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The complex relationship between increases to speed limits and traffic fatalities: Evidence from a meta-analysis

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ABSTRACT

Speed plays an important role in road safety as it affects accident risk and severity. Among safety policies implemented to control driving speed, speed limits are the most highly developed. Since the 1970′s, numerous studies have focused on the effectiveness of speed limits, but even today there is still no clear consensus as to the impact that raising the speed limit has on traffic fatalities. With the aim of consolidating knowledge on this topic, a meta-analysis has been carried out of a set of econometric studies assessing the effects on traffic fatalities of increasing speed limits in the US. Two sub-samples were obtained, taken from the traffic fatality measures considered by studies (*fatality count* and *fatality rate normalized per vehicle miles traveled*), and two approaches were analyzed: rural interstates (where speed limits were increased in 1987 and 1995), and a statewide approach (all roads network). Our findings show that by count traffic fatalities went up on both rural interstates and statewide level, although the effect was higher on rural interstates. In other respects, statewide fatality rates could be improved in relative terms by raising legal speed limits, although the effect would be weak.

1. Introduction

Of all the strategies available to control speed, speed limits are the most widely used to manage traffic speed (Aarts and van Schagen, 2006; Archer et al., 2008; Augeri et al., 2015). It is true that in some countries there are highways where no legal speed limits exist as such, including Germany, with *recommended speed limits* on the *Autobahns* (Manner and Wünsch-Ziegler, 2013) and the US state of Montana, where *reasonable and prudent speed limits* were in place from 1996 to 1999 (Yowell, 2005). However, there is a consensus in the highway safety community as to the need and appropriateness of applying legal speed limits on all types of roads, as drivers may not always subjectively choose the optimum speed from the social point of view (Elvik, 2002, 2012).

The research has addressed the relationship between modifications to the maximum speed limit and road safety in depth, with studies dealing with both the effect of a rise in the maximum permitted speed limit (Imprialou et al., 2016; Ritchey and Nicholson-Crotty, 2011; van Benthem, 2015) and a reduction in the limit (De Pauw et al., 2014; Islam and El-Basyouny, 2015; Kloeden et al., 2007). Similarly, many other studies focus on improvements to road safety through the setting of variable or dynamic speed limits depending on traffic or atmospheric conditions (Islam et al., 2013; Yu and Abdel-Aty, 2014; Zhibin et al., 2014) or temporary speed limits imposed to save energy, for example (Castillo-Manzano et al., 2014) or reduce air pollution levels (Elvik, 2013).

As part of this relationship between speed limits and road safety, the present research seeks to conduct a meta-analysis of the influence that increases to maximum speed limits have on traffic fatalities, based on a quantitative systematic review of the empirical evidence in this field of research.

If we focus only on scholars who have addressed the impact of raised speed limits on road safety, there are studies of a range of countries, such as Finland (Peltola, 2000), Australia (Sliogeris, 1992), New Zealand (Scuffham and Langley, 2002), Israel (Friedman et al., 2007; Richter et al., 2004), and China (Wong et al., 2005). However, most are of the United States (US) and focus either on the national level (Grabowski and Morrisey, 2007; Ritchey and Nicholson-Crotty, 2011; Shafi and Gentilello, 2007), an individual state (Bartle et al., 2003; Ledolter and Chan, 1996; Upchurch, 1989), or a group of states (Baum et al., 1990; Farmer et al.,1999; Patterson et al., 2002).

The reason for this predominance lies in the relevant legal changes

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to the maximum permitted speed limit implemented in the US since 1974. Speed limit regulations have traditionally come under state responsibility. However, in March 1974, all states adopted a maximum 55 mph limit set by Congress on the countrywide level with the National Maximum Speed Law. This measure was aimed at offsetting the rise in oil prices (Friedman et al., 2009; Shafi and Gentilello, 2007) caused by the embargo put in place by the Organization of Petroleum Exporting Countries -OPEC- (Grabowski and Morrisey, 2007). Two changes were subsequently made to the law to raise the speed limit. First, in 1987, Congress enacted the Surface Transportation and Uniform Relocation Act, which allowed states to put up speed limits from 55 mph to 65 mph on rural interstates (Greenstone, 2002). Second, in 1995 Congress repealed the National Maximum Speed Law with the passing of the National Highway System Designation Act, devolving powers to individual states to set their own speed limits (Retting and Cheung, 2008; Vernon et al., 2004). This Repeal enabled many states to quickly move to raise speed limits from 65 mph to 70 mph or more on both rural and urban interstates (Albalate and Bel, 2012; Friedman et al., 2009; Retting and Teoh, 2008). As Farmer (2016) highlights, even states like Texas have followed this trend toward higher speed limits in recent years, with an increase to over 80mph on specified segments of interstate roads (see IIHS, 2017a, 2017b and The Insurance Institute for Highway Safety website for a broader treatment of the topic: http://www.iihs.org/iihs/topics/laws/speedlimits?topicNamen = speed).

Two possible focuses can be highlighted regarding US studies that measure the effect on road safety of increases to the speed limit. On the one hand, some studies propose an analysis of the consequences of increased speed limits solely on the roads on which the new legislation is implemented (see, for example, Gallaher et al., 1989 for the state of New Mexico; Haselton et al., 2002 for the state of California; and Pfefer et al., 1991 for the state of Illinois). In contrast, other studies such as Garber and Graham (1990), Lave and Elias (1994) and McCarthy (1994a, 1994b) have put forward the argument that the effects of an increase to the speed limit should be studied on all the roads in the network and not only the roads where the new limit has been applied (in a statewide approach).

This broader approach is based on the influence of two results of raising speed limits: the allocation of surveillance resources and changes in driver behavior. Regarding the former, according to Lave and Elias (1994) a rise in the speed limit can lead to the reallocation of surveillance patrols from speed enforcement to other accident prevention activities that may be more effective in reducing fatalities (e.g., enforcing drunk-driving laws). On the other hand, two different and contradictory effects of increases to speed limits have to be taken into account with regard to driver behavior. The first, the so-called “diversion effect” (Lave and Elias, 1994; Rock, 1995; Wagenaar et al., 1990), assumes that drivers will divert toward roads and highways where the permitted driving speed is higher, so road safety improves on roads that are not affected by the increase to the limit. The second effect is the “speed spillover effect” (Brown et al., 1990; Garber and Graham, 1990), according to which drivers get used to driving at higher speeds, even on roads where the maximum speed limit has not changed. This “speed adaption or generalization” effect (Rock, 1995) would therefore lead to a decline in road safety on roads not affected by the increase to the speed limit.

As far as the findings of these studies are concerned, major discrepancies can be observed in the estimations obtained by the wide range of studies on the topic, irrespective of the geographic areas and roads under study. Comments will be made on these in the following paragraphs.

First, several studies conclude that there is no doubt that increases to speed limits have a harmful effect on road safety. The following can be cited as examples: Ossiander and Cummings (2002) for the state of Washington; Bartle et al. (2003) for the state of Alabama; Baum et al. (1991) for a set of 40 states and Ashenfelter and Greenstone (2004) for a set of 21. A study by Ledolter and Chan (1996) should also be highlighted for having found an increase in fatal accidents both on the roads affected by the rise in the speed limit and on the network of road that form the US road system.

Other authors found the opposite. Examining each of the US states individually, Lave and Elias (1994), for example, observed a fall in the fatality rate when analyzing a set of roads in the majority of states where the maximum speed limit had been increased. Houston (1999) reached the same conclusion when examining the road network in each of the 50 states.

Lastly, some studies found no clear evidence of a link between road safety and increases to speed limits. For example, Garber and Graham (1990) found inconclusive evidence from all 40 states where the measure had been adopted to increase the speed limit to 65mph. In the same line, Yowell (2005) was unable to confirm the existence of a clear correlation between speed limit and fatality rate in 27 analyzed states. Lastly, on the individual state level, McCarty (1994b) concluded that no great changes to road safety were apparent in California after the speed limit was raised.

Bearing all the above considerations in mind and following Ritchey and Nicholson-Crotty (2011), it can be stated that, despite many years of research, there is still no clear consensus in the literature as to the impact that increased legal speed limits have on traffic safety. The contribution that the present study therefore makes is to shed some light on the debate in the highway safety community on the relevance and real effects of increasing speed limits on road safety, measured in our case by fatalities. We therefore use a meta-analysis to give a quantitative systematic review of empirical evidence on the topic.

To achieve this goal, the present study is organized as follows. After this introduction, a section is included on the methodology used for the meta-analysis. Next, there is a results and discussion section, and lastly, some conclusions are given. Finally, two appendixes offer a broader technical explanation of the meta-analysis and a description of the sample.

2. Data and method

2.1. Methodology

Following Glass et al. (1981) and Castillo-Manzano and Castro-Nuño (2012), meta-analysis is a methodology that consists of the integration and scientific analysis of results obtained in prior analyses of a specific topic with the aim of conducting a synthetic quantitative estimation of all of these together. According to Borenstein et al. (2009), this enables questions to be answered that cannot be addressed by a traditional systematic review, applying the same methodological rigor as required in experimental research (Rosenthal, 1995).

Following Lipsey and Wilson (2001), to do this, the technique obtains what is called a *Summary Effect* of the estimates taken from a sample of chosen studies using a combination of a range of statistical procedures.[1] The degree of accuracy of the estimates is the information offered by the statistics for each of the estimates (Chalmers et al, 2002).

The Methodological Appendix at the end of the paper provides a broader treatment of methodological issues related to meta-analysis.

2.2. Study search and selection

The meta-analysis of the current paper has been conducted following the international PRISMA and QUORUM protocols established for both systematic reviews and meta-analysis studies (see Moher et al., 2010; and Urrutia and Bonfill, 2010 for a more extensive explanation). All the articles that might potentially meet defined eligibility criteria

[1] The Summary Effect (SE) is the pooled outcome of a meta-analysis, obtained through a statistical combination of estimates derived from primary studies (Borenstein et al., 2009).

were independently selected for initial review by two reviewers.

The keywords used in the first phase were general: *speed limits* and *road safety*. However, the search criteria were later refined and the keywords further specified. The following were used: *road safety analysis; speed limit policies; mandatory maximum speed limit change; speed limit change implications; speed limit change effects; speed limit change impact; speed limit legislation; speed limit laws; driving speed regulation; motor vehicle accidents; motor vehicle crashes; motor vehicle collisions; injuries; fatalities; mortality;* and *morbidity*.

Further articles were compiled in two ways; i) with cluster searching (using bibliography referenced in previous studies) and ii) reviewing the bibliography used as a sample in previous meta-analyses (Elvik, 2005, 2009; Elvik et al., 2004; Elvik and Vaa, 2006) and published systematic reviews (Aarts and van Schagen, 2006; Dougherty, 2000; Feng 2001; Fildes and Lee, 1993; Finch et al., 1994; Godwin and Lave, 1992; Richter et al., 2006; Wilmot and Khanal, 1999).

A total of 428 documents were obtained during this first phase.[2] To select the studies that were to form part of the sample, several different filters were applied, specifically, five (see Fig. 1).

2.3. Coding framework

As Fig. 1 shows, the final sample for coding was 39 studies that measure the influence of increases to the speed limit on traffic fatalities in the US.

The following codes were used:

1. Geographical Scope. Each study was coded according to the US State or States considered in the analysis.

2. Increased speed limits studied. Coded according to the increase to speed limits in US States whose subsequent effects are analyzed in studies in the sample. We followed the Elvik and Vaa (2006) meta-analysis specifications that consider the impact on fatalities caused by any increase in the speed limit, without specifying any variation ranges.

3. Roads studied. Each study is coded according to the road or roads for which the effect that an increase in the speed limit has had on fatalities has been quantified. To be precise, two codes have been used:

a. **Rural interstate roads** as they are a type of road that was subject to two increases to speed limits (from 55mph to 65mph in 1987, and a further increase in 1995 when all speed limit restrictions were removed), following Patterson et al. (2002) and Davis et al. (2015).

b. **Statewide**, considering the entire road network, as commented in the Introduction Section.[3]

4. Control variables. Coded according to the control variables used in each of the studies and grouped in the categories in Table A.1.

5. Measurement of outcome. Each of the studies is coded according to the way that the outcome (fatalities) is measured, with the use of only two codes: by count or, as proposed by Houston (1999) and Lave and Elias (1994), by rate normalized by risk exposure by vehicle miles traveled (VMT). The Dee and Sela (2003) study was excluded from the sample as it normalizes fatalities by number of inhabitants.

6. Methodology used. Each of the studies is coded by specifying the methodology followed to evaluate the impact of a rise in speed limits on fatalities (e.g., Poisson model, negative binomial model, time series, inter alia). Some studies were excluded for the following reasons when coding the methodology:

a. Papers that were only descriptive, such as reviews or comments on papers (Feng, 2001; Godwin and Lave, 1992; Grabowski and Morrisey, 2001; Griffith and Lave, 1995; Jolly, 1998a, 1998b; McCarthy, 2001; Richter et al., 2006).

b. Studies not based on regressions. According to Garber and Graham (1990), the regression-based focus is preferable to the use of methods of a "quasi-experimental design" tradition. Moreover, in our case the regression-based studies form the largest group and so allow a larger sample size for our meta-analysis. Thus, certain studies, such as Bartle et al. (2003); Baum et al. (1989, 1990, 1991); Haselton et al., (2002); Ossiander and Cummings (2002); and Yamane and Bradshaw (2008), were excluded for this reason.

7. Result of the experiment. The result obtained by each of the studies (primary estimation) was coded. Studies that did not enable a clear and accurate link to be made between increased speed limits and traffic fatalities were therefore excluded from the sample (Chang and Paniati, 1990; Chang et al., 1993).

8. Sample size. The sample size considered in each of the studies was coded.

9. Accurate measures. The accuracy of the measures used in the various studies was coded (confidence intervals, tests for statistical significance or p-values, standard errors or deviations, t-ratios, etc.). Following other authors such as Sommer et al. (2004) and Watson and Rees (2008), studies that did not explicitly report accurate measures were excluded (e.g., Friedman et al., 2009; Hoskin, 1986; Jehle et al., 2010; Rock, 1995).

Consequently, the final sample contained 17 papers for analysis, which were included in the present meta-analysis. In the Sampling Appendix, Table A.1 summarizes important information about each of these 17 studies.

2.4. Sample of estimates

When coding the 17 papers selected in Section 2.3 with code 5, **Measurement of outcome,** 9 were found to measure fatalities as count; 9 measure fatalities as rate normalized by VMT; and one, Farmer et al. (1999), uses both measures (fatality count and fatality rate). We have split the sample into two groups (fatality count and fatality rate) with 9 studies each.

These 17 studies were in turn separated into two scenarios as per code 3, **Roads studied.**

- **Scenario I:** Rural interstate roads
- **Scenario II:** Statewide (the entire road network).

129 estimates (primary data) were obtained from the sub-sample of 9 studies that measure traffic fatalities as count (*fatality count*). More specifically, for Scenario I, 43 independent estimates (corresponding to 4 studies) and 4 dependent estimates were found, which produced 2 combined[4] estimates (provided by 2 different studies); for Scenario II, 82 independent estimates (from 3 different studies) and 8 dependent estimates were found, generating 2 combined estimates (provided by 2 different studies).

With respect to the sub-sample of 9 studies that measure traffic fatalities by rate (*fatality rate*), it was only possible to obtain estimates

[2] When studies had been published on different dates and/or in different journals, the criterion followed was to include the most recent study in order to prevent a duplication of records (for example, Lave and Elias, 1994, 1997).

[3] When coding with this code, the only exception is the inclusion of the Garber and Graham (1990) study that analyzes the influence of a speed limit increase on both rural interstate and rural non-interstate roads; as the authors themselves state, the latter are a good framework for studying both the traffic diversion and speed spillover effects commented in our introduction.

[4] When the same study presented primary estimates that could be considered dependent on one another as they had come from the same sample, following Borenstein et al. (2009) and Scammacca et al. (2014) a technique was used to combine them through a weighted average ES in order to obtain a single primary study estimate.

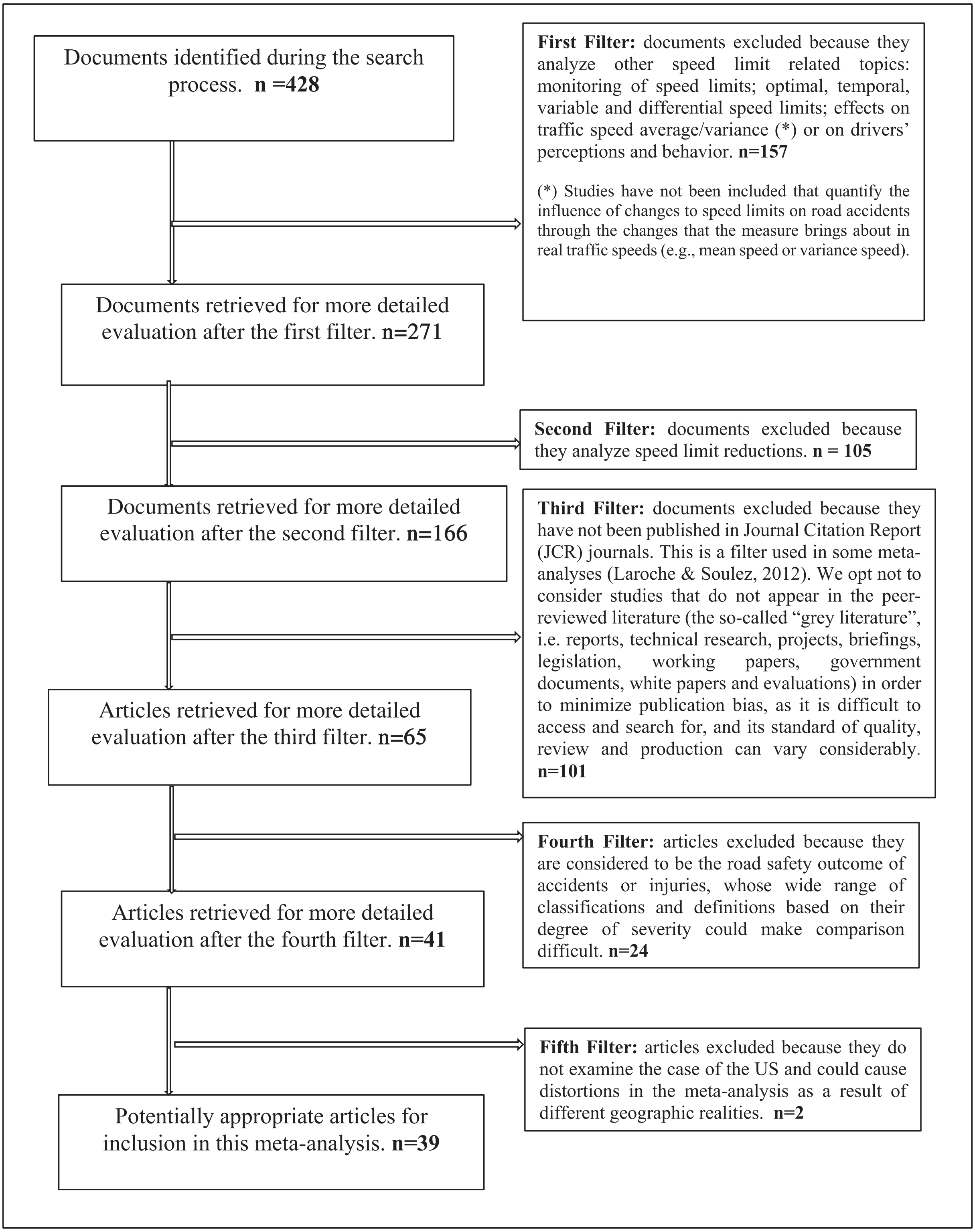

Fig. 1. Flow chart of filters.

for Scenario II. Specifically, 75 independent estimates were found.

Comprehensive meta-analysis 3.0. (see www.meta-analysis.com) software was used to analyze these data, enabling the primary estimates to be converted or standardized into a common measure of Effect Size. Effect Size (ES) from each study may be considered as the effect of an intervention analyzed by individual studies on a specific topic (i.e., the unit of the meta-analysis) that the meta-analysis uses to synthesize a collection of results in the form of a Summary Effect (see e.g., Borenstein et al., 2009).

The basis for the current paper is primary studies analyzing the effects of increasing speed limits on road traffic fatalities with regression studies. ES from these studies are therefore standardized regression coefficients. As is known, these coefficients can be interpreted as the size of the effect of the exogenous variable (increasing speed limits, in our case) on the endogenous variable (road traffic fatalities, in our case).

Table 1
Meta-analysis outcomes and heterogeneity analysis.

Sub-sample	Scenarios	No. of estimations (sample size)	FEM summary effect estimation/Z-value	REM summary effect estimation/Z-value	Heterogeneity	
					Q-value	I^2
Fatalities: Count	I Rural Interstates	45	0.214^{***}/10.897	0.155^{***}/3.858	131.174^{**}	0.664
	II Statewide	84	0.092^{***}/15.676	0.084^{***}/3.518	786.973^{*}	0.894
Fatalities: Rate	II Statewide	75	-0.001^{***}/−3.169	−0.001/−0.683	823.365^{***}	0.910

Note: Statistical significance at 1% (***), 5% (**) and 10% (*), respectively.

3. Meta-analysis results from fixed effects model (FEM) and random effects model (REM) estimates

Table 1 summarizes the meta-analysis outcomes subdivided into the two sub-samples (count and rate) and the two scenarios considered. The fourth and fifth columns show the Summary Effect (SE) (the meta-analysis outcome through a pooled combination of estimates from primary studies), obtained with the Fixed Effects Model (FEM) and the Random Effects Model (REM), respectively, and calculated by the weighted mean of the Effect Size (ES) for each sample, for a 95% confidence statistical significance interval. Measures to identify and quantify ES variability due to heterogeneity have also been included for both samples and scenarios in the last column of Table 1.[5]

If we first analyze the studies that measure fatalities by count, Table 1 shows a positive SE for Scenario I (Rural Interstate Roads) irrespective of the estimate model used, FEM or REM. Note that in this meta-analysis, positive SE indicates an increase in traffic fatalities due to an increase to the speed limit, and vice versa. Therefore, raising the speed limit appears to increase fatalities on roads where the increase to limits is applied. This result corroborates the evidence given by previous scholars such as Friedman et al. (2009), Imprialou et al. (2016) and Richter et al. (2004).

However, when the two scenarios are considered jointly, further interesting results are found. First, as the obtained SE estimates in both scenarios are positive and statistically significant, it can be stated that increases to speed limits increase mortality if the entire road network is considered (Friedman et al., 2007; Wagenaar et al. 1990).

Second, and interpreting the results with caution, the fact that the SE coefficients obtained for Scenario II (statewide) are substantially lower than those for Scenario I (Rural Interstate Roads) might indicate a reduction in the number of fatalities recorded on other types of roads (non Rural Interstates) included in the statewide focus (Greenstone, 2002; Houston, 1999; Lave and Elias, 1997). According to what was stated in the introduction, this effect might suppose that traffic switches to roads with higher speed limits, which reduces fatalities on roads not affected by the increase to the speed limit, but which are included in the statewide focus. Unfortunately, it has not been possible to carry out a meta-analysis only for roads not affected by increases to speed limits. This is due to the lack of suitable primary estimates derived from studies that would allow us to test for a possible increase of traffic fatalities on these roads (the so-called "spillover effect" according to Brown et al., 1990).

From a heterogeneity perspective, results in Table 1 show that the sub-sample for fatality counts considered for Scenario I is heterogeneous. Consequently, the homogeneity null hypothesis is rejected using a Q statistic test. According to Huedo-Medina et al. (2006), and Lipsey and Wilson (2001), the null hypothesis of homogeneity between estimates refers to variability between ES being greater than might be expected from pure randomness (within-study variance due to sampling error). Considering the I^2 result for Scenario I, it can be deduced from the values commented in the Methodological Appendix that approx. 66.46% of the total observed variability can be attributed to moderated true heterogeneity or between-study variability rather than to randomness.

Considering the fatality count sub-sample in Scenario II, both the Q statistic test (null hypothesis of homogeneity rejected) and the high value of the I^2 statistic (0.894) obtained, indicate that the ES distribution among these estimates is highly heterogeneous for the statewide focus. Consequently, the resulting SE may be less representative of the study population. Taking into account this high proportion of variability, and considering the major differences found among primary studies, REM may be considered an appropriate technique to pool ES (Borenstein et al., 2009, 2010; Higgins et al., 2009). The REM procedure is based on the weighted average of ES to minimize any bias caused by the considerable variance. By definition, the REM model allows for the true effect varying from study to study, because the estimates included in the meta-analysis are assumed to be a random sample of the relevant distribution of effects, and the combined effect estimates (SE) to be the mean effect in this distribution (Borenstein et al., 2009).

In order to perform a sensitivity analysis of both FEM and REM estimates for the two scenarios, Comprehensive Meta-Analysis software was used to find any potential outlier studies, removing one to one estimates from the initial sample and recalculating the SE and meta-analysis outcomes for both scenarios. The limited variability observed in the iterative analyses allows it to be stated that robust estimates exist in both scenarios, irrespective of the model; no estimate that might be considered an outlier was detected in the respective samples.[6]

Lastly, the obtained results for the sub-sample that measures fatalities by rate (see Table 1, row 4) only show SE estimate significance for FEM, with a value approaching zero and a negative sign. Thus, in line with other studies such as Houston (1999) and Lave and Elias (1994), we have determined that when the statewide focus is applied, increases to speed limits reduce fatality rates, albeit only slightly. This conclusion is in line with Garber and Graham (1990), who stress that, as fatalities normalized by VMT are generally lower on rural interstates, traffic diversion might indeed improve safety for all roads.

With respect to heterogeneity, it can be deduced from the value of the Q statistic that the null hypothesis of homogeneity is rejected, and the 91.1% I^2 statistic can be interpreted as a high between-estimates proportion of variance that cannot be explained by observed effects. As above, REM estimation may be more appropriate in this circumstance, although, as can be deduced from Table 1, the result is not statistically significant.

3.1. Publication bias analysis

Finally, the main quantitative methods used to address publication bias are considered for the two sub-samples and two Scenarios analyzed in the current paper. The software is applied following the Borenstein et al. (2009) methodological indications to test whether a bias might modify the robustness of the findings. The results are given in Table 2,

[5] All meta-analysis outcome graphics for both Scenarios are available from the authors upon request.

[6] All the sensitivity analyses based on one to one studies excluded from the respective sample are available from the authors upon request

Table 2
Publication bias analysis.

Sub-sample	Scenarios	Sample size	Classic fail safe N (no. of missing estimates that would raise p-value > .05)	Egger's regression (intercept B_0)	Duval & Tweedie's Trim and Fill technique	
					No. of missing estimates under REM	Re-adjusted Random Point estimation
Fatality count	I Rural Interstates	45	591	−0.790	0 (to right/left of mean)	–
	II Statewide	84	1918	−0.101	0 (to left of mean) 6 (to right of mean)	– 0.107
Fatality rate	II Statewide	75	0	1.277	0 (to right of mean) 7 (to left of mean)	– 0.0007

considering the three usual bias indicators commented in the methodological appendix.

No major bias can be seen to exist in any of the analyzed cases that might significantly undermine the validity of the current meta-analysis.

4. Conclusions

Of all the safety policies implemented worldwide to control driving speed, legal speed limits are the most highly developed and most widely used strategy. Numerous studies have been conducted of the impact on road safety of increased speed limits, mostly for case studies of US states due to different legal speed limit increases implemented since 1987. Nevertheless, this research did not identify a clear relationship between higher speed limits and traffic fatalities. The findings seem to vary depending, in part, on the analytical techniques applied, the type of roads considered, and the available data.

The quantitative synthesis provided in the current paper aims to consolidate knowledge of the effect of raised speed limits on traffic fatalities with a meta-analysis that follows standard technical protocols. We selected 17 econometric studies for the US case returned by a broad search procedure with a variety of scientific and academic search engines.

Later, after carrying out an appropriate coding process, the final sample was separated into two sub-samples according to the type of traffic fatalities measures considered (fatality counts; fatality rates normalized per vehicle-miles-traveled, VMT). Following the same approaches introduced by previous studies (e.g., Greenstone, 2002; Houston, 1999; Lave and Elias, 1994, 1997, among many others), two Scenarios were considered: Scenario I for rural interstate roads where speed limits were increased, and Scenario II, which was a statewide approach.

After applying both statistical Fixed and Random Effects Models and heterogeneity analyses, our results showed, first, that, generally, there is a positive link between higher speed limits and higher traffic fatalities (in line with previous studies such as e.g., Davis et al., 2015; Farmer et al., 1999, Patterson et al., 2002). More specifically, increasing speed limits increases traffic fatalities measured by fatality count in both Scenario I (rural interstate roads) and Scenario II (the entire road network at the statewide level).

If we observe the values of the coefficients, the higher impact found for rural interstate roads over all roads as a whole (statewide approach) could suggest a possible reduction in fatalities on roads unaffected by the increase to the limit. The academic literature attributes this result to the so-called "diversion effect", or traffic switching to roads with a higher speed limit (see e.g., Houston, 1999; Lave and Elias, 1994; Rock, 1995; Wagenaar et al., 1990, among others). However, unfortunately we have not been able to test this result independently as it has not been possible to perform a separate meta-analysis only for roads where speed limits were not raised due to the lack of suitable estimates from primary studies. Should enough studies be conducted that tackle this focus, new lines of future study could address the development of meta-analyses by different types of road or segments.

Additionally, we have analyzed the statewide approach considering a sub-sample of regression estimates of traffic fatalities normalized by a proxy variable of exposure risk in terms of vehicle miles traveled (VMT). The results obtained have a negative coefficient and indicate that increasing speed limits could slightly reduce traffic fatality rates per VMT, although with a statistical significance only when a Fixed Effects Model is run.

Finally, certain methodological issues must be considered when interpreting the findings of this meta-analysis. Although the obtained results are generally robust and stable from the perspective of sensitivity analysis and publication bias detection, significant heterogeneity was observed between studies that may be due to differences in study design or in the way outcomes were defined and data collected. Consequently, caution is needed when generalizing the present meta-analysis' findings to make inferences outside the US.

Even so, as our conclusions synthesize the results of the prior literature, they can contribute to the debate about changes to speed limits. They do this by positing the need to consider the effects of any such changes on the traffic accident rate on the roads that the changes affect and on the entire road network, and any possible diversion of traffic from one road to another. In this regard, it would be advisable for public transportation and road safety departments to present their road safety data in detail and disaggregated by section of road, and using comparable definitions for road types within the same territorial area. This recommendation can be extended to include the scientific community in their studies, as this would enable a comparison of studies with the ultimate aim of obtaining conclusive findings that lead to an improvement in knowledge about the speed limit-road safety relationship.

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Appendix A. Methodological appendix

According to Glass et al. (1981) and Lipsey and Wilson (2001), the meta-analysis method consists of obtaining a *Summary Effect* or overview effect of the combination of different estimates (*Effect Size*) of a selected sample of studies using a range of statistical techniques; the most usual of these are the *Fixed Effects Model* (*FEM*) and the *Random Effects Model* (*REM*).

Following a *FEM*, the chosen studies are combined under the premise that there is no significant heterogeneity among them and that, according to Borenstein et al. (2009), there is one *true effect size* (θ) shared by all the studies. This inference is only dependent upon the studies that are considered, and no variability among them is taken into account. The only factor that determines the weight of each of the studies in the meta-analysis is its own variance (*within-study variance*).

The technique to combine studies in a *FEM*, known as the *inverse-variance weighted method*, was described by Birge (1932) and Cochran (1937). Each effect size is reflected in the summary effect in such a way that it is inversely weighted according to its accuracy (*statistical weight*). Considering a sample of "*m*" estimates or effect sizes (i = 1, 2,… m) that represents a measure of the analyzed effect, called *Ti*, an overall effect or summary effect called $\overline{T}$ can be formulated from expression (1) (Borenstein et al., 2009):

$$\overline{T} = \frac{\sum w_i T_i}{\sum w_i} \tag{1}$$

where w_i is the statistical weight of the *i-esima* estimate:

$$w_i = 1/v_i \tag{2}$$

and $v_i$is the *i-ésima* variance estimate.

Summary effect variance is formulated as:

$$Var(\overline{T}) = \frac{1}{\sum w_i} \tag{3}$$

Between-study variability may be greater due, simply, to pure randomness, and this will be detected by the homogeneity hypothesis in the first instance. The most used test, based on the computation of the so-called *Q* parameter, was originally developed by Cochran (1954) and subsequently developed by DerSimonian and Laird (1986).

$$Q = \sum w_i (T_i - \overline{T})^2 \tag{4}$$

Due to the low reliability of this test, as demonstrated by Takkouche et al. (1999), *subgroup analysis* is recommended of studies with similarities and/or the use of additional procedures to detect and quantify any possible heterogeneity. Among these alternatives, I^2 is a parameter proposed by Higgins and Thompson (2002) and Higgins et al. (2003) that determines the proportion of dispersion among the studies (*between-study variance*) compared to total dispersion.

$$I^2 = \frac{\tau^2}{\tau^2 + \sigma^2} \tag{5}$$

where τ^2 is between study variance and σ^2 is the study's internal variance.

This I^2 statistic can be interpreted as follows: when $I^2 > 0.75$ there is high heterogeneity; $0.50 < I^2 < 0.75$ represents moderate heterogeneity; and $0.25 < I^2 < 0.50$ equals low heterogeneity.

If heterogeneity is detected, a *REM* could be used to find the summary effect (Borenstein et al., 2009). This technique considers that the estimated effects of the included studies are only a random sample of all those that are possible. Following these authors, according to a *REM*, the real effect (θ) could vary from study to study. If it were possible to undertake an infinite number of studies, the sizes of their real effects would be distributed around a *mean effect* that would explain two possible sources of variation: internal, within each of the studies (random error) and external, between the studies (true dispersion), so:

$$T_i = \theta_i + e_i \tag{6}$$

where e_i is the error when T_i estimates the real effect θ_i.

Summary effect variance $\overline{T}$ is now given by expression (7):

$$Var(\overline{T}) = \tau_\theta^2 + v_i \tag{7}$$

where v_i is variance due to sampling error in the *i-ésima* estimate, and τ_θ^2 is *between study variance*.

If the weighted variance method explained by expression (2) is applied with a *REM* application, there would be a transformation with some adjusted weights (w_i^*) obtained for each individual *i-ésimo* effect estimated, as in expression (8):

$$w_i^* = \frac{1}{\frac{1}{w_i} + \tau^2} \tag{8}$$

where τ^2 is the between study variance and w_i the statistical weight for each *i-ésimo* under a *FEM*.

The summary effect $\overline{T}$ (i.e., a *mean effect* obtained from *an effect size distribution*) and its variance can be calculated from (9):

$$\overline{T} = \frac{\sum w_i^* T_i}{\sum w_i^*}; \qquad Var(\overline{T}) = \frac{1}{\sum w_i^*} \tag{9}$$

It must also be taken into account that the presence of so-called *publication biases*, due to which many completed studies have not really been published, either because they do not achieve significant effects, or they are unfavorable, or because they have negative effects (Sterne et al., 2000; Thornton and Lee, 2000), may be induced when computing the summary effect. In analytical terms, publication biases can be detected with the *Begg Method* (rank correlation test: Begg and Mazumdar, 1994) and the Egger intersection test (Egger et al., 1997). These methods are usually complemented with so-called *funnel plots*, which require the application of the Duval and Tweedie trim and fill algorithm (Duval and Tweedie, 2000) to estimate the number of missing studies. Another statistic to measure meta-analysis stability is the Failsafe-N test, which computes the number of estimates or studies that would be required to nullify the summary effect calculated by meta-analysis (Rosenthal, 1979).

Finally, to assess the solidity or stability of the computed summary effect, and following Castro-Nuño et al. (2013), it is useful to perform a *sensitivity analysis* based on the iterative repetition of the meta-analysis, alternatively omitting each of the estimates and re-computing the meta-analysis with those remaining. Thus, if both the direction and size of the effect and the statistical significance of the obtained results for are similar, this is an indication that the solution is robust and stable.

Table A1
Overview of the studies used in the present meta-analysis.

Study	Geographical scope Increased speed limits studied	Roads studied	Control variables	Fatality measure	Methodology Sample size	Main findings Number and type of estimates
Davis et al. (2015)	United States (49 states)	Rural Interstate	Risk Exposure (VMT); Driving Behavior (seat belt use); Motorization (% of Trucks); Weather Conditions (temperature)	Count	Negative binomial model	Fatalities increased in states where speed limits were increased to 70mph or to 75mph or higher
	Increases due to 1995 national maximum speed law repeal				n = 619	Combination of 2 dependent estimates
Farmer et al. (1999)	United States (24 states)	Statewide	Economic (Employment)	Count	Time series cross section regression	Fatalities increased on the roads in 24 states that adopted higher interstate speed limits. No trend changes in states that did not raise speed limits
	Increases due to 1995 national maximum speed law repeal			Rate	Not reported	2 independent estimates
Farmer (2016)	United States (41 states	Statewide	Economic (unemployment); demographic (age groups); driving behavior (alcohol consumption; seat belt use)	Rate	Poisson regression	An increase in the maximum state speed limit was associated with an increase in fatality rates on interstates and on other roads
	Increases due to 1995 national maximum speed law repeal				Not reported	1 independent estimate
Garber and Graham (1990)	United States (40 States)	Rural interstate	Economic (unemployment); driving behavior (seat belt use); seasonal variables (calendar effect)	Count	Multiple regression	The 65mph speed limit increased fatalities in most of the 40 US States that had adopted this higher limit by mid-1988. Differences among states also observed
	Increases due to 1987 National Maximum Speed Relaxation Law	Rural interstate; rural non-interstate			N = 4558	80 independent estimates
Grabowski and Morrisey (2007)	United States (50 States)	Rural interstate	Economic (unemployment); Risk exposure (VMT); driving behavior (seat belt use); road safety policies (BAC limits; license revocations; seat belt law; minimum legal drinking age; graduated driving license)	Count	Negative binomial model	The repeal of the National Maximum Speed Law and the adoption of higher speed limits on rural interstates resulted in an increase in fatalities on rural interstate highways. However, no evidence was found for any decrease in rural non-interstate fatalities
	Increases due to both1987 national maximum speed relaxation law and 1995 national maximum speed law repeal	Statewide			N = 1008	2 combinations of 2 dependent estimates
Greenstone (2002)	United States (40 States)	Statewide	Economic (unemployment); road safety policies (seat belt law)	Rate	Time series model	The 1987 increase to speed limits dramatically increased the fatality rate on rural intestate roads. No empirical evidence of the reallocations effect suggested by Lave and Elias (1997)
	Increases due to 1987 national maximum speed relaxation law				N = 360	1 independent estimate
Houston (1999)	United States (50 States)	Statewide	Demographic (population density; age groups); driving behavior (alcohol consumption), economic (income per capita); weather conditions (temperature); road safety policies (seat belt law; minimum legal drinking age; public expenditure)	Rate	Pooled time series analysis	The 65mph speed limit increased fatality rates on roads directly affected by the change to speed limits. However, a study of the traffic system as a whole showed an overall decrease in state fatality rates. These results are consistent with the traffic diversion hypothesis but contrary to the speed spillover hypothesis
	Increases due to 1987 national maximum speed relaxation law				N = 750	1 independent estimate
Jernigan and Lynn (1991)	United States (State of Virginia)	Rural Interstate	Risk Exposure (VMT)	Count	Regression analysis	The 1987 National Maximum Speed Relaxation Law increased fatalities on Virginia's rural interstates more than in other states that raised their maximum speed limit to 65mph
	Increase due to 1987 national maximum speed relaxation law				Not reported	1 independent estimate

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Table A1 (*continued*)

Study	Geographical scope Increased speed limits studied	Roads studied	Control variables	Fatality measure	Methodology Sample size	Main findings Number and type of estimates
Lave and Elias (1997)	United States (40 States) Increases due to 1987 national maximum speed relaxation law	Statewide	Economic (unemployment); Driving Behavior (seat belt use); Seasonal Variables (calendar effect)	Rate	Regression analysis Not reported	This study is characterized by measuring the effect of a speed limit by its system wide effect rather than its local effects. The conclusion was that statewide fatality rates fell in the group of states that adopted the 65mph limit 40 independent estimates
Morrisey and Grabowski (2005)	United States (50 States) Increases due to both1987 national maximum speed relaxation law and 1995 national maximum speed law repeal	Statewide	Economic (unemployment; income per capita); road safety policies (driving license requirements; seat belt law; BAC limits; license suspension)	Count	Negative binomial model N = 768	Results showed conflicting outcomes when seeking to measure the effects of higher speed limits on fatalities for the sample used Combination of 6 dependent estimates
Neeley and Richardson (2009)	United States (49 States) Increases due to 1995 national maximum speed law repeal	Statewide	Economic (capital expenditures per capita; maintenance expenditure; income per capita; unemployment); Demographic (population density); Risk Exposure (diesel fuel consumption); Driving behavior (alcohol consumption); weather conditions (rainfall; temperature); road safety policies (truck length and weight limits; BAC limit; seat belt law; public expenditure)	Rate	Cross-sectional time series model N = 735	Higher speed limits contributed to higher fatality rates 1 independent estimate
Patterson et al. (2002)	United States (34 States) Increases due to 1995 national maximum speed law repeal	Rural interstate	Risk exposure (VMT)	Count	Negative binomial model Not reported	The elimination of the federal mandate for the National Maximum Speed Law resulted in more fatalities in the states that increased their rural interstate speed limits 1 independent estimate
Ritchey and Nicholson-Crotty (2011)	United States (48 States) Increases due to both 1987 national maximum speed relaxation law and 1995 national maximum speed law repeal	Statewide	Economic (income per capita; public expenditure); demographic (population density); weather conditions (temperature); road safety policies (highway patrol; fines; BAC limit; seat belt law)	Rate	Cross-sectional time series model N = 816	These results, based on an analysis of state-level traffic fatalities, showed that lower speeds saved a significant number of lives 3 independent estimates
Shafi and Gentilello (2007)	United States (50 States + District of Columbia) Increases due to 1995 National Maximum Speed Law repeal	Statewide	Economic (income); demographic (ethnicity; population density; % urban and rural population); driving behavior (alcohol consumption); motorization (registered vehicles per capita; type of registered vehicles); road safety policies (seat belt law; restraint use; statewide trauma system)	Rate	Negative binomial model Not reported	The effect of the repeal of National Maximum Speed Law on the national level was an increase in traffic fatalities in 29 states with speed limits of over 65mph 1 independent estimate
Wagenaar et al. (1990)	United States (State of Michigan) Increase due to 1987 national maximum speed relaxation law	Rural Interstate	Economic (unemployment); risk exposure (VMT); driving behavior (alcohol consumption)	Count	Time series model Not reported	Results revealed significant increases in fatalities on roads where the speed limit was raised and suggested spillover effects on segments of freeways where the limit was not changed 1 independent estimate
Welki and Zlatoper (2007)	United States (State of Ohio) Increase due to 1987 national maximum speed relaxation law	Statewide	Economic (unemployment); demographic (age groups); risk exposure (VMT); driving behavior (alcohol consumption); road safety policies (seat belt law; number of motor vehicles inspected); traffic violations (number of arrests for DUI; speeding and seat belt laws)	Count	Time series model N = 28	These authors suggested that highway fatalities increased with higher speed limits 1 independent estimate

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Table A1 (*continued*)

Study	Geographical scope Increased speed limits studied	Roads studied	Control variables	Fatality measure	Methodology Sample size	Main findings Number and type of estimates
Yowell (2005)	United States (27 States) Increases due to 1995 national maximum speed law repeal	Statewide	Economic (unemployment)	Rate	Regression model Not reported	Unclear correlation between state speed limit and its effect on fatality rate. The repeal and the raising of speed limits in certain states did not lead to a statistically significant rise in the fatality rate 26 independent estimates

Appendix B. Sampling appendix

Tables A.1 gives the main characteristics of the studies used in the present meta-analysis. The first column in the table identifies the different studies in the sample by author's or authors' name/s and year of publication, listed in alphabetical order.

Appendix C. Supplementary material

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.ssci.2018.08.030.

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