exposure for light truck drivers because of the stress that comes from heavy traffic or a lack of parking space. On the other hand, specific light truck features (e.g., a high center of gravity that may increase the risk of rollover, a more rigid structure and worse maneuverability, Anderson, 2008) may also drive up accident risk. Abdelwahab and Abdel-Aty (2004), Abdel-Aty and Abdelwahab (2004), Harb et al. (2007) and White (2004) provide evidence of a greater likelihood of rear-end and multivehicle collisions in urban settings involving light trucks because drivers' visibility of other smaller vehicles (passenger cars, bicycles, motorcycles) and pedestrians is impeded. Also, Desapriya et al. (2010) suggest that light trucks pose a greater risk of pedestrian injuries and deaths.

Other studies analyze factors that also contribute to higher accident risk for light trucks compared to heavy trucks. For example, the number of light trucks has grown considerably in recent years (Welki and Zlatoper, 2009). Certain authors even conclude that the behavior and qualification levels of drivers in these two truck categories are different. For example, a

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[3] These vehicles are already circulating in some Scandinavian countries with less advanced rail systems (Sweden and Finland), and other States have carried out pilot tests (the Netherlands, Germany, Denmark, Belgium). Mega truck or LHV cross-border traffic is a controversial issue in the EU due to a conflict of interests between the haulage industry, governments, institutions and public opinion (with a powerful campaign opposing mega trucks on the www. nomegatrucks.eu website, with opposition from 243 organizations in 24 countries. Even the European Parliament has shown its reluctance).

comparison by Huang et al. (2011) finds that heavy truck drivers (with more stringent requirements to obtain the corresponding driving license) are more frequently commercial drivers who are supposed to be better qualified to respond in hazardous situations. Using a Florida accident database the same study also detects that light truck drivers are more aggressive behind the wheel.

In sum, the evidence of the net effect of light trucks on traffic fatalities seems to be ambiguous. Depending on the methodological design, we find studies that only focus on the fact that in a fatal collision the greater mass of a light truck may provide better protection for its occupants compared to smaller vehicles, e.g., cars (Evans and Frick, 1993, 1994; Gayer, 2004; Ossiander et al., in press). However, there are also a number of studies such as Brozović and Ando (2009), Gayer (2004) and White (2004) that attempt to split the net fatality effect of light trucks into its internal and external impacts (i.e., also considering the externalities for other road users). Using an alternative approach based on the combination of both accident-level data and U.S. state-level data, Anderson (2008) indicates that because of their greater mass and specific features, light trucks may generate an external safety cost to the occupants of other vehicles that could neutralize the initial safety advantage for their own occupants.

In keeping with official EU statistics available from Eurostat, our research focuses on three mutually exclusive truck categories classified by load capacity:

(1) Light: trucks with a load capacity of under 5000 kg.
(2) Medium: with a load capacity of between 5000 kg and 14,999 kg.
(3) Heavy: with a load capacity of 15,000 kg or over.

Considering all the above evidence (mostly for the U.S. case), we therefore formulate the following hypotheses H1 and H2:

Hypothesis 1 (H1). Heavy truck usage is related to fewer traffic accidents compared to light trucks.

Hypothesis 2 (H2). Heavy truck usage is related to more traffic fatalities compared to light trucks.

Returning to the literature that analyzes the impact of heavy trucks on safety, a number of studies, almost all for the U.S., consider a broad truck category called "*large trucks*" for vehicles with a gross vehicle weight in excess of 10,000 lb. For example, Blower et al. (2010) analyze mechanical conditions and crash involvement; Hauer (2001) explores the safety of certain vehicle types of driver groups; Lyman and Braver (2003) consider truck accidents in terms of occupant deaths; and Zaloshnja and Miller (2004) calculate the cost of truck crashes.

However, as Park and Pierce (2013) state, considering a separate specific medium trucks category (for example, for trucks between 10,001 and 26,000 lb) would improve knowledge of truck safety. The research that considers a separate category of medium size trucks in road safety is quite scarce. Nevertheless, in general terms the few studies that follow this disaggregation agree that, compared to heavy trucks, there are differential operational characteristics and accident environments for medium trucks that lead to both a higher risk of accidents and more severe accidents: e.g., higher speeds with more severe results in the case of an accident, more aggressive driving, and drivers who are often not required to possess a commercial driver's license. These studies are for the U.S. (Huang et al., 2011; Park and Pierce, 2013; Pierce and Park, 2014) and for Sweden (Bálint et al., 2013) respectively, but they only evaluate truck types in terms of length and do not take into account other aspects, such as load capacity. However, there is one study of the U.S. (Corsi et al., 2014) that explains how and why vehicles in a truck category equivalent to our study's medium trucks (10,001–26,000 lb) present worse driver performance and higher traffic violation rates than heavy trucks.

Consequently, the previous research and logic lead us to expect that medium trucks might possess a mix of the characteristics of both heavy and light trucks – for example, they can be used for both urban and inter-urban journeys – as a result of which medium trucks might also possess a combination of safety risks. Thus, we formulate the following Hypotheses, H3 and H4:

Hypothesis 3 (H3). Heavy truck usage is related to fewer traffic accidents compared to medium trucks.

Hypothesis 4 (H4). Heavy truck usage is related to fewer traffic fatalities compared to medium trucks.

3. Empirical framework

We apply a country fixed effects model that allows us to consider any omitted constant variable that correlates with the explanatory variables. We use different techniques (ordinary least squares and negative binomial) to verify the robustness of the results to the dependent variable being treated in different ways: as a continuous or a count variable. Specifically, our model takes the following form for country i during period t:

$$Y_{it} = \alpha + \beta_k X_{it} + \gamma_k Z_{it} + \lambda_k W_{it} + \mu_i + \nu Year_t + \varepsilon_{it} \qquad (1)$$

in which we consider two different Y_{it} dependent variables estimated in two different regressions. First, we consider the log of the total per capita fatality rate (within 30 days of the accident, according to the Vienna Convention definition) as the dependent variable.[4] Second, we consider the log of the total accident rate as the dependent variable.

X_{it} contains the vector of the country's economic and demographic attributes; Z_{it} refers to truck-related variables, and W_{it} represent road safety policy-related variables. μ_i are country fixed effects that control for omitted time-invariant country-specific variables; Year is an annual time trend that controls for the common trend in all the countries in the dataset, and ε_{it} is a mean-zero random error. Note here that the only data available are annual and aggregated at the country level. This results in some limitations, as we cannot control for seasonal effects or regional differences.

We use data for the EU28 countries from 1999 to 2012 and the unit of observation is the country-year pair: 1999 is a relevant year for our scope, as it is the year that the so-called 'Eurovignette' Directive 1999/62/EC (modified by Directive 2006/38/EC and Directive 2011/76/EU) was passed that aimed to harmonize the tolls and vignettes associated with the cost of road infrastructure in Member States and charge them to Heavy Goods Vehicles. 2012 is the most recent year for which data were available for the majority of the countries considered.

However, data for truck-related variables were not available for some countries (Belgium, Bulgaria, Greece and the United Kingdom) and so these countries were excluded from the econometric analysis. Data were available for Austria, Croatia, Cyprus, the Czech Republic, Denmark (1999–2002), Estonia (2007–2012), Finland, France (2010–2012), Germany (1999–2008), Hungary (1999–2008, 2010), Ireland (1999), Italy (2004–2012), Latvia, Lithuania (all years except 2008), Luxembourg (1999–2009), Malta (all years except 2003–2007), the Netherlands (all years except 2012), Poland (2002–2012), Portugal (2011–2012), Romania (2008–2012), Slovenia (all years except 2003–2004), Spain (2005–2012) and Sweden (all years except 2010 and 2012).

With respect to the countries for which data were not available for all years, we include data for the years for which we do have information, as is generally done in unbalanced panel data regressions. Note here that data for truck variables account for 231 observations and data for other variables, such as fatalities and accidents, are also incomplete. Thus, for some country-pairs we may have information for truck variables but not, for example, for fatalities. Hence, the final sample comprises 222 observations. Note here that any regressions with only one observation for a country fixed effect (as is the case for Ireland, for example) automatically exclude said observation.

Tables 1 and 2 give the descriptions, information sources, descriptive statistics and number of observations available for all of the variables used in the analysis. We also specify the variables that capture country attributes, truck numbers and specific safety policy variables. All the variables present adequate variability, given that standard deviation is relatively high in relation to mean values. However, the variability of some variables, such as motorway density, may be low over time.

As explanatory variables we include the per capita gross domestic product (GDP) as an indicator of the country's economic development (Castillo-Manzano et al., 2014a,b, 2015b; Grimm and Treibich, 2013; Yannis et al., 2014). The relationship between a country's economic development and road safety outcomes could be expected to be an inverted U-shape (Bishai et al., 2006; Kopits and Cropper, 2005; Loeb and Clarke, 2007). Indeed, fatality and accident rates may increase with economic development in very poor countries, due to increased exposure to road traffic accidents. However, the relationship between economic development and traffic safety outcomes may become flat or even invert after reaching a certain wealth threshold. We test the hypothesis concerning non-linearity between GDP and traffic safety outcomes by including the GDP and the square of the GDP as explanatory variables. If the non-linear relationship is confirmed, then the coefficient for the GDP variable will be positive and the coefficient for the GDP^2 variable will be negative.

The number of passenger cars per capita (motorization) is also taken into account. This variable relates to the level of development of private transportation. Regarding the expected sign of this coefficient, on the one hand, higher motorization rates may imply higher exposure to road traffic accidents, while on the other, more developed countries may have better infrastructure and vehicles, more advanced policies and more beneficial social attitudes towards road safety (Kopits and Cropper, 2005). By way of example, Albalate and Bel (2012) found a negative relationship between traffic fatalities and the motorization rate.

We also take into account the influence of the quality of transport infrastructure by including a variable for motorway density. The sign of the coefficient for this variable is expected to be negative. Indeed, a negative relationship can be expected between the quality of transport infrastructure and road safety outcomes, as was found in Jamroz (2012) and Noland (2003). It should be noted that Malta and Latvia do not possess any motorways, which explains why the sample includes countries with zero motorway density.

We also include the density of other roads (state, provincial and district roads) as an explanatory variable. This variable could capture the influence of inter-urban trips on lower quality roads or more frequent short trips. Hence, a priori the sign expected for this variable is not clear in either the traffic fatalities or accidents equations. By including this variable, we seek to take into account the methodological indications in the relevant meta-analysis by af Wåhlberg (2008). Said author identifies the lack of appropriate exposure data regarding road type as the main problem in studies that analyze the safety impact of different truck configurations. Larger trucks usually circulate on larger, safer roads (highways), which could represent a certain advantage and possibly skew the comparison of the findings for different truck configurations.

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[4] This is the dependent variable typically used to assess road safety outcomes, as the interpretation of policy variables is clearer.

Table 1
Variables used in the empirical analysis.

Variables	Description	Source	Type of data
Fatalities per capita	Number of traffic fatalities per million inhabitants	CARE (EU road accident database)	Dependent variable
Accidents per capita	Number of traffic accidents per million inhabitants	CARE (EU road accident database)	Dependent variable
Motorization	Number of registered passenger cars per thousand inhabitants	UNECE, EUROSTAT (for population)	Country attribute
GDP per capita	Per capita gross domestic product in International Comparable Prices (US$ at 2005 prices and PPP)	EUROSTAT	Country attribute
Motorway density	Number kms of motorways divided by km^2 of the country	UNECE, EUROSTAT	Country attribute
Other roads density	Number kms of other roads (state, provincial and district) divided by country km^2	UNECE, EUROSTAT	Country attribute
Old	% population aged 60+	EUROSTAT	Country attribute
Young	% population aged 15–24	EUROSTAT	Country attribute
Population density	Density of population	EUROSTAT	Country attribute
Trucks_light	Number of trucks (trucks + semi-trailers with load capacity <5000 kg) per million inhabitants	EUROSTAT	Trucks
Trucks_medium	Number of trucks (trucks + semi-trailers with load capacity 5000–14,999 kg) per million inhabitants	EUROSTAT	Trucks
Trucks_heavy	Number of trucks (trucks + semi-trailers with load capacity $\geqslant$ 15,000 kg) per million inhabitants	EUROSTAT	Trucks
BAC_05	Dummy variables that take a value of 1 if the permitted maximum BAC rate is under 0.5 g/l	European Commission Road Safety Website	Road safety policy
Points_system	Dummy variable that takes a value of 1 if a points driving license system is in force	European Transport Safety Council (ETSC)	Road safety policy
Speed limits	Maximum speed limits	European Commission Road Safety Website	Road safety policy

Table 2
Descriptive statistics of the variables used in the empirical analysis.

Variables	Mean	Standard deviation	Minimum value	Maximum value	Number of observations
Fatalities per capita	103.46	45.26	21	257	379
Accidents per capita	42798.45	77732.46	633.9	395,689	379
Motorization	430.54	111.61	134	686	388
GDP per capita	25331.75	11622.87	6737	74,128	391
Motorway density	1.73	1.74	0	6.35	388
Other roads density	129.09	134.09	0.49	979.87	388
Old	21.00	2.64	15.1	27.1	389
Young	13.22	1.65	10	17.2	392
Population density	0.16	0.23	0.02	1.37	392
Trucks_light	52007.98	32449.33	2396.3	159,826	231
Trucks_medium	5472.032	2540.95	1297	17,100	231
Trucks_heavy	4140.57	2596.62	31	11,395	231
BAC_05	0.28	0.45	0	1	392
Points_system	0.60	0.49	0	1	392
Speed limits	121.5	13.51	80	112	392

We also consider two control variables for the percentage of vulnerable population in each country. First, we include a variable for the percentage of the population over 60 years old. Second, we also consider a variable for the percentage of the population aged 15–24 years. While we may expect that risk exposure is higher for the younger population, since younger road users usually take more risks (Langford and Koppel, 2006), the impact of accidents may be greater for senior road users, and so morbidity and mortality rates may be higher for older populations (Braver and Trempel, 2004; Yee et al., 2006). Thus, we expect positive signs in the traffic fatalities equation for the coefficients for these two explanatory variables, while a negative sign is expected in the accidents equation for the old population coefficient and a positive sign for the young population coefficient.

Additionally, we include a variable for the population density of the country. We may expect that the proportion of urban trips (short distance trips in intra-urban neighborhoods; Holz-Rau et al., 2014) over total trips will be higher in more densely populated countries; and specifically, following Allen et al. (2012), trips for urban freight activities are associated with city population density. The accident rate should be higher for intra-urban trips than inter-urban or rural trips, but the severity of accidents may be lower for intra-urban trips, due, according to Rakauskas et al. (2009) and Zwerling et al. (2005) among others, to factors such as road design, emergency medical service proximity and lower differential speeds. Hence, the coefficient for this variable is expected to have a positive sign in the accidents equation, while a negative sign might be found in the traffic fatalities equation.

We also include additional variables for road safety policies. Following previous studies on road safety (Albalate, 2008; Castillo-Manzano and Castro-Nuño, 2012; Castillo-Manzano et al., 2014a,b), we consider the influence of prevention policies

such as legal blood alcohol limits. A dummy variable is included with a value of one for countries and periods where the maximum blood alcohol concentration allowed for professional drivers is under 0.5 g/L. Most EU28 countries have set the limit at 0.5 or below, so we are able to test whether blood alcohol concentration rates of under 0.5 for professional drivers are effective for improving road safety outcomes.

Moreover, we add a variable that captures the implementation of points-based driving licenses through a dummy variable with a value of one if a penalty driving license system is applied. The introduction and application of any type of points system to driving licenses may lead to lower traffic fatality and accident rates, although the long-term effect of this policy has been questioned (see Castillo-Manzano and Castro-Nuño, 2012, for an international meta-analysis of the effects of this type of policy).

Another road traffic policy variable that we take into account is the maximum speed limit on motorways. According to previous studies (Elvik, 2012), a positive sign may be expected for the coefficient for this variable, as one of the consequences of a higher speed limit may be a higher number of road traffic fatalities and accidents.

The most relevant variables in our analysis are related to truck load capacity.[5] We include three variables for the number of trucks per capita[6] that consider three separate load capacity categories, as explained in the previous section (i.e., Heavy trucks for ⩾15,000 kg; Medium trucks for 5000–14,999 kg; Light trucks for <5000 kg). We opt for load capacity to distinguish between truck types as, following the ITF (2010), load volume determines the number of trucks required per unit of freight, and a higher load capacity can result in fewer vehicle-kilometers traveled.

For the U.S. case study, and following both the Federal Highway Administration (FHWA) and the National Highway Traffic Safety Administration (NHTSA), most papers on the topic classify trucks in three groups by Gross Vehicle Weight (GVW) expressed in pounds. However, there are no equivalents to these groups in terms of load capacity in any official statistics available in Europe. Thus, as has been clearly stated above, our grouping criteria is based on available Eurostat data.

As was to be expected, the mean value data in Table 2 show that light trucks are much more numerous than trucks in the other categories. In contrast, the numbers of trucks in the other two categories are quite similar.

We would like to state that the variables used in the empirical analysis are not proxies for country size. Variables are measured in per capita terms (fatalities, GDP, motorization, truck load capacity variables, population and motorway density – the latter two in per km terms) and are not linked to country size (road safety policy variables, percentage of vulnerable population).

4. Results and discussion

Table 3 shows the correlation matrix of the variables used in the empirical analysis. Some variables are highly correlated. Table 3 reports a particularly high correlation between the GDP per capita and motorization variables, and a high correlation between the population density and other roads density variables. These high correlations may cause a multicollinearity issue. Multi-collinearity can exaggerate estimates of the parameter variance and distort its statistical significance or even result in parameter estimates of implausible magnitude in the most extreme cases.

The Variance Inflation Factor (VIF) is a measure that is widely used to examine the degree of multicollinearity between explanatory variables. Several rules of thumb for VIF have been considered as a sign of severe multicollinearity. The usual rule of thumb considered in the econometric textbooks is 10, although practitioners may use lower threshold values and a value of 5 is common.

Table 4 shows the variance inflation factors of all the variables used in the empirical analysis. The computed VIFs are below 5 for the majority of the variables and below 10 for all of the variables. If we exclude the motorization and other roads density variables, the computed VIFs are below 5 for all variables. It is important to note that the truck motorization variables do not seem to be affected by any multicollinearity issues in our research.

Estimates may present problems of heteroscedasticity and temporal autocorrelation in the error term. Running the Wool-dridge test for autocorrelation in panel data shows that there may be a problem of serial autocorrelation that needs to be addressed. Additionally, the Breusch–Pagan/Cook–Weisberg test indicates that we have an issue with heteroscedasticity. We also apply the panel unit root test developed by Levin et al. (2002), which can be regarded as an augmented Dickey–Fuller (ADF) test when lags are included. This test indicates that there is no non-stationarity problem with our dependent variable. We also apply the Ramsey Reset Test, which confirms that no relevant variables have been omitted from our model. The results of these tests are given in Tables 5 and 7.

Taking the results of these tests into account, we performed the estimation using two different techniques to check for robustness. In Table 5 we report the results of the traffic fatality regressions using the ordinary least squares (OLS) method

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[5] Overall, we may expect a stronger (negative) impact of trucks on traffic fatality than passenger cars. Castillo-Manzano et al. (2015a) examine the differential impact between the motorization rates for trucks and passenger cars but do not distinguish between different truck categories, which are essential for our analysis.

[6] Motorization variables (both for passenger cars and trucks) are in per capita terms, as this is a common indicator in international statistics and the road safety literature. It might be interesting to test our model with an alternative indicator of motorization, such as the ratios between numbers of passenger cars and trucks and total road-kilometers. Unfortunately, Eurostat data for the number of road-kms are very poor and are not available for several countries. Reported data show significant differences among countries (taking load capacities into account) and significant changes within some countries in just one year.

Table 3
Correlation matrix of the variables used in the empirical analysis.

Variables	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	1														
2	−0.05	1													
3	−0.41	0.27	1												
4	−0.45	0.03	0.77	1											
5	−0.32	0.08	0.53	0.68	1										
6	−0.20	−0.06	0.10	−0.01	0.10	1									
7	−0.36	0.36	0.23	−0.02	−0.16	−0.12	1								
8	0.38	−0.34	−0.11	−0.02	0.05	0.03	−0.43	1							
9	−0.21	0.08	0.27	0.17	0.21	−0.07	−0.32	0.02	1						
10	0.42	−0.20	−0.03	−0.17	−0.39	0.29	−0.09	0.03	−0.16	1					
11	−0.18	−0.31	0.33	0.51	0.30	0.27	−0.06	−0.12	−0.01	0.17	1				
12	−0.36	0.04	0.13	0.10	0.16	0.79	−0.07	−0.02	0.17	0.24	0.23	1			
13	0.01	−0.02	0.01	−0.06	−0.19	−0.09	0.18	−0.02	−0.08	0.15	0.11	−0.25	1		
14	−0.05	0.13	0.23	0.04	0.31	0.08	0.05	−0.09	0.15	−0.23	0.18	−0.31	−0.02	1	
15	0.14	0.27	0.11	0.21	−0.20	−0.14	0.04	−0.05	−0.38	−0.31	−0.03	−0.32	−0.02	0.17	1

Note: Denomination of variables: 1 = fatalities per capita; 2 = accidents per capita; 3 = motorization; 4 = GDP per capita; 5 = motorway density; 6 = other roads density; 7 = old population; 8 = young population; 9 = trucks_light; 10 = trucks_medium; 11 = trucks_heavy; 12 = population density; 13 = BAC_05; 14 = points_system; 15 = speed limits.

Table 4
Variance inflation factors of the variables used in the empirical analysis.

Variables	Fatalities per capita		Accidents per capita	
	All variables	Excluding motorization and other roads density	All variables	Excluding motorization and other roads density
Motorization	4.60	–	4.63	–
GDP per capita	6.70	3.18	6.54	2.97
Motorway density	3.51	3.36	3.22	3.13
Other roads density	7.91	–	7.74	–
Old	4.51	3.91	4.62	3.65
Young	4.72	4.30	4.94	4.40
Population density	8.73	1.65	8.48	1.65
Trucks_light	2.58	1.77	2.47	1.67
Trucks_medium	2.12	1.86	2.14	1.87
Trucks_heavy	1.97	1.93	1.89	1.84
BAC_05	1.32	1.27	1.31	1.26
Points_system	1.71	1.83	1.59	1.73
Speed limits	2.14	2.30	2.10	2.26

with country fixed effects. The standard errors are robust to heteroscedasticity and clustered by country to address the auto-correlation problem. In Table 6 we report the results of the traffic fatalities equations using the population-averaged panel-data model with a negative binomial distribution. The standard errors are robust to heteroscedasticity, as they are in the OLS regression. An advantage of these latter regressions is that we can specify an AR(1) within-group correlation structure for panels. Population is used as an exposure variable. In Table 7 we show the results of the accidents equation using both techniques.

It should be noted that the negative binomial distribution explicitly models the dependent variable as the number of occurrences. The dependent variable in the OLS regression is total fatalities or accidents per capita, while in the regression that uses the negative binomial distribution the dependent variable is total fatalities or total accidents, with population as an exposure variable. Note that in the OLS regression the dependent variable is expressed in logs, while the implementation of the log-link function in the negative binomial distribution regression means that the log transformation can be used without transforming the dependent variable. The log-link function can be implemented in the framework of generalized linear models assuming a negative binomial distribution of the dependent variable, which is what we consider in our analysis.

In Tables 5 and 6 we report the results of five different specifications of the road traffic fatalities equation, while Table 7 shows the results for the accidents equation. We report the results of different specifications. Specification (1) is the baseline regression. Specification (2) adds the lagged value of the dependent variable as an explanatory variable to check whether results with a dynamic estimator differ from the baseline model. Specifications (3) and (4) add two different interaction variables (centering the variables to prevent any multicollinearity issues): interaction between GDP per capita and motorization rate, since the effects of the motorization rate on road safety outcomes may vary depending on GDP per capita; and interaction between trucks per capita and the motorization rate, since mixing higher levels of car and truck traffic may lead to worse safety outcomes. Specification (5) excludes the motorization variables, other roads density and the square of the GDP per capita variables to check whether results for the truck variables are affected by multicollinearity between any of

Table 5
Results of estimates (OLS model).

Independent variables	Dependent variable: Number of traffic fatalities per capita				
	(1)	(2)	(3)	(4)	(5)
Number of traffic fatalities per capita (lagged)	–	0.43*** (0.11)	–	–	–
Motorization	0.00037 (0.0005)	−0.00021 (0.00044)	0.0009 (0.0007)	0.00012 (0.0006)	
GDP per capita	0.000039*** (0.000013)	0.000024*** (9.31e−06)	0.000047*** (0.000013)	0.000046*** (0.000013)	0.000028** (0.000012)
GDP per capita^2	−2.48e−10*** (1.48e−10)	−1.90e−10* (9.89e−11)	−9.37e−10*** (2.78e−10)	−3.60e−10** (1.58e−10)	–
Motorway density	−0.003 (0.06)	−0.008 (0.05)	−0.06 (0.08)	−0.01 (0.06)	−0.05 (0.06)
Density of other roads	0.002*** (0.006)	0.0022*** (0.0007)	0.0029*** (0.0005)	0.002*** (0.0005)	–
Old	0.03 (0.02)	0.03* (0.017)	0.06 (0.03)	0.02 (0.02)	0.06** (0.02
Young	0.04** (0.02)	0.03* (0.018)	0.03 (0.02)	0.03* (0.01)	0.02 (0.02)
Population density	−1.99*** (0.53)	−1.88*** (0.55)	−2.27*** (0.59)	−1.96*** (0.53)	−0.62 (0.43)
Trucks_light	1.63e−06 (1.55e−06)	−6.61e−08 (1.14e−06)	1.64e−06 (1.87e−06)	2.49e−06 (2.20e−06)	1.35e−06 (1.82e−06)
Trucks_medium	0.000026*** (8.38e−06)	0.000021*** (3.62e−06)	0.000022** (9.00e−06)	0.000026*** (8.48e−06)	0.000026** (0.000011)
Trucks_heavy	−0.000015 (0.000012)	3.35e−07 (5.35e−06)	−9.20e−06 (0.000011)	−9.48e−06 (0.000011)	−0.000022 (0.000013)
BAC_05	0.023 (0.07)	−0.0017 (0.05)	0.004 (0.07)	0.006 (0.06)	0.006 (0.07)
Points_system	0.00006 (0.04)	−0.03 (0.03)	0.02 (0.04)	0.004 (0.04)	0.10 (0.06)
Speed limits	0.04*** (0.01)	0.014 (0.010)	0.04*** (0.01)	0.04*** (0.01)	0.02* (0.013)
Motorization × GDP per capita	–	–	1.27e−07*** (4.81e−08)	–	–
Motorization × Trucks per capita	–	–	–	1.25e−08** (4.97e−09)	–
Time_trend	−0.09*** (0.012)	−0.056*** (0.010)	−0.09*** (0.011)	−0.09*** (0.011)	−0.09*** (0.010)
Intercept	−0.03 (1.75)	0.64 (1.33)	1.08 (2.15)	−0.36 (2.03)	1.59 (2.07)
Country fixed effects	YES	YES	YES	YES	YES
R^2	0.96	0.96	0.96	0.96	0.94
Test joint sign (Wald χ^2)	100.58***	120.69***	104.84***	100.63***	86.49***
Ramsey Reset Test (Ho: No omitted variables)	1.21	0.22	1.83	0.23	1.52
Breusch-Pagan/Cook-Weisberg test for heteroscedasticity (Ho: Constant variance)	7.96***	6.79***	8.10***	6.03***	6.26***
Wooldridge test –autocorrelation (Ho: First-order autocorrelation)	4.88**	6.02**	5.49**	4.88**	3.46*
Test: – Trucks_light + Trucks_heavy = 0	1.67	10.98**	3.08*	5.07**	5.39**
Number of observations	222	222	222	222	222

Note 1: Standard errors are given in brackets. Robust to heteroscedasticity and clustered by country.

* Statistical significance at 10%.
** Statistical significance at 5%.
*** Statistical significance at 1%.

Table 6
Results of estimates (Population-averaged panel-data model with a negative binomial distribution).

Independent variables	Dependent variable: Number of traffic fatalities				
	(1)	(2)	(3)	(4)	(5)
Number of traffic fatalities (lagged)	–	0.33*** (0.10)	–	–	–
Motorization	0.00020 (0.0004)	−0.00012 (0.0004)	0.001* (0.0005)	0.00012 (0.00046)	–
GDP per capita	0.000043*** (9.19e−06)	0.000028*** (8.75e−06)	0.000051*** (8.98e−06)	0.000048*** (9.23e−06)	0.000032*** (0.000010)
GDP per capita^2	−2.80e−10*** (1.26e−10)	−2.52e−10*** (1.00e−10)	−1.02e−09*** (2.24e−10)	−3.60e−10*** (1.19e−10)	–
Motorway density	−0.02 (0.05)	−0.003 (0.05)	−0.08 (0.06)	−0.021 (0.05)	−0.06 (0.04)
Density of other roads	0.0027*** (0.0004)	0.002*** (0.0006)	0.003*** (0.0004)	0.002*** (0.00043)	–
Old	0.21 (0.17)	0.03* (0.017)	−0.005 (0.015)	0.019 (0.016)	0.04** (0.02)
Young	0.04*** (0.01)	0.04*** (0.016)	0.023* (0.0014)	0.035*** (0.011)	0.02* (0.01)
Trucks_light	5.16e−07 (1.44e−06)	−1.17e−07 (1.15e−06)	5.15e−07 (1.70e−06)	9.53e−07 (1.98e−06)	5.23e−07 (1.61e−06)
Trucks_medium	0.000022*** (6.54e−06)	0.000022*** (3.15e−06)	0.000019*** (5.68e−06)	0.000022*** (6.22e−06)	0.000024*** (8.70e−06)
Trucks_heavy	−7.95e−06 (8.40e−06)	−1.39e−06* (4.56e−06)	−4.75e−06 (6.90e−06)	−5.95e−06 (7.20e−06)	−8.70e−06 (8.03e−06)
Population density	−2.18*** (0.42)	−2.02*** (0.46)	−2.50*** (0.46)	−2.15*** (0.43)	−0.71 (0.33)**
BAC_05	0.013 (0.05)	−0.001 (0.04)	−0.01 (0.05)	0.001 (0.05)	0.002 (0.05)
Points_system	0.011 (0.03)	−0.019 (0.026)	0.029 (0.03)	0.014 (0.035)	0.06 (0.04)
Speed limits	0.03*** (0.009)	0.02** (0.01)	0.03*** (0.01)	0.03*** (0.010)	0.02** (0.01)
Motorization × GDP per capita	–	–	1.49e−07*** (4.01e−08)	–	–
Motorization × Trucks per capita	–	–	–	1.20e−08** (5.38e−09)	–
Time_trend	−0.08*** (0.009)	−0.06*** (0.01)	−0.09*** (0.009)	−0.09*** (0.009)	−0.08*** (0.009)
Intercept	0.74 (1.26)	0.51*** (1.23)	2.15 (1.61)	0.59 (1.47)	1.97 (1.52)
Country fixed effects	YES	YES	YES	YES	YES
Test joint sign (Wald χ^2)	46.12***	51.34***	45.65**	44.26**	39.81***
Test: – Trucks_light + Trucks_heavy = 0	5.62**	17.43***	5.12**	6.58**	6.12***
Number of observations	222	222	222	222	222

Note 1: Standard errors are given in brackets (robust to heteroscedasticity). Regressions specify an AR(1) within-group correlation structure for the panels. Population is used as exposure variable.
* Statistical significance at 10%.
** Statistical significance at 5%.
*** Statistical significance at 1%.

the explanatory variables. For the sake of simplicity, we do not report the results of specification (3) for the accidents equation, as the interaction variables are not statistically significant when the dependent variable is the accident rate.

As the reported R^2 in the OLS regression shows, the overall explanatory power of the regressions is very high. However, several explanatory variables are not statistically significant and the country fixed effects may capture the effect of several explanatory variables with little variability over time.

Regarding our main explanatory variables, we find differential impacts for the truck load capacity variables (in both the fatalities and accident equations).

First, Hypotheses 1 and 2 suggest that heavy truck usage leads to fewer but more severe traffic accidents (with more fatalities) compared to light trucks. Our findings indicate that the coefficient for the heavy trucks variable is generally not statistically significant in the regressions that take traffic fatalities as the dependent variable. However, the coefficient for the heavy trucks variable is negative and generally significant (at the 10% level) in the regressions that take accidents as the dependent variable. We therefore deduce that accident risk does not necessarily increase with a rise in the load capacity of trucks circulating in the EU, while we do not find that heavy truck usage has a significant impact on traffic fatalities.

Lower accident risk for heavy trucks may be supported by a combination of explanations provided by scholars such as: Lemp et al. (2011), who point to larger trucks resulting in fewer truck trips; Milton et al. (2008) who state that the presence of heavier trucks on roads may have a slowing effect on average traffic speed; and others, such as Cantor et al. (2009, 2010), Carson (2011), Corsi et al. (2012), Mejza et al. (2003) and Mooren et al. (2014), who consider other factors. For instance, larger motor carriers are subject to stricter regulatory systems to promote safer and more efficient vehicles; they are leaders in the implementation of safety technologies and performance measures to improve dynamic stability and prevent collisions with vulnerable road users,[7] and they have more experienced and qualified drivers in stable and secure employment.

The non significant coefficient obtained for traffic fatalities is a more complex issue. Unlike most prior studies we have included control variables for different road types to take into account the fact that heavier trucks tend to circulate on better

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[7] See, for example, additional safety equipment proposed in London to avoid heavy truck accidents involving pedestrians and cyclists: https://consultations.tfl.gov.uk/buses/safer-lorries.

Table 7
Results of estimates (Accidents per capita).

Independent variables	Dependent variable: accidents per capita							
	OLS				Population-averaged panel-data model with a negative binomial distribution			
	(1)	(2)	(3)	(4)	(1)	(2)	(3)	(4)
Number accidents (lagged)	–	0.55*** (0.09)	–	–	–	0.51*** (0.05)	–	–
Motorization	−0.0006 (0.002)	−0.002 (0.002)	−0.001 (0.002)	–	−0.00014 (0.0017)	−0.0019 (0.0016)	−0.0002 (0.0018)	–
GDP per capita	0.00011** (0.00005)	0.00004 (0.00003)	0.00014** (0.00006)	0.00005 (0.00006)	5.96e−06 (0.000022)	5.17e−06 (0.00002)	0.000013 (0.000026)	−0.000024 (0.000022)
GDP per capita^2	−1.38e−09*** (4.99e−10)	−7.80e−10 (3.73e−10)	−1.89e−09* (7.69e−10)	–	−5.98e−10 (3.97e−10)	−5.95e−10* (3.27e−10)	−7.02e−10 (4.68e−10)	–
Motorway density	0.13 (0.29)	0.043 (0.29)	0.14 (0.28)	0.03 (0.26)	−0.04 (0.22)	−0.07 (0.22)	−0.03 (0.22)	−0.07 (0.17)
Density of other roads	0.001 (0.0023)	0.00043 (0.0018)	0.002 (0.002)	–	−0.002 (0.002)	−0.002 (0.002)	−0.002 (0.002)	–
Old	−0.26 (0.16)	−0.30* (0.15)	−0.28* (0.16)	−0.16 (0.14)	−0.21* (0.13)	−0.30*** (0.12)	−0.21 (0.13)	−0.17 (0.11)
Young	0.33*** (0.08)	0.26*** (0.09)	0.29*** (0.08)	0.24** (0.09)	0.30*** (0.07)	0.20*** (0.07)	0.29*** (0.08)	0.25*** (0.07)
Trucks_light	0.000027* (0.000013)	0.000029** (0.000010)	0.000030** (0.000013)	0.000026 (0.000015)	0.000032*** (0.000011)	0.000033*** (9.11e−06)	0.000033*** (0.000011)	0.000033*** (0.000011)
Trucks_medium	−2.21e−06 (0.000043)	−0.000014 (0.000041)	−3.66e−06 (0.000043)	−0.000010 (0.000015)	−4.87e−06 (0.000022)	−0.000015 (0.000026)	−4.58e−06 (0.000022)	1.71e−06 (0.000023)
Trucks_heavy	−0.00011* (0.00008)	−0.000099 (0.00008)	−0.000081 (0.000085)	−0.00010 (0.00006)	−0.000098* (0.000053)	−0.00012** (0.00005)	−0.000094* (0.000054)	−0.000067* (0.000038)
Population density	6.83*** (2.45)	6.55** (2.09)	7.10*** (2.38)	3.49*** (2.03)	8.64*** (1.92)	8.70*** (1.70)	8.68*** (1.99)	6.20*** (1.39)
BAC_05	−0.14 (0.24)	−0.12 (0.20)	−0.21 (0.24)	−0.15 (0.24)	−0.003 (0.10)	−0.001 (0.11)	−0.01 (0.10)	0.0017 (0.11)
Points_system	−0.02 (0.22)	−0.007 (0.21)	−0.01 (0.22)	0.15 (0.21)	0.06 (0.13)	0.07 (0.14)	0.06 (0.13)	0.06 (0.10)
Speed limits	0.29*** (0.07)	0.22** (0.05)	0.31*** (0.08)	0.23*** (0.06)	0.24*** (0.05)	0.21*** (0.04)	0.24*** (0.05)	0.21*** (0.04)
Motorization × Trucks per capita	–	–	5.58e−08 (4.50e−08)	–	–	–	1.56e−08 (2.83e−08)	–
Time_trend	−0.05 (0.06)	0.04 (0.04)	−0.08 (0.06)	−0.07 (0.06)	−0.00004*** (0.03)	0.07** (0.03)	−0.006 (0.04)	−0.01 (0.03)
Intercept	−26.79*** (8.14)	−19.09*** (5.91)	−26.46** (8.41)	−20.66** (7.64)	−23.16*** (5.76)	−19.99*** (4.54)	−23.44*** (5.87)	−19.66*** (5.45)
Country fixed effects	YES	YES	YES	YES	YES	YES	YES	YES
Test joint sign (Wald χ^2)	29.11***	37.18***	28.75***	41.61***	185.36***	101.49***	94.55***	221.65***
R^2	0.86	0.90	0.86	0.88	–	–	–	–
Ramsey Reset Test (Ho: No omitted variables)	1.86	1.40	1.61	1.94	–	–	–	–
Breusch-Pagan/Cook-Weisberg test for heteroscedasticity (Ho: Constant variance)	7.17***	9.23***	4.69**	3.09*	–	–	–	–
Wooldridge test – autocorrelation (Ho: First-order autocorrelation)	88.04***	90.05***	86.16***	143.77***	–	–	–	–
Test: – Trucks_medium + Trucks_heavy = 0	1.74	1.13	1.05	2.28	4.17**	3.36*	3.98**	3.26*
Number of observations	222	222	222	222	222	222	222	222

Note 1: Standard errors are given in brackets (robust to heteroscedasticity). Regressions specify an AR(1) within-group correlation structure for the panels. Population is used as exposure variable in the regressions that use negative binomial distribution.
  * Statistical significance at 10%.
  ** Statistical significance at 5%.
  *** Statistical significance at 1%.

and safer roads. Nevertheless, our unprecedented broad panel data for 28 EU countries do not allow us to collect available data to consider other variables that, according to the relevant af Wåhlberg (2008) meta-analysis, might explore this result further (e.g., differences in age and experience of drivers of different types of trucks; drivers that adapt their behavior to heavy truck safety problems).

Second, the coefficient for the light trucks variable is positive and statistically significant in all of the accidents equation regressions, but it is not statistically significant in the traffic fatalities equation. Therefore, in line with prior studies for the American case, higher numbers of light trucks on EU roads lead to greater accident risk but not necessarily to more severe accidents. According to Abdelwahab and Abdel-Aty (2004), Abdel-Aty and Abdelwahab (2004), Anderson (2008), Harb et al. (2007) and White (2004), among others, some specific features of light trucks and greater risk exposure, generally in (more hazardous) urban settings, might explain this effect, although with ambiguous net impacts in terms of fatality risk.

In Tables 5 and 6 we report the results of a test for any differences in the light truck and heavy truck coefficients when the dependent variable is fatalities per capita. Broadly speaking the test results suggest that the coefficients are indeed different, bearing in mind that the coefficient for heavy trucks is smaller than for light trucks. Thus, our results suggest that light trucks cause more fatalities than heavy trucks. However, as the coefficients are not statistically significant, the evidence that we find for heavy trucks having a lesser impact on traffic fatalities than light trucks is weak.

Consequently, the above findings confirm Hypothesis H1, while Hypothesis H2 is not confirmed.

Third, our Hypotheses 3 and 4 suggest that heavy truck usage leads to fewer traffic accidents and fewer fatalities compared to medium trucks. In this regard, we find that medium trucks increase the number of traffic fatalities, as the medium trucks variable is positive and statistically significant in all of the traffic fatalities equation regressions.

The European Accident Research and Safety Report (by Volvo Trucks, 2013) provides evidence of different heavy and medium truck patterns, which might explain this: accidents involving unprotected road users or involving other vehicles are more common for medium trucks. It should also be noted that the greater mass of medium trucks compared to smaller vehicles may mean that they are less flexible and have more complex dynamics than light trucks, while they may also be faster than heavy trucks due to their lower weight compared to heavier vehicles. Regarding the drivers of medium trucks, Corsi et al. (2014) show that driving performance is worse and traffic violation rates are higher for medium trucks than heavy trucks in the U.S.

To provide additional proof of the strength of the medium trucks variable we implement two different tests to show the unique explanatory power of this independent variable when it is added to the model. More specifically, we apply two different tests for nested models. The F-test for the null hypothesis that the variable omitted from the restricted model – the number of medium trucks – equals zero takes a value of 15.62 and is statistically significant at the 1% level. Furthermore, the likelihood-ratio test of the null hypothesis that the variable omitted from the restricted model – the number of medium trucks – equals zero takes a value 23.06 and is also statistically significant at the 1% level. Thus, both tests confirm the strength of the variable being considered.

Note here that in Table 7 we report the results of a test for the difference between the medium trucks and heavy trucks coefficients when the dependent variable is accidents per capita. The results of the test confirm the differences in the coefficients when using negative binomial distribution (which is our preferred estimation technique) but not when using an OLS regression. Thus, our results clearly suggest that medium trucks result in more traffic fatalities than heavy trucks. Furthermore, we find some evidence for the hypothesis that heavy trucks are involved in fewer accidents than medium trucks.

Therefore, these results confirm Hypothesis H4, while we find some evidence in favor of Hypothesis H3.

In general, not only statistical significance needs to be examined, but also the elasticities obtained from the estimated coefficients (evaluated at the sample means). Regarding the OLS regressions, a 10% increase in the number of medium trucks leads to an approximately 1.5% increase in the number of road traffic fatalities, while the increase is approximately 0.9% for light trucks. Additionally, a 10% increase in the number of heavy trucks leads to an approximately 0.5% decrease in the number of road traffic fatalities. Regarding the regressions with a negative binomial distribution, there is an approximately 1.2% increase in the number of road traffic fatalities for medium trucks and an approximately 0.4% increase for light trucks. The elasticities for the heavy trucks variable imply that a 10% increase in the number of heavy trucks leads to an approximately 0.3% reduction in the number of road traffic fatalities.

Regarding accidents, elasticities obtained from the coefficient estimates are similar whichever estimation technique is used. Thus, a 10% increase in the number of light trucks leads to an increase in the number of accidents of about 11%. Furthermore, a 10% increase in the number of medium trucks leads to an approximately 0.2% decrease in road accidents. Finally, the elasticities for the heavy trucks variable imply that a 10% increase in the number of heavy trucks leads to a reduction in the number of road accidents of approximately 4%.

In summary, our analysis suggests that it may be optimal from a safety perspective to implement policy measures to reduce the number of medium trucks (which are the trucks that lead to higher numbers of traffic fatalities) and encourage a switch to heavy trucks. According to our results, this may improve road safety outcomes.

Concerning the results of our control variables, regardless of the estimation technique used, we find evidence of a non-linear relationship between the road traffic fatality rate and a country's level of economic development, as was found in Bishai et al. (2006), Kopits and Cropper (2005) and Loeb and Clarke (2007). Indeed, the coefficient for the GDP variable is positive and statistically significant, while the square of the same variable is negative and statistically significant. In contrast, the GDP per capita variable does not seem to be consistently relevant in the accidents equation. In the accidents equation, the inverse U-relationship between GDP and accidents is only found in the OLS regressions that do not include the lag of the dependent variable as the explanatory factor.

The number of passenger cars per capita motorization rate variable is generally not statistically significant in either the traffic fatalities or the accidents equation. In the traffic fatalities equation, the interaction between motorization and the GDP per capita variable is positive and statistically significant. This provides some evidence that the effects of motorization on

road traffic fatalities may vary according to GDP per capita. Furthermore, the interaction between trucks per capita and the motorization rate variable is statistically significant whichever technique is used. In contrast, the correlation between the interaction variable and the truck load capacity variables may be distorting the individual identification of the above-mentioned variable.

The motorway density variable is not significant regardless of the dependent variable and estimation technique used. The variability of this variable over time is low, meaning that the country fixed effects model may already be capturing its effect. In contrast, the other roads density variable is positive and statistically significant in all the regressions that use traffic fatal-ities as the dependent variable, although it is not statistically significant when the dependent variable is the accident rate. Hence, this variable seems to capture the effect of inter-urban trips with lower quality infrastructure.

The young population variable is positive and statistically significant in most of the traffic fatalities equation regressions and in all of the accidents equation regressions. This confirms that younger people are subject to higher risk exposure. In contrast, the old population variable is positive but generally not statistically significant in the traffic fatalities equation and negative and generally statistically significant in the road accidents equation. This result confirms that the elderly incur less risk than other age groups, although this may not have a strong effect on the fatalities outcome.

The population density variable is negative and statistically significant in most of the fatalities equation regressions, and is positive and statistically significant in all of the accidents equation regressions. As mentioned above, the proportion of urban trips may be higher in more densely populated countries. Hence, the results for this variable suggest that accidents strongly correlate with urban trips, but that the accidents for these urban trips are not as severe.

Regardless of the technique used, we find that speed limits are effective for reducing road traffic fatalities and accidents (in line with previous research, such as Saifizul et al., 2011) while points-based driving license systems are less effective (in accordance with the findings of a worldwide meta-analysis by Castillo-Manzano and Castro-Nuño, 2012). Contrary to our expectations, we do not find that legal blood alcohol limits have a significant effect.

The time trend is negative and statistically significant in the traffic fatalities equation, whichever estimation technique is used. This is proof of a systematic reduction in road traffic fatalities over time. The results for this variable are less clear in the accidents equation, as the sign and statistical significance vary in the different regressions reported in Table 7.

5. Concluding remarks

The aim of the current paper was to explore the different impacts of three truck configurations based on truck load capac-ity (i.e., heavy, medium and light trucks) on road safety outcomes (i.e., accidents and fatalities) using European panel data. This is the first study to examine truck road safety with this breakdown of truck types, and the first to examine this break-down in the European Union (EU). Compared to earlier research, mostly skewed towards the U.S. case and with certain methodological inconsistencies that come from exposure data for different types of roads not being adequately considered, our study provides robust estimates that aim to fill these gaps. Specifically, our study applies different econometric tech-niques in the panel data framework to address the relationship between truck groups classified by load capacity and differ-ent accident categories for a broad geographical study case (several EU Member States), considering a variety of control variables, such as proxies for the types of road and for a wide timeframe.

Our results enable us to answer the research questions initially posed in the article. Differences in truck load capacity seem to influence road safety in the EU, but this influence is non-linear and depends on the accident type. Medium trucks are the worst performers in terms of traffic fatalities, while light trucks are the worst performers in terms of traffic accidents. Overall, heavy trucks do not seem to be associated with either more accidents or more fatalities.

Medium trucks may be less flexible than light trucks and can reach higher speeds than heavy trucks. Additionally, light trucks may be more frequently used for urban trips and are associated with greater risk exposure to traffic accidents.

Heavy trucks may be more resistant to accidents and are leading adopters of safety equipment. They also usually circulate on wider, better and safer roads and are subject to stricter speed limits due to their weight and size. Furthermore, they could replace a greater number of light or medium trucks, thus reducing vehicle-kilometers traveled and improving road safety per unit of freight moved.

In summary, as the correlation between economic activity and road safety is not linear but an inverse U-shaped curve, our findings seem to point to the existence of a complex relationship between trucks categorized by load capacity and road safety. We find a negative linear relationship between accidents and truck load capacity, where the highest number of acci-dents can be observed for light trucks. In the case of the most severe accidents (with fatalities), this relationship can resem-ble an inverse U-shaped curve, where the maximum of the curve can be observed for medium trucks: whereas the af Wåhlberg (2008) meta-analysis pointed to the existence of a positive non-linear relationship between the accident rate and truck load capacity, our estimations further clarify the relationship.

This reinforces the general idea that an apparently complicated correlation exists between variables to explain road acci-dents and their severity that goes beyond simple linear relationships. Further research is clearly needed into this issue, espe-cially in other geographical areas outside the EU, to test the validity of this inverse U-shaped curve between trucks categorized by load capacity and traffic fatalities.

From practical and policy perspectives, our results show that heavy trucks might be safer than light trucks. This may pro-vide a basis for improving engineering designs, managing more innovative systems and adopting customized regulatory

frameworks for different truck weights and configurations in the EU. This is in line with e.g., the Corsi et al. (2014) study, which recommends the adoption of stricter vehicle inspections and enforcement for medium trucks in the U.S.

Heavy trucks may therefore improve road safety and the logistics sector may benefit from increased efficiency and productivity due to their exploitation of scale economies, as higher capacity trucks carry more freight in fewer vehicles and may also offer benefits in the form of less traffic congestion and fewer emissions (ITF, 2010; Lemp et al., 2011; Thompson, 2015). In short, our findings point to roads being made safer through freight consolidation in a smaller number of heavy trucks in the EU. However, this could obviously also result in other problems in the supply chain.

With respect to urban freight pick-up and delivery in the so-called "*last mile*", heavy truck traffic has to contend with greater restrictions due to the built form of major European medium size and large cities focusing on the city center, which results in dense traffic, parking problems and high pollution levels (Dablanc et al., 2013). Heavy and medium trucks are regarded as slow vehicles that may contribute significantly to traffic congestion and pollution in urban areas. In addition, local governments have implemented regulations that impose access restrictions based on truck weight and dimensions (Nuzzolo and Comi, 2014).

This, together with the effect of liberalization processes in the European road haulage market during recent years, has resulted in greater numbers of light trucks than heavier trucks being involved in urban traffic, as they are apparently more efficient and, in certain cases, may be safer. This may be important for further research into the optimal dimension of freight transport vehicles with sustainability/safety/efficiency approaches, but is beyond the scope of the current article.

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