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Analyzing the safety impact of longer and heavier vehicles circulating in the European market

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ABSTRACT

Introduction: The European Union (EU) has developed different strategies to internalize the costs of excessive motor traffic in the road freight transport sector. One of these is a relaxation of restrictions on the size and load capacity of trucks that circulate between member States and a proposal has been made for Longer and Heavier Vehicles (LHVs) to be allowed to circulate across borders. LHVs are the so-called "megatrucks" (i.e., trucks with a length of 25 meters and a weight of 60 tonnes). Megatrucks have allowed to circulate for decades in some European countries such as Norway, Finland, and Sweden, world leaders in traffic accident prevention, although the impact that cross-border traffic would have on road safety is still unknown. *Methods:* This article provides an econometric analysis of the potential impact on road safety of allowing the circulation of "megatrucks" throughout the EU. *Results:* The findings show that countries that currently allow megatrucks to circulate present lower traffic accident and fatality levels, on average. *Conclusions:* The circulation of this type of vehicle is only advisable in countries where there is a certain degree of maturity and demonstrated achievements in the field of road safety. *Practical applications:* European countries that have allowed megatruck circulation obtaining better road safety outcomes in terms of accidents, although the accident lethality rate seems to be higher. Consequently, introducing megatruck circulation requires a prior proper preparation and examination.

1. Introduction

Road traffic is currently the main mode of transport used in the European Union (EU) to address increasing freight demands. The European Commission (EC) expects that by 2030 the volume of road freight transportation could rise 83% over the 2005 level (Korzhenevych, Dehnen, Broecker, Holtkamp, Meier, Gibson, & Cox, 2014). However, the external costs associated with motorized transportation modes (accidents, congestion, noise, and pollution) that are generally attributable to heavier-duty vehicles (Alises & Vassallo, 2015; Piecyk & McKinnon, 2010) have led the EC to take decisive action to create a more efficient and safer transport logistics chain with less impact on the environment. The purpose of this paper is to evaluate one of these strategies, Longer and Heavier Vehicles (LHVs), and the related road safety issues.

The inclusion in EU policies of concepts such as multi-modality and inter-modality reflects the depth of the challenges facing the road transport sector (Teutsch, 2013). These policies aim to improve the individual modes of transport, to make better use of infrastructure, and to combine the different modes into multimodal chains to create a sustainable transport system to gain a competitive advantage (Liotta, Stecca, & Kaihara, 2015) within a framework of liberalization, deregulation, and competition (see e.g., Koliousis, Koliousis, & Papadimitriou, 2013). These issues are apparent in Transport Policy matters such as the *Eurovignette* Directive 2006/38/EC (see McKinnon, 2006); Short Sea Shipping (SSS) (Douet & Cappuccilli, 2011)—which has attracted a great deal of attention as a substitution mode for freight transportation (Suárez-Alemán, Trujillo, & Medda, 2014)—and, specifically, the Motorways of the Sea (MoS), designed to reduce long-distance inter-State land transport freight operations (Baindur & Viegas, 2011). The freight rail system also appears to offer an alternative to road freight transport that could reduce congestion, increase energy efficiency, and generate less pollution.

These expectations have not been fully met. According to Golinska and Hajdul (2012), the evidence shows that transportation policies have serious limitations and drawbacks, which suggests that there has still not been the widespread freight modal shift that was being sought. The EU has, therefore, considered another alternative to road freight transport based on the relaxation of the current

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restrictions imposed by Directive 1996/53/EC (see http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:31996L0053)[1]. This would clear the way for the unrestricted circulation of longer heavier vehicles (LHVs) known as "megatrucks," gigaliners or eurocombis (up to 25 meters in length and 60 tonnes in weight). Larger freight vehicles have been circulating in some Scandinavian countries with underdeveloped rail systems (e.g., Norway, Sweden[2], and Finland) since the mid-1990s. Interestingly, these countries are also leaders in road safety. Subsequently, megatruck circulation has also been authorized in some other EU states, such as Spain (Ortega, Vassallo, Guzmán, & Pérez-Martínez, 2014). Several other countries have also carried out trials to test the effects of megatrucks on infrastructure capacity and fuel consumption, the implications for the environment and energy, and consequent changes in transportation costs (e.g., see Meers, van Lier, & Macharis, 2018 for Belgium and Sanchez-Rodrigues, Piecyk, Mason, & Boenders, 2015 for Germany). The results of almost all these pilot schemes have been positive and the EC has, therefore, proposed the legalization of cross-border megatruck circulation.

In June 2012, the EC announced the cross-border circulation of megatrucks between two member states that approved their use within their borders but strong opposition from the European Parliament and some member states eventually led to the initial Directive being amended by Directive EU/2015/719 (see http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv%3AOJ.L_0.2015.115.01.0001.01.ENG). This amendment, which has still not been fully enacted in all EU countries, included a derogation from the maximum weights and lengths laid down in the original Directive to improve the safety and environmental emissions of heavy freight vehicles and also recommended that no changes should be made to restrictions on the cross-border movement of megatrucks laid down in Directive 1996/53/EC.

As the cross-border circulation LHV is currently a controversial issue in the EU (see e.g., Odeck & Engebretsen, 2014), this paper uses multivariate models to carry out an econometric exploration of the impact of megatruck circulation on road safety outcomes. Novel panel data are used for European countries (EU members + European Free Trade Association_EFTA_members) over the 1996–2014 period; i.e., the period between the two EU Directives that regulate the circulation of this type of vehicle. We aim to cover the gap in the literature on the impact of megatruck circulation on traffic safety as, to date, there has been no precedent that uses a rigorous econometric approach to address this topic globally for the entire European study case.

We estimate a multivariate regression model that controls for all explanatory variables that previous studies consider relevant for identifying the determinants of road accidents and fatalities. The use of country fixed effects allows us to control for time-invariant unobserved factors and the inclusion of a time trend allows us to control for unobserved shocks common to all countries. Finally, we apply the logic of differences in differences to enable the identification of changes in safety performance due to megatruck circulation in the treated countries (countries where megatrucks have been permitted to circulate at some point during the considered period) compared to the control countries (countries where the circulation of megatrucks has not been allowed).

Our main novel contribution to the literature is an empirical exploration of the implications of LHV circulation for safety performance. We consider a broad sample formed not of one specific country but of European countries (EU and others) that have allowed megatruck circulation. Countries where megatrucks do not circulate are used as a control group. Our research provides evidence of the potential consequences for safety of LHV fleet circulation in different states and these can be taken into consideration by policymakers designing measures to mitigate negative safety effects. This investigation also follows suggestions in earlier studies such as Sanchez-Rodrigues et al. (2015) as to the need to assess the impact of LHVs for more than a single country case.

Previous analyses of the effects of increasing the maximum weight and size of freight vehicles in Europe conducted by our research group in this line of research suggest that the largest trucks are not necessarily responsible for a higher mortality rate in Europe (Castillo-Manzano et al., 2015; Castillo-Manzano, Castro-Nuño, & Fageda, 2016). We now focus on responding to the following research questions: although part of the literature shows that megatrucks might be more efficient from the economic, logistical, and environmental points of view (Bergqvist & Behrends, 2011; Guzmán, Vassallo, & Hortelano, 2016; McKinnon, 2008; Ortega et al., 2014), can it also be stated that European highways are safer in places where these types of vehicles are allowed to circulate freely? Are countries where LHV or megatruck circulation is permitted safer when the impact is evaluated in terms of global road safety (i.e., involving all types of users and vehicle crashes)? Would it be advisable to allow megatrucks to circulate throughout Europe?

In short, our aim is that, via some practical managerial implications, our findings might shed some light on the road freight transport industry's skepticism around the introduction of LHVs due to a lack of sound information and knowledge.

This paper is organized as follows: after this Introduction, Section 2 sets out the state-of-the-art on LHV impacts; Section 3 describes the empirical analysis and methodology; Sections 4 present and discuss the results, Section 5 offers the conclusions of the study, followed by some relevant practical applications of the work in Section 6.

2. Literature review

Earlier researchers agree that differences in truck weight and configuration affect road safety (Castillo-Manzano et al., 2016; Corsi et al., 2012, 2014; Evgenikos et al., 2016). Specifically, much recent literature has addressed the effects of LHVs across Europe and evaluated certain states' experiences of implementing megatrucks or conducting trials; however, these have mostly been published as government or institutional reports (see e.g., ETSC, 2011; ITF, 2010; Knight et al., 2008; TML, 2008), with only a small number of academic papers (Knight, Burgess, Maurer, Jacob, Irzik, Aarts, & Vierth, 2010). Additionally, most scientific works analyzed the changes in truck dimensions and weight post-Directive 1996/53/EC, which raised these from 18.75 to 25.25 meters and 40 to 60 tonnes, respectively. The majority of these reports have focused on Scandinavian and Northern and Central European countries (Pålsson & Sternberg, 2018), including Sweden (Vierth, Lindgren, & Lindgren, 2018), the United Kingdom (Leach, Savage, & Maden, 2013; Liimatainen, Greening, Dadhich, & Keyes, 2018; McKinnon, 2005; Palmer, Mortimer, Greening, Piecyk, & Dadhich, 2018), Norway (Odeck & Engebretsen, 2014), Finland (Lajunen, 2014; Liimatainen, Pöllänen, & Nykänen, 2020; Lindt, Janka, & Dehdari, 2020; Palander, Haavikko, & Kärhä, 2018), Belgium (Meers et al.,

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[1] This Directive allows the circulation of Heavy Goods Vehicles (HGV) with a maximum permitted length of 16.50 meters for articulated vehicles (semis) and 18.75 meters for road trains with a total combined weight of 40 tonnes but does not permit cross-border LHV traffic.

[2] Sweden has pioneered the use of Longer and Heavier Vehicle combinations and currently allows the circulation of heavier and longer road freight vehicles (maximum gross weight of 64 tonnes and length of 25.25 meters) than most European countries. The introduction of so-called High Capacity Vehicles (HCVs) has also recently been tested on certain segments of public roads. These are vehicles with a gross weight of 74 tonnes and a length of 34 meters (see Pålsson & Sternberg, 2018). HCVs with a gross weight of 76 tonnes and a length of 25.25 meters have been circulating on the road network in Finland since 2013 (Liimatainen & Nykänen, 2017).

2018), the Netherlands (Quak, 2012), and Germany (Burg, Neumann, Bühne, & Irzik, 2019; Sanchez-Rodrigues et al., 2015) and even specific corridors between countries such as Sweden and Germany (Vierth & Karlsson, 2014). Other papers have also investigated the most recent case: Spain (Guzmán & Vassallo, 2014; Guzmán et al., 2016; Ortega et al., 2014).

Considering all the evidence, the evaluations of LHV introduction can be grouped by their objectives. Several studies focus on the effects on infrastructure, highlighting increases in the cost of road maintenance and conservation caused by megatruck circulation, especially the strengthening of bridges and the replacement of fatigued road pavements (Christidis & Leduc, 2009; OBrien, Enright, & Caprani, 2008; UIC, 2014).

Another group of contributions explores the impact of LHVs on the modal split in logistics and provides evidence that the free movement of megatrucks in the EU would result in higher productivity and, therefore, the opportunity for road haulers to offer better prices (Christidis & Leduc, 2009; ITF, 2010; Ortega et al., 2014; Steer, Dionori, Casullo, Vollath, Frisoni, Carippo, & Ranghetti, 2013). Some studies determine that increasing truck dimensions and capacity would lead transport operators to consolidate and optimize loads with a consequent fall in the numbers of vehicles required (Nykänen & Liimatainen, 2014) due to the improved efficiency reducing the number of trips per freight tonne (McKinnon, 2005). This would translate into lower transport (McKinnon, 2011; Woodrooffe et al., 2010) and travel time costs (Pérez-Martínez & Vassallo, 2013; Proost et al., 2002). These changes might achieve a modal shift from rail and increase demand (Eom, Schipper, & Thompson, 2012; Knight et al., 2008; Nealer, Matthews, & Hendrickson, 2012) and more unfavorable consequences could also be generated for other collectives. For example, this measure might trigger the progressive transfer of a share of freight transport from rail to road, which would benefit LHVs (Meers et al., 2018; Rijkswaterstaat, 2010). The maritime transport sector might not be affected, however (Ortega et al., 2014). The introduction of the use of these vehicles might also have harmful effects for small haulage operators as the number of routes would be reduced and this could affect regional-level employment (Guzmán et al., 2016). Ortega et al. (2014) state that megatrucks would reduce costs per tonne-kilometer transported. This would have a knock-on effect with a cost reduction for the consumer, thus giving a boost to the economy. According to Vierth et al. (2018), all these arguments are inconclusive as results can vary depending on country-specific conditions and price elasticities. Other analysts predict a much more moderate modal split (Salet et al., 2010) that may even suggest a complementary relationship between LHVs and rail freight transport (Bergqvist & Behrends, 2011).

A third group of studies analyzes the impact of LHVs from an energy efficiency and environmental perspective based on energy consumption and greenhouse gas emissions. Several authors argue that the introduction of megatrucks (with lower freight transport operating costs) would lead to greater growth in road freight traffic than rail traffic, with a consequent increase in pollution (McKinnon, 2005; Palander, 2017). Other scholars such as Pålsson and Sternberg (2018) and Vierth et al. (2008) point to savings in fuel consumption and reductions in air pollutants per tonne-kilometer transported compared to HGVs due to the reduction in the number of journeys (Leach et al., 2013). Researchers such as Sanchez-Rodrigues et al. (2015) emphasize the key role of the effective payload to explain this environmental effect.

Finally, very little academic literature can be found that considers the effects of European megatrucks on road safety, which is the object of this article. Safety should be considered a key concern. According to Grïslis (2010), researchers have generally adopted two approaches to the study of LHV safety. The first concerns vehicle safety assessment and is focused on elements of vehicle engineering, operational characteristics, and design requirements (Debauche & Decock, 2007; Hanley & Forkenbrock, 2005; Knight et al., 2008).

The second approach considers the impact of LHVs on safety performance indicators (e.g., accidents, fatalities), although no study has been able to conclusively determine the real effect of their introduction (Grïslis, 2010). Some of the trial-based research (e.g., Backman & Nordström, 2002; Knight et al., 2008; Rijkswaterstaat, 2010) concludes that megatruck circulation should lead to a decrease in traffic, which would improve road safety (fewer accidents), especially if the stability and maneuverability of the vehicles were improved through the installation of certain technological advances (as suggested by Christidis & Leduc, 2009; Klingender, Ramakers, & Henning, 2009) or appropriate driver training (Sanchez-Rodrigues et al., 2015). Other analyses state that accident severity is expected to be higher when vehicles of this type are involved (Glaeser & Ritzinger, 2012; Glaeser, Kaschner, Lerner, Roder, Weber, Wolf, & Zander, 2006; Vierth et al., 2008), especially in some specific environments such as tunnels and bridges (McKinnon, 2008; Ortega et al., 2014) or on certain roads such as two-lane highways (Hanley & Forkenbrock, 2005). Other authors such as Debauche and Decock (2007) did not find any evidence of LHV circulation impacting safety.

Following Grïslis (2010) literature review, this lack of uniformity in safety findings for LHVs could be explained by the different methodologies used and statistical datasets that vary from country to country. In other cases, it may not be possible to find any empirical proof due to a lack of specific data on traffic accidents involving LHVs. Compared to two other studies that analyze LHVs and road safety (see Grïslis, 2010, for a literature review and Klingender et al., 2009, for a detailed safety method), our paper provides a novel quantitative evaluation based on an econometric analysis. The present research, therefore, pursues a line of research suggested by Sanchez-Rodrigues et al. (2015): a comparative study of a wide set of EU and non-EU European countries to generalize findings.

3. Empirical framework and method

The empirical regression used to estimate the impact of megatruck circulation on road safety takes the following form for country *i* during period *t*:

$$\mathrm{Y}_{\mathrm{it}} = \alpha + \beta_{\mathrm{k}}\mathrm{X}_{\mathrm{it}} + \gamma_{\mathrm{k}}\mathrm{Z}_{\mathrm{it}} + \lambda_{\mathrm{k}}\mathrm{W}_{\mathrm{it}} + \mu_{\mathrm{i}} + \nu\mathrm{Time\_trend}_{\mathrm{t}} + \varepsilon_{\mathrm{it}} \tag{1}$$

In this equation, we consider two different dependent variables (Y_{it}) in two different regressions: the total number of fatalities (fatalities within 30 days of the accident, as per the Vienna Convention definition) and the total number of accidents (accidents involving personal injury, according to available statistical sources, see Table 1). Note that both of the endogenous safety variables are related to crashes involving any road user type to enable an assessment of the effects of megatruck circulation on all traffic safety, not only crashes involving trucks.

The model (1) also contains a vector X_{it} for the country's economic and demographic attributes; a vector Z_{it} that refers to the megatruck variable, and W_{it}, which represents road safety policy-related variables. μ_{i} are country fixed effects that control for omitted time-invariant country-specific variables; Time trend is an annual time trend that controls for unobserved shocks common to all countries, such as the evolution of oil prices, for example, and $\varepsilon_{\mathrm{it}}$ is a mean-zero random error.

We consider data for the 27 current European Union member countries (and also United Kingdom) and three EFTA countries (Iceland, Norway, and Switzerland). More specifically, we study European countries that allowed megatruck circulation or carried

Table 1
Variables used in the empirical analysis.

Variables	Description	Source	Type of data
Fatalities	Number of traffic fatalities	CARE (EU road accident database)	Dependent variable
Injury accidents	Number of traffic injury accidents	CARE (EU road accident database)	Dependent variable
Population	Number of inhabitants (in millions)	EUROSTAT	Country attribute
Motorization	Number of registered passenger cars per thousand inhabitants	UNECE, EUROSTAT (for population)	Country attribute
GDP per capita	Per capita Gross Domestic Product in Internationally Comparable Prices (US$ at 2005 prices and PPP)	EUROSTAT	Country attribute
Superhighway density	Number of kms of superhighway over country area in km^2	UNECE, EUROSTAT	Country attribute
Age	Median age of population (in years)	EUROSTAT	Country attribute
Population density	Number of inhabitants over country area in km^2	EUROSTAT	Country attribute
Passengers_km_railways	Number of rail passengers per km of track (in billions)	Eurostat, International Transport Forum, UNECE, Union Internationale des Chemins de Fer	Country attribute
Passengers_km_roads	Number of passenger-cars-km expressed in 1,000 million km	European Commission (Directorate General for Mobility and Transport)	Country attribute
Heating-degree_index	Index based on the number of cold days per year.	Eurostat	Country attribute
BAC	Maximum blood alcohol concentration rate allowed while driving in g/l	European Commission Road Safety Website	Road safety policy
Point_system	Dummy variable that takes a value of 1 if a point-based driving license system is in force; 0 otherwise	European Transport Safety Council (ETSC)	Road safety policy
Speed limit	Maximum speed limit allowed on superhighways (in km/h)	European Commission Road Safety Website	Road safety policy
Megatrucks	Dummy variable that takes a value of 1 when intra-border megatruck circulation is permitted; 0 otherwise	Directorate general for internal policies: a review of megatrucks (2013) and national legislations	Main explanatory variable

out trials during our timeframe, compared to a control group formed of the remaining countries, which did not. So, the megatrucks variable takes a value of one for the following countries in our sample (year megatruck circulation came into force in parentheses): Denmark (2008), Finland (1996), Germany (2010), Netherlands (2007), Norway (2008), Portugal (2014), Sweden (1996).

Given that the second Directive (which strengthened the first Directive) has still not been fully executed in all EU countries, we chose the 1996–2014 period for the study as it is the time period between the two EU Directives that regulate truck size and weight limits (i.e., Directive EU/1996/53 and Directive EU/2015/719).

The unit of observation is the country-year pair. Our panel data are unbalanced, as data for some variables are not available for some countries for all years. 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.

Explanatory variables used in the analysis model were GDP per capita and the square of GDP per capita at the country level since a non-linear relationship is expected between a country's economic development and its road safety outcomes (Bishai, Quresh, James, & Ghaffar, 2006; Castillo-Manzano et al., 2014, 2015, 2016; Kopits & Cropper, 2005; Loeb & Clarke, 2007; Yannis, Papadimitriou, Mermygka, & Engineer, 2015). Countries where the economy is more developed may be affected by greater exposure to accidents. However, after reaching a certain wealth threshold, richer countries may have better infrastructure, vehicles, policies, and social attitudes, and so they may have better safety outcomes. The sign of the coefficient of the GDP variable is, therefore, expected to be positive and that of GDP^2, negative. Note also that the GDP variables allow us to control for the severe economic crisis that occurred during the considered period and which generated a great deal of debate about how the economic recession has influenced road safety (e.g., road user behavior, particularly among high-risk drivers) and road traffic in Europe (Antoniou, Yannis, Papadimitriou, & Lassarre, 2016; Wegman et al., 2017).

As in previous studies (Albalate & Bel, 2012; Castillo-Manzano et al., 2015, 2016; Kopits & Cropper, 2005), a further explanatory variable is included in the model as a proxy of the level of development of private transport: the number of passenger cars per capita (motorization). It is not clear which sign should be expected for this variable since, as in the case of the GDP variables, higher motorization rates may imply greater exposure to road traffic accidents but may also be linked to better and safer vehicles. We also take into account the influence of the quality of transport infrastructure by including a variable for superhighway density. The literature has proven a negative correlation between the quality of road infrastructure and safety outcomes, so a negative sign is expected for the coefficient of this variable (see, e.g., Castillo-Manzano et al., 2014; Jamroz, 2012; Wang, Quddus, & Ison, 2013). Another variable included in the model is the median age of the population. The sign that can be expected for this variable is not clear *a priori*. Younger road users may take more risks (Constantinou, Panayiotou, Konstantinou, Loutsiou-Ladd, & Kapardis, 2011; Langford, Methorst, & Hakamies-Blomqvist, 2006) but accidents may have a greater impact on older drivers (Koppel, Bohensky, Langford, & Taranto, 2011; Yee, Cameron, & Bailey, 2006).

The number of passengers-km on roads is an additional explanatory variable in our model. This variable seeks to capture road traffic intensity. We could expect a positive relationship between the amount of traffic and road fatalities since the total amount of driving is an indication of the population's exposure to road accident risks (Orsi et al., 2012). However, as Li, Graham, and Majumdar (2012) find, such a relationship could be dependent upon congestion levels.

A variable for the country's population density is also considered. We may expect that the proportion of urban journeys over total journeys will be higher in more densely populated countries. So, the number of accidents for urban journeys should be higher than for inter-urban journeys but the severity of accidents may be lower for urban journeys (Rakauskas, Ward, & Gerberich, 2009; Zwerling et al., 2005). Therefore, the sign that should be expected for the coefficient associated with this variable is not clear *a priori*. We also include a variable for the amount of traffic by rail (Passengers_km_railways). Given that the safety outcomes of rail journeys are systematically better than of cars and trucks (Bubbico, Di Cave, & Mazzarotta, 2004; Demir, Huang, Scholts, & Van Woensel, 2015; Forkenbrock, 2001), we can expect the coefficient for this variable to have a negative sign.

As in some previous studies (Albalate, 2008; Castillo-Manzano et al., 2015, 2016), several variables for specific road safety policies are also considered in the equation. A variable is included for the maximum permitted blood alcohol concentration. To capture the

Table 2
Descriptive statistics of variables used in empirical analysis.

Variables	Mean	Standard Deviation	Minimum value	Maximum value	Number of observations
Fatalities	1473.18	1942.12	4	8920	589
Injury accidents	43.52	76.17	0.58	395.69	585
Population_density	16.31	21.47	0.12	81.81	589
Motorization	422.37	115.91	103	667	589
GDP per capita	31092.33	13738.1	9249	87,873	579
Superhighway density	2207.76	3488.55	0	14,701	508
Age	38.59	2.62	31.1	45.6	584
Population density	158.72	228.35	2.7	1352.4	578
Passengers_km_railways	14.43	21.47	0.2	89.6	532
BAC	0.39	0.22	0	0.8	589
Point_system	0.57	0.49	0	1	589
Speed limit	120.06	14.11	80	130	589
Heating_degree_index	2909.386	1185.23	345.03	6179.75	513
Passengers-km-roads	150.58	238.06	1.7	920.8	589
Megatrucks	0.11	0.31	0	1	589

implementation of a point-based driving license, a dummy variable is included with a value of one if a penalty driving license system is applied. The introduction and application of any type of point system to driving licenses can lead to lower numbers of traffic fatalities and accidents (Castillo-Manzano & Castro-Nuño, 2012; Castillo-Manzano, Castro-Nuño, & Pedregal, 2011). A road traffic policy variable for the maximum speed limit allowed on superhighways is also considered. As one of the main effects of higher speed limits may be worse road safety performance (Elvik, 2012) (i.e., greater numbers of fatalities and accidents), a positive sign can be expected for the coefficient of this variable.

Regarding weather and meteorological conditions, country-level rain data are not available for the long period examined in this paper. We include the Heating Degree Days index (HDD) as a proxy of temperature. *HDD* measures cold severity during a specific time period and takes into consideration both *outdoor* and *average room* temperature. *HDD* calculation relies on the *base* temperature, defined as the lowest daily mean air temperature not leading to indoor heating. Although the base temperature depends on several factors associated with the building and the surrounding environment, the index adopts a general climatological approach and sets the value at 15 °C. With T_m^i as the mean (m) air temperature of day *i* (measured in °C), the *HDD* of a certain year is given by:

$$HDD = \begin{Bmatrix} \sum_i^I 18 - T_m^i & \text{for} T_m^i \leq 15 \\ 0 & \text{for} T_m^i > 15 \end{Bmatrix}$$

where *I* denotes the number of days in the considered year. For example, if the daily mean air temperature is 12 °C, the value of the HDD index for that day is 6 (i.e., 18 °C–12 °C). However, if the daily mean air temperature is 16 °C, the HDD index for that day is 0.

One limitation of this variable is that it is only available for European Union countries, which implies excluding relevant cases in our context such as Norway and the United Kingdom. So, we also report results of regressions omitting the HDD variable.

The main variable of interest in our analysis is a dummy variable that takes a value of one for countries where the use of megatrucks is permitted, as we have explained above.

We apply the logic of differences in differences (DiD), which is a common methodology used in the treatment evaluation framework (for details, see Angrist & Pischke, 2009; Gertler, Martinez, Premand, Rawlings, & Vermeersch, 2016). The identification strategy in a DiD analysis relies on collecting several years of data for two groups of observations: one group affected by the treatment/policy at some point during the considered period and a control group not affected by the policy in any year of the considered period. In our context, we have a panel dataset that includes countries where megatruck circulation is not permitted (control countries) and countries where megatrucks have been allowed to circulate at some point in the considered period or earlier (treated countries). Hence, the DiD variable in our analysis is a dummy variable that takes a value of one for countries where the use of megatrucks has been authorized since the year in which the policy was implemented. Therefore, if we control for all the relevant explanatory factors, we can identify changes in safety performance due to megatruck circulation in treated countries compared to the safety performance of the control countries. Examples of recent studies that evaluate policies in the transportation sector in the DiD framework include Aguirre, Mateu, and Pantoja (2019), Bernardo and Fageda (2017), Conti, Ferrara, and Ferraresi (2019, Haojie Li, Graham, and Majumdar (2012), Jiménez, Perdiguero, and García (2018), Oum, Wang, and Yan (2019), Wolff (2014).

According to previous studies (see Section 2, literature review), we are uncertain about the sign that this variable should take. The scarce literature that analyzes the safety impact of megatruck circulation for isolated cases in specific countries includes both scholars who argue an improvement in road safety due to the reduction in the number of traffic accidents resulting from fewer journeys made (e.g., Knight et al., 2008; Rijkswaterstaat, 2010) and studies that emphasize the greater severity of road accidents due to the vehicles' size and lack of maneuverability, especially in certain infrastructures (Ortega et al., 2014; Vierth et al., 2008).

4. Results

Table 3 shows the correlation matrix of the variables used in the empirical analysis. Multicollinearity can exaggerate estimates of the variance parameter and distort its statistical significance or even result in parameter estimates of implausible magnitude in the most extreme cases. Taking this into account, there are four variables that are highly correlated (Passengers-km-roads, Motorization, Superhighway density, Passengers-km-railways). The high correlation between the heating_degrees_index variable and the megatrucks variable must also be considered. To examine the influence of the high correlation between these variables, we report the results of various regressions. First, we include all the variables. Second, we exclude the heating_degrees_index variable, which also has the limitation of only being available for European Union countries. Then, we exclude the Passengers-km-roads variable. Further regressions also exclude the Motorization and Passengers-km-railways variables, respectively.

Heteroscedasticity and temporal autocorrelation problems may be present in the error term. Running the Wooldridge test for autocorrelation in our panel data shows that there may be an autocor-

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

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
Fatalities (1)	1													
Accidents (2)	0.75	1												
Megatrucks (3)	−0.16	−0.01	1											
Heating_degree_index (4)	−0.36	−0.28	0.56	1										
Passengers_km_roads (5)	0.80	0.80	0.01	−0.30	1									
Motorisation (6)	0.13	0.36	0.20	−0.04	0.40	1								
Passengers_km_railways (7)	0.80	0.82	0.02	−0.26	0.97	0.33	1							
GDP per capita (8)	−0.05	0.14	0.22	−0.02	0.17	0.74	0.16	1						
Superhighway density (9)	0.70	0.78	0.02	−0.37	0.89	0.38	0.86	0.20	1					
Age (10)	−0.02	0.29	0.27	−0.01	0.27	0.47	0.24	0.16	0.27	1				
Population density (11)	0.19	0.34	−0.12	−0.37	0.27	0.23	0.27	0.34	0.24	0.06	1			
BAC (12)	0.12	0.25	0.06	−0.13	0.29	0.54	0.23	0.41	0.33	0.19	0.18	1		
Point_system (13)	0.13	0.18	0.05	−0.05	0.26	0.32	0.25	0.17	0.22	0.43	−0.01	0.17	1	
Speed limit (14)	0.27	0.21	−0.18	−0.40	0.23	0.11	0.26	0.12	0.16	−0.02	0.34	−0.10	0.24	1

relation issue and the Breusch–Pagan/Cook–Weisberg test indicates that we have a heteroscedasticity issue. We, therefore, run the regressions with standard errors robust to heteroscedasticity and specifying an AR (1) within-group correlation structure for the panels to address the autocorrelation issue. The variables used in the empirical analysis also have to be tested for normal distribution. We apply the Doornik–Hansen test for multivariate normality, which shows that our variables are not normally distributed.

The estimation is made using the population-averaged panel-data model with a negative binomial distribution. Count models are commonly used in the analysis of the determinants of road traffic fatalities (Albalate, Fernández, & Yarygina, 2013; Hauer, 1995; Johansson, 1996; Karlaftis & Tarko, 1998; Quddus, 2008). As is usual in road safety studies, we estimate a negative binomial model that is a standard count model. The advantage of negative binomial distribution is that it explicitly models the dependent variable as the number of occurrences and it takes into account the non-normality distribution of the variables. Note that the country population variable is included as an exposure variable, so its coefficient is restricted to one. This enables us to interpret the results in terms of rates per capita.

The sample considered in this study has been structured as panel data as we have information available for 31 countries and several years. The two main panel data models are random effects and fixed effects. The fixed-effects model is usually the preferred model because it controls for omitted variables that are correlated with the variables of interest and are time-invariant. For example, the effect of time-invariant variables such as latitude are already captured by the country fixed effects. Country fixed effects may also capture the fact that weather conditions are systematically worse for some countries than others. In contrast, the random-effects model may cause a bias in the estimation as the variables of interest may be correlated with the rest of the explanatory variables. The fixed-effects model identifies changes from one period to another, so it is the most appropriate method for the evaluation of the megatrucks policy. As it is based on the ("within") transformation of the variables as deviations from their average, the fixed-effects model allows us to compare changes in road safety outcomes in countries where megatrucks are permitted with countries where they are not. Note that we report the results of an F-test that confirms that the country fixed effects variable is statistically significant, which rules out the use of a pooled model.

Tables 4 and 5 reports the results of the different regressions described above. Table 4 considers traffic fatalities as the endogenous variable while that Table 5 considers traffic injury accidents as the endogenous variable

Note: Standard errors in parentheses (robust to heteroscedasticity). All regressions include country fixed effects. Regressions specify an AR (1) within-group correlation structure for the panels. Population is used as an exposure variable. Statistical significance at 1% (***), 5% (**), 10% (*).

Note: Standard errors in parentheses (robust to heteroscedasticity). All regressions include country fixed effects. Regressions specify an AR (1) within-group correlation structure for the panels. Population is used as an exposure variable. Statistical significance at 1% (***), 5% (**), 10% (*).

Regarding the control variables, we find evidence of a non-linear relationship between road traffic fatalities and the country's level of economic activity. This corroborates the findings of Bishai et al. (2006) and Kopits and Cropper (2005). A positive and statistically significant coefficient is obtained for the GDP variable, while GDP^2 is negative and statistically significant. Similar results are found when the dependent variable is traffic accidents, although the statistical significance of GDP^2 is more modest.

The motorization variable is generally not statistically significant. As argued by Castillo-Manzano et al. (2016), the sign of the effect of the motorization variable on safety outcomes may vary depending on the country's GDP level. The superhighway density variable is negative and statistically significant in most of regressions for traffic fatalities. There is, therefore, some evidence to support the hypothesis that more advanced infrastructure may reduce traffic fatalities (according to previous studies such as Castillo-Manzano et al., 2014; Wang et al., 2013, for example) but does not have a clear effect on injury accidents.

The rail traffic variable is negative and statistically significant in several regressions considering fatalities as the dependent variable. So, countries in which rail plays a greater role in mobility may have better safety outcomes, at least in terms of lower fatalities (as was expected, in line with e.g., Litman, 2007). More alcohol-tolerant policies seem to have generally negative effects both in terms of fatalities and injury accidents, which is in line with previous analyses such as Castillo-Manzano, Castro-Nuño, Fageda, and López-Valpuesta (2017). Higher speed limits may lead to higher fatalities, corroborating previous studies such as Castillo-Manzano, Castro-Nuño, López-Valpuesta, and Vassallo (2019) and Elvik (2012). The time trend is negative and statistically significant irrespective of the regression, which suggests an improvement in road safety outcomes even after controlling for all the observed factors that might affect these outcomes. Finally, we do not find any significant effects of the population density and point-system driving license variables. It may be that the variability in our sample is not high enough to identify any relevant effects for these variables.

As usual, the negative binomial uses a log-link function, so the coefficients can be interpreted in terms of elasticities. Taking this into account, we find that the coefficient of the megatrucks vari-

Table 4
Results of estimates (population-averaged panel-data model with negative binomial distribution).

Independent variables	Dependent variable: fatalities				
	Regression (1)	Regression (2)	Regression (3)	Regression (4)	Regression (5)
Megatrucks	0.19	0.15	0.15	0.15	0.12
	(0.07)***	(0.06)***	(0.06)***	(0.06)***	(0.06)**
Heating_degree_index	−0.000008	–	–	–	–
	(0.00005)				
Passengers_km_roads	−0.0005	−0.001	–	–	–
	(0.001)	(0.002)			
Motorisation	−0.0006	−0.0004	−0.0005	–	–
	(0.0003)*	(0.0003)	(0.0004)		
Passengers_km_railways	−0.03	−0.02	−0.03	−0.02	–
	(0.007)***	(0.01)**	(0.01)**	(0.01)*	
GDP per capita	0.00004	0.00005	0.00005	0.00005	0.00005
	(0.00001)***	(0.00001)***	(0.00001)***	(0.00001)***	(0.00001)***
GDP^2 per capita	−2.65e10	−3.31e10	−3.29e10	−3.00e10	−2.1e10
	(1.01e-10)***	(1.12e-10)***	(1.11e-10)***	(1.09e-10)***	7.85e-11)***
Superhighway density	−0.0006	−0.0006	−0.0007	−0.0007	−0.00008
	(0.00002)*	(0.00003)*	(0.00004)*	(0.00004)*	(0.00006)
Age	0.0006	0.0008	0.0003	−0.001	0.009
	(0.03)	(0.03)	(0.03)	(0.03)	(0.03)
Population density	−0.001	0.003	0.004	0.005	−0.0011
	(0.005)	(0.005)	(0.005)	(0.005)	(0.003)
BAC	8.62	5.84	4.03	4.03	1.51
	(4.56)**	(5.22)	(1.43)***	(1.44)***	(0.45)***
Point_system	0.01	0.00005	0.003	−0.0001	0.08
	(0.04)	(0.04)	(0.04)	(0.04)	(0.06)
Speed limit	−0.08	0.07	0.08	0.08	0.04
	(0.06)	(0.04)*	(0.04)*	(0.04)*	(0.03)
Time_trend	−0.06	−0.06	−0.06	−0.07	−0.07
	(0.009)***	(0.009)***	(0.009)***	(0.009)***	(0.01)***
Intercept	145.88	120.92	119.71	122.94	151.05
	(16.82)***	(18.87)***	(19.69)***	(20.84)***	(20.60)***
Test joint sign (Wald χ^2)	1081.64***	367.13***	975.62***	257.80***	269.98***
Test F (Ho: Country fixed effects = 0)	88.63***	96.90***	105.37***	108.13***	93.27***
Breusch–Pagan/Cook–Weisberg test for heterogeneity (Ho: Constant variance)	235.88***	299.01***	267.51***	292.83***	298.76***
Wooldridge test for autocorrelation (Ho: No first-order autocorrelation)	416.22***	375.91***	348.07***	348.56***	309.73***
Doornik–Hansen test for multivariate normality	40632.90***	40184.35***	39321.40***	39017.66***	40007.85***
No. of observations	413	464	464	464	494

Note: Standard errors in parentheses (robust to heteroscedasticity). All regressions include country fixed effects. Regressions specify an AR (1) within-group correlation structure for the panels. Population is used as an exposure variable. Statistical significance at 1% (***), 5% (**), 10% (*).

able is positive and statistically significant in all regressions where the dependent variable is fatalities per capita. More precisely, we find an impact that ranges between a 12–19% increase in traffic fatalities in countries where megatrucks have been permitted post-1996. Finally, we do not find any clear change in traffic injury accidents associated with the authorization of megatruck circulation, as the corresponding variable is not statistically significant in the regressions where the dependent variable is road accidents.

As a robustness check, we re-do our analysis by applying propensity score matching. The matching procedure pairs observations in the treated countries (where megatrucks are allowed to circulate) with control countries (where megatrucks are not allowed to circulate) with similar characteristics in terms of traffic density and latitude (as a proxy of weather conditions). Following Rosenbaum and Rubin (1983), we first estimate the probability of being treated, conditional on traffic density and climate, to obtain a propensity score for each observation. In a second step, we use the first nearest neighbor algorithm to match the observations in the treated and control groups with respect to the propensity score. Then, we drop all the observations without common support and re-estimate the model using the matching sample. The matching sample only includes treated and control countries comparable in terms of traffic density and climate.

Table 6 shows the results of the regressions that use the matching sample. In our context, one clear limitation of propensity score matching is that the number of observations that have common support is small. In particular, the main source of variability in the reduced matching sample is whether countries allow or do not allow the circulation of megatrucks. This may explain why most of the control variables are not statistically significant. However, propensity score matching is a sound robustness check given that the megatrucks variable remains positive and statistically significant with an estimated impact on the increase in fatalities ranging from 11% to 17%. Furthermore, we find no evidence of a relevant impact of megatrucks on traffic accidents.

Megatrucks may not have led to an increase in traffic accidents as they need to circulate on “better” roads due to their specific technical features or because they incorporate safer technological advances or drivers are more appropriately trained, as suggested by Sanchez-Rodrigues et al. (2015). However, the presence of megatrucks increases the severity and lethal consequences of accidents, as is the case for all types of heavier and larger trucks (Castillo-Manzano et al., 2016; Forkenbrock & Hanley, 2003; Glaeser & Ritzinger, 2012; Glaeser et al., 2006; Hanley & Forkenbrock, 2005). So, our wide set of European countries (EU + EFTA) corroborates the specific findings for megatrucks found in previous studies for individual countries such as Spain (Ortega et al., 2014; Pérez-Martínez & Vassallo, 2013) and the United Kingdom (Knight et al., 2010).

Our results might represent a European case extension of the af Wåhlberg (2008) U.S. meta-study, which concludes that as larger trucks replace higher numbers of smaller vehicles, heavier trucks

Table 5
Results of estimates (population-averaged panel-data model with negative binomial distribution).

Independent variables	Dependent variable: accidents				
	Regression (1)	Regression (2)	Regression (3)	Regression (4)	Regression (5)
Megatrucks	0.03	−0.02	−0.02	−0.02	−0.07
	(0.08)	(0.09)	(0.09)	(0.09)	(0.08)
Heating_degree_index	1.96e-06	–	–	–	–
	(0.00005)				
Passengers_km_roads	−0.0008	−0.001	–	–	–
	(0.002)	(0.002)			
Motorisation	−0.0008	−0.0007	−0.0009	–	–
	(0.0006)	(0.007)	(0.0008)		
Passengers_km_railways	−0.04	−0.03	−0.03	−0.03	–
	(0.01)***	(0.01)*	(0.02)	(0.02)	
GDP per capita	0.00005	0.00005	0.00006	0.00004	0.00005
	(0.00002)***	(0.00002)***	(0.00002)***	(0.00002)**	(0.00001)***
GDP^2 per capita	−2.73e-10	−3.83e-10	−3.83e-10	−3.20e-10	−2.90e-10
	(1.83e-10)	(1.78e-10)**	(1.85e-10)**	(1.96e-10)*	(1.71e-10)*
Superhighway density	−0.00001	−0.00005	−0.00006	−0.00009	−0.00006
	(0.00003)	(0.00004)	(0.00005)	(0.00005)	(0.00008)
Age	0.07	0.07	0.07	0.07	0.08
	(0.05)	(0.06)	(0.06)	(0.06)	(0.07)
Population density	−0.01	−0.005	−0.003	−0.002	−0.01
	(0.008)*	(0.08)	(0.01)	(0.01)	(0.006)*
BAC	8.17	8.59	5.80	5.80	2.59
	(5.52)	(6.44)	(2.15)***	(2.16)***	(0.78)***
Point_system	0.06	0.05	0.06	0.05	0.12
	(0.06)	(0.06)	(0.06)	(0.06)	(0.08)
Speed limit	−0.01	0.006	0.02	0.02	−0.05
	(0.08)	(0.07)	(0.08)	(0.08)	(0.05)
Time_trend	−0.04	−0.04	−0.04	−0.04	−0.06
	(0.01)***	(0.01)***	(0.01)***	(0.01)***	(0.02)***
Intercept	90.08	80.31	78.67	84.05	124.45
	(31.15)***	(30.34)***	(31.06)***	(32.95)***	(38.90)***
Test joint sign (Wald χ^2)	99.21***	85.42***	93.10***	103.24***	81.14***
Test F (Ho: Country fixed effects = 0)	256.13***	234.48***	424.85***	424.35***	338.16***
Breusch–Pagan/Cook–Weisberg test for heterogeneity (Ho: Constant variance)	639.74***	592.44***	698.48***	668.32***	678.27***
Wooldridge test for autocorrelation (Ho: No first-order autocorrelation)	51.12***	49.66***	36.06***	36.05***	36.87***
Doornik–Hansen test for multivariate normality	9685.79***	9705.83***	9795.09***	10191.20***	11649.58***
No. of observations	413	464	464	464	494

Note: Standard errors in parentheses (robust to heteroscedasticity). All regressions include country fixed effects. Regressions specify an AR (1) within-group correlation structure for the panels. Population is used as an exposure variable. Statistical significance at 1% (***), 5% (**), 10% (*).

are involved in a greater number of fatal accidents due to their specific maneuverability issues, especially in some particular environments such as urban settings.

Note: Standard errors in parentheses (robust to heteroscedasticity). All regressions include country fixed effects. Regressions specify an AR (1) within-group correlation structure for the panels. Population is used as an exposure variable. Statistical significance at 1% (***), 5% (**), 10% (*). Propensity score matching uses passengers_km_roads in the baseline period and latitude of the capital city in each country as predictors of the probability of being treated. Treated countries are Denmark, Germany, Netherlands and Norway. Control countries are Estonia, France, Poland and United Kingdom. Note that some control variables are not considered; GDP per capita^2 is omitted because testing the non-linear relationship between traffic fatalities and income requires a sample with a large number of countries. BAC and speed variables are excluded because they do not have variability over time in the matching sample. Finally, traffic density and climate conditions are already captured in the matching procedure.

5. Conclusions

The debate that has emerged around cross-border Longer and Heavier Vehicle (LHVs)/megatruck circulation on European roads to reduce excessive motorized transportation costs is a topic that affects a wide range of interest groups linked to the road freight sector and has sparked a growing interest in the literature as to its economic, environmental and logistics impacts. Authorizing the circulation of megatrucks would doubtlessly result in greater productivity and, consequently, better prices for road haulers, due to a reduction in costs per tonne-kilometer transported. However, one serious consequence of this measure is that it might trigger a dynamic process that would result in a large amount of freight transport switching from rail to road. As far as infrastructure is concerned, everything points to the introduction of megatrucks possibly influencing investments in infrastructure maintenance and conservation as, for example, Ortega et al. (2014) and Pérez-Martínez and Miranda (2016) find for Spain, Sanchez-Rodrigues et al. (2015) suggest for Germany, and Vierth and Haraldsson (2012) analyze for the Swedish case.

It is noticeable that several earlier studies consider the influence of megatrucks on road safety to be considerably lower but the results of their analyses are, to some extent, inconclusive, as their conclusions on this matter are not unanimous. As previous scholars state (e.g., Sanchez-Rodrigues et al., 2015), a better understanding and assessment of the benefits and risks of LHVs are needed. The present article has, therefore, pioneered the application of multivariate econometric analysis to *ad-hoc* panel data for a sample of European Union and EFTA countries.

To close the gap on the potential safety consequences of megatrucks (in terms of road safety performance indicators), the current research contributes to the literature by providing an original study case focused not on one single country (as is usually the case) but on a set of European countries, some of which permit LHVs to circulate on their national road networks, and others that do not. Our results point to European countries that have allowed

Table 6
Results of estimates: matching sample (population-averaged panel-data model with negative binomial distribution).

Independent variables	Dependent variable: fatalities			Dependent variable: accidents		
	Regression (1)	Regression (2)	Regression (3)	Regression (4)	Regression (5)	Regression (6)
Megatrucks	0.11	0.13	0.17	−0.005	0.06	0.11
	(0.05)**	(0.05)***	(0.09)*	(0.05)	(0.03)*	(0.08)
Motorisation	−0.0007	-	-	−0.002	-	-
	(0.001)			(0.001)**		
Passengers_km_railways	−0.02	−0.02	-	−0.03	−0.03	-
	(0.02)	(0.02)		(0.02)*	(0.01)	
GDP per capita	0.00001	0.00001	0.00004	0.00002	0.00001	0.00004
	(0.00003)	(0.00004)	(0.00002)**	(0.00003)	(0.00004)	(0.00002)
Superhighway density	−0.0001	−0.0001	−0.0001	−0.0002	−0.0002	−0.0001
	(0.0001)	(0.0001)	(0.0002)	(0.0001)	(0.0001)	(0.0002)
Age	0.08	0.08	0.07	0.15	0.15	0.14
	(0.12)	(0.12)	(0.12)	(0.12)	(0.13)	(0.14)
Population density	0.01	0.01	0.004	−0.001	0.002	−0.005
	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.009)
Point_system	−0.04	−0.04	0.15	−0.26	−0.24	−0.007
	(0.13	(0.12)	(0.10)	(0.12)**	(0.13)*	(0.10)
Time_trend	−0.07	−0.07	−0.11	−0.02	−0.05	−0.09
	(0.04)*	(0.03)**	(0.02)***	(0.03)	(0.03)	(0.02)***
Intercept	138.53	152.58	219.06	48.43	95.34	177.15
	(82.00)*	(69.35)**	(39.75)***	(67.10)	(64.45)	(47.68)***
Test joint sign (Wald χ^2)	26.33***	24.12***	25.08***	18.44***	17.32***	12.21***
Test F (Ho: Country fixed effects = 0)	91.18***	89.90***	59.21***	834.80***	926.05***	707.34***
Breusch–Pagan/Cook–Weisberg test for heterogeneity (Ho: Constant variance)	11.76***	8.22***	0.19	41.69***	35.21***	3.79**
Wooldridge test for autocorrelation (Ho: No first-order autocorrelation)	58.01***	56.23***	46.66***	8.42**	8.45**	7.09
Doornik–Hansen test for multivariate normality	470.76***	487.08***	529.94***	506.59***	525.54***	617.72***
No. of observations	137	137	137	137	137	137

Note: Standard errors in parentheses (robust to heteroscedasticity). All regressions include country fixed effects. Regressions specify an AR (1) within-group correlation structure for the panels. Population is used as an exposure variable. Statistical significance at 1% (***), 5% (**), 10% (*). Propensity score matching uses passengers_km_roads in the baseline period and latitude of the capital city in each country as predictors of the probability of being treated. Treated countries are Denmark, Germany, Netherlands and Norway. Control countries are Estonia, France, Poland and United Kingdom. Note that some control variables are not considered; GDP per capita^2 is omitted because testing the non-linear relationship between traffic fatalities and income requires a sample with a large number of countries. BAC and speed variables are excluded because they do not have variability over time in the matching sample. Finally, traffic density and climate conditions are already captured in the matching procedure.

megatruck circulation obtaining higher accident lethality rates. This highlights the need to develop a parallel set of specific strategies that, as part of a country's road safety policy, are designed to mitigate the likely ensuing increase in the mortality rate.

Finally, some issues need to be clarified regarding our research object. First, we are assessing an item on the policymaker agenda that is still unresolved, ongoing, and currently under examination. This could be considered both a natural limitation of our study and, also, a future line of research as new countries introduce LHVs and new statistical data become available. Second, our paper analyzes the impact of megatruck circulation on road safety performance in our wide sample of European countries (i.e., on crashes involving all road users, not just an evaluation of crashes involving megatrucks). This is due to separately-classified statistical data for LHV traffic accidents only being available for the United States, where LHV trucks are allowed by law. Third, before our findings are generalized, it should be noted that a variety of trials and temporary planning strategies were implemented in the countries where megatrucks are permitted before they were introduced, so some caution is required when extending their authorization to other countries or regions. In this line, if at all possible, it would be interesting to extend this analysis to evaluate other dimensions derived from the introduction of LHVs (environmental, modal split, infrastructure, logistics costs), with a comparison of safety issues in European Union and non-European Union countries, as in this paper.

Other recent phenomena in the European continent that could potentially affect road freight transportation in general and megatruck circulation in particular, such as the United Kingdom's exit from the EU or the application of the *Eurovignette* Directive, might present future research opportunities to complement this paper's findings.

6. Practical application

The positive impact of megatruck circulation might be enhanced through measures that maximize logistics efficiency gains and minimize the consequences of fatal accidents. As road freight companies are likely to be interested in using longer vehicles and, especially, bearing in mind that traffic safety depends on multiple parameters related to vehicles' technical characteristics, infrastructure design, and driver behavior (Douglas, Swartz, Richey, & Roberts, 2019), among others, a set of multi-approach actions can be recommended to ensure that the introduction of megatrucks compensates any stakeholders who would be negatively affected. By way of example, strategies might include warning other drivers of the danger of being involved in an accident with a megatruck or adapting post-accident emergency medical care protocols to crashes involving LHVs. It would also be advisable to implement legislative measures to make truck manufacturers raise the minimum safety technical requirements for LHVs and/or stricter training program requirements for LHV drivers.

Considering the potential generalization of LHV authorization to other states and the possibility of LHV cross-border circulation, a better enforcement and surveillance framework (such as, e.g., Teoh, Carter, Smith, & McCartt, 2017 have concluded for U.S. states) should be applied to ensure that these vehicles comply with the maximum load, size, and speed regulations, among others.

Megatruck circulation is a strategy that requires proper preparation and proper examination before it is applied. In this case, unlike other measures such as the point-system driver's license that also originated in the international benchmark countries of northern Europe, the imitation effect in other countries may be more doubtful. Extrapolation to countries with high accident rates and/or the lack of a high capacity road network/superhighways, which are the ideal natural habitat for this type of LHV, is not a simple matter.

Conflict of interest

Authors declare no conflict of interest.

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