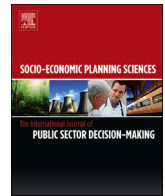




Contents lists available at ScienceDirect

## Socio-Economic Planning Sciences

journal homepage: [www.elsevier.com/locate/seps](http://www.elsevier.com/locate/seps)

## Road speed limit matters – Are politicians doing the right thing?

Vicente Alcaraz Carrillo de Albornoz<sup>\*</sup>, Juan Molina Millán, Antonio Lara Galera, Belén Muñoz Medina

Polytechnic University of Madrid, C/ Profesor Aranguren S/n, 28040, Madrid, Spain

## ARTICLE INFO

## Keywords:

Speed limit  
 Cost-benefit analysis  
 Road transportation  
 Social cost  
 Travel time  
 Accidents  
 Pollution  
 Value of statistical life  
 Externalities

## ABSTRACT

Public Authorities are responsible for setting speed limits on roads. It is obvious that the modification of speed limits affect travel time. Also, there are many academic studies highlighting the relationship between vehicle speed and other particular isolated social costs, such as speed and accidents, speed and pollution or speed and fuel consumption. However, there are very few comprehensive studies on the subject of optimum speed limits. Furthermore, when Public Authorities modify speed limits usually they justify the measure to achieve a particular goal. The aim of this paper is to develop a comprehensive methodology that relies on cost-benefit analyses to determine the optimum speed limit for a particular road. The methodology is then applied to two recent case studies in Spain. In the first one, the Authorities decreased speed limits on national highways from 120 to 110 km per hour to save fuel. In the second case, the Authorities also reduced speed limits on the M – 30 ring road from 90 to 70 km per hour on specific days to reduce pollution. It seems that the Authorities might not always perform a technical analysis of these measures before implementing these policies.

## 1. Introduction

An interesting question that has been raised by different Public Administrations recently is whether speed limits should be decreased to achieve specific benefits and goals for society. In 2007, the regional government of Catalonia, in Spain, reduced the speed limit to 80 km per hour (kph) on motorways in the area of Barcelona to improve air quality. In 2011, the Spanish Central Government limited the maximum speed on highways from 120 kph to 110 kph to save fuel, to decrease the country's trade deficit [1]. In 2017, the Municipal government of Madrid, Spain, introduced as part of their antipollution protocol, a speed limit regime on the M – 30 ring road from 90 to 70 kph that is activated when CO<sub>2</sub> pollutant levels rise above a given threshold [2]. France introduced in 2018 a speed limit decrease on secondary roads, from 90 to 80 kph, to reduce accidents.

Considering that driving slower results in an increase of some transportation costs, most notably time, and a decrease in other costs, such as pollution, fuel consumption, or number and severity of accidents, there ought to be an optimum speed limit.

This paper aims to apply a cost-benefit analysis to determine the optimum statutory speed limit on roads for light vehicles and apply the methodology to two real case studies to determine whether it was

justified to modify speed limits and whether the new speed limits were the appropriate ones.

Although many academic studies focus on the relationship between speed and externalities, very few seem to take a comprehensive approach, as outlined in Section 2 of this paper (Literature review).

It is important to clarify that we analysed statutory speeds, that is, the general speed limit set by the government with jurisdiction over that particular road [3]. This paper is thus not concerned with posted speeds, defined as the maximum legal speed for a particular location [4].

## 2. Literature review

Cost-benefit analysis (CBA) is a technique that allows determining if a particular project should be undertaken. The methodology has been employed for many years now and is widely accepted and integrated into the decision-making process across many fields, from civil engineering to medicine. There are many books, manuals and academic papers that develop this topic (see for instance Refs. [5,6,7] and [8]).

The relationship between speed and external costs has been widely and thoroughly studied [9–13]. Driving faster modifies the likelihood of having an accident, and the consequences will be more severe as well [14,15]. The relationship between speed and fuel consumption and the

<sup>\*</sup> Corresponding author.

E-mail addresses: [vicente.alcarazc@upm.es](mailto:vicente.alcarazc@upm.es) (V. Alcaraz Carrillo de Albornoz), [juan.molina@upm.es](mailto:juan.molina@upm.es) (J. Molina Millán), [alargal@ciccp.es](mailto:alargal@ciccp.es) (A. Lara Galera), [mariabelen.munoz@upm.es](mailto:mariabelen.munoz@upm.es) (B. Muñoz Medina).

<https://doi.org/10.1016/j.seps.2021.101106>

Received 28 October 2020; Received in revised form 11 June 2021; Accepted 21 June 2021

Available online 27 June 2021

0038-0121/© 2021 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

emission of pollutants and greenhouse gases is U-shaped [16,17]. There is a strong argument for limiting the speed at which cars can circulate on roads.

Nevertheless, decreasing speed also increases the travelling time. It must not be forgotten that time is a scarce resource, and as such has an important value [18,19,20].

Determining the optimum speed limit is a question that economists should be able to answer. According to Ref. [21], there are four ways to determine the optimum statutory speed limits, providing different results: The societal perspective, road user perspective, the tax-payer perspective, and the residential perspective.

Comprehensive studies that focus on the societal optimum statutory speed limit are usually limited to quantifying the effects of a pre-determined change in speed limits, rather than on finding the optimum speed limit. Also, they use empirical data to carry out ex-post analysis of Government decisions concerning the modification of speed limits (see for instance Refs. [22,23]). An exception would be the work performed by Refs. [24,25], in which models are proposed to determine the optimum speed limit.

The case studies proposed in this paper have already been analysed by other researchers. This previous work however doesn't take a holistic approach to determine if it was appropriate to modify statutory speed limits, but rather focus on particular benefits obtained – such as fuel savings and fatalities achieved with the temporary reduction of speed limits in Spanish highways [1], or pollution reduction in M – 30 ring road [2].

### 3. Theoretical framework

The proposed theoretical framework adopts the societal perspective. The objective is thus to minimize the total transportation cost to society.

As a starting point, the methodology proposed uses a cost-benefit analysis (CBA). A CBA is a quantitative analysis widely used and generally accepted for decision making related to the implementation of projects that have an important social component, such as public infrastructure. A CBA requires the establishment and quantification of two scenarios, one representing the state of the world with the project that is under study, and one representing the state of the world without the project. The costs of both scenarios are then compared to determine under which situation society is better off.

Thus, it can be concluded that reducing the speed limit makes sense as long as the following expression holds:

$$C_0 - C_1 > 0 \quad (1)$$

with:  $C_0$ : Total cost of the scenario without the project (current limitation on speed limits).

$C_1$ : Total cost of the scenario with the project (new limitation on speed limits).

To determine the optimum new speed limit, it would be necessary to maximize the difference between the scenarios with and without the project. This can be done using derivatives, through the following expression:

$$\frac{dC_0}{dS} - \frac{dC_1}{dS} = 0 \quad (2)$$

with  $S$  being the new statutory speed limit. Since the total cost of the scenario without the project does not depend on the new statutory speed limit, we arrive at the following expression:

$$\frac{dC_1}{dS} = 0 \quad (3)$$

Therefore, it is necessary to determine the relationship between road transportation costs and speed to find the solution for equation (3).

The total transportation cost of the scenario with project is the sum of the individual costs of the  $N$  vehicles that travel through the road, as per

the following equation:

$$C_1 = \sum_{i=1}^N c_i \quad (4)$$

The cost of a particular vehicle, during a certain period of time  $T$ , can be expressed as follows:

$$c_i = \int_0^T cost_i(s) dt \quad (5)$$

With:  $c_i$  = Cost of vehicle  $i$  during the period of time going from  $0$  to  $T$ .

$cost_i(s,)$  = Instantaneous cost function for vehicle  $i$ .

$s$  = Instantaneous speed.

$t$  = Time.

The cost function of a particular vehicle depends on speed, as shown in Section 4. The instantaneous speed ( $s$ ) in turn depends on time ( $t$ ) and the statutory speed limit ( $S$ ). This can be easily shown by analysing the trip of a car, from the moment the trip begins (time  $0$ , speed  $0$ ) until the moment the car parks at destination (time  $T$ , speed  $0$ ) – on scenarios with different statutory speed limits (see Fig. 1).

Thus, the total cost of the scenario with a change to the statutory speed limit on a road with  $N$  cars during  $T$  time would be the following:

$$C_1 = \sum_{i=1}^N \int_0^T cost_i(s) dt \quad (6)$$

The optimum statutory speed limit would be provided by the following expression:

$$\frac{dC_1}{dS} = \frac{d\left(\sum_{i=1}^N \int_0^T cost_i(s) dt\right)}{dS} = 0 \quad (7)$$

It is possible to simplify the above expression by substituting the instantaneous speed  $s$  with the average speed of the vehicles  $\bar{s}$ . The average speed by definition doesn't depend on time, facilitating the solution of equation (7). For non-urban roads with no big changes in their geometric characteristics (and similar low flow levels), this might be true.

For an optimum statutory speed limit to exist, the instantaneous speed of a vehicle (or its average speed if the previously mentioned simplification is adopted) must show certain elasticity to the statutory speed limit [14]. states that this is the case only as long as the new statutory speed limit is not too different from the old one or appears consistent with the surrounding context of the roadway and meets drivers' expectations. If these conditions are not met, it may be difficult

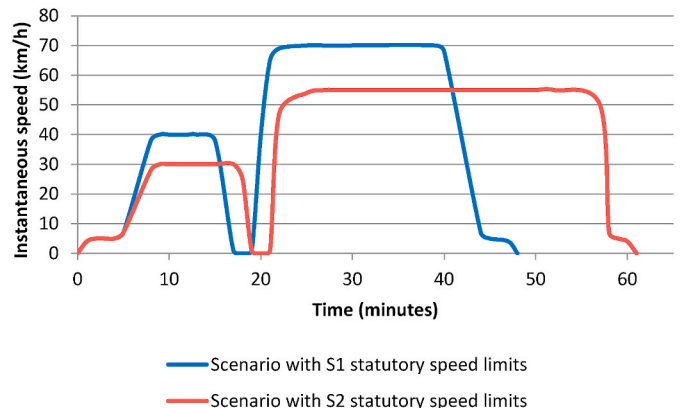


Fig. 1. Speed changes of a particular car during a sample trip.

to implement, since it may not seem credible to road users and there may be no change in the instantaneous (or average) speed. Speed enforcement might be a key element in this regard as well [26].

It could be argued that this approach does not take into consideration the geometric characteristics of the road. It is not the case since the proposed framework can consider instantaneous speed as a function of road geometry as well. Also, the model can consider traffic accidents as a cost, and there is a clear link between accidents and road geometry (see for instance Refs. [27,28]).

Finally, there is the issue of traffic flow. During rush hours in congested roads, there will be no elasticity of instantaneous speed to changes on statutory speed limits – since the instantaneous speed will be limited by the traffic flow [29]. There will be times, however, when the traffic flow is not relevant in determining the speed at which vehicles travel. Determining the optimum statutory speed limit is thus relevant, even on roads with important traffic flows.

#### 4. Road transport costs

The different costs associated with road transport are well identified and documented, both in academic literature [30,31,32] as well as in guidance manuals [33,34,5,35].

The most significant costs in road transportation are travel time, vehicle operating costs (VOC), accidents, climate change, air pollution, noise, vibration and infrastructure wear and tear.

In what follows we describe these costs and how they are affected by speed. In some instances, we have obtained the relationship between a particular cost and speed from the empirical data provided by other authors, and then running regressions on the data.

##### 4.1. Travel time

Passengers allocate some of their time to go from one place to another. This is a resource that could be used for other activities, such as work or leisure.

Travel time depends to a large extent on the distance to be covered for the trip, as well as the average speed at which the vehicle circulates.

$$t = \frac{d}{\bar{s}} \quad (8)$$

with:  $t$ : Time spent on the journey, in hours.

$d$ : Distance covered for the journey, in km.

$\bar{s}$ : Average speed for the journey, in kilometres per hour.

Thus, the lower the average speed, the longer the journey.

The annual travel time cost would then be provided by the following expression:

$$TT = n \times \bar{\sigma} \times \frac{\bar{d}}{\bar{s}} \times VT \quad (9)$$

with:  $n$ : Number of light vehicles affected by the change in the speed limit.

$\bar{\sigma}$ : Average vehicle occupancy rate.

$\bar{d}$ : Average distance covered by a light vehicle in a year, in km.

$\bar{s}$ : Average speed during the journey, in kilometres per hour.

$VT$ : Value of time, in Euros per hour.

##### 4.2. Vehicle operation costs (VOC)

These are the costs borne by owners of vehicles to make them function. These costs usually include energy consumption, wear and tear of tyres, repair and maintenance costs, insurance, overheads, etc. VOC depend mainly on the type of vehicle, the type and conditions of the infrastructure (in particular its surface), the geography (in particular the

accumulated drop) and on average travel speed.

The relationship between vehicle speed and the rate of fuel consumption has been extensively studied and is U-shaped (see for instance Ref. [36]; and [37]. According to Ref. [22], when the vehicle speed increases from 55 to 65 miles per hour (mph) the average fuel economy decreases by 18%. With all these studies and the empirical data available in them, it is possible to obtain a fuel consumption curve that depends on the average speed. For simplicity purposes, we conduct a regression using a second-degree polynomial, which offers a reasonable good adjustment. Thus, the annual fuel consumption can be obtained from the following expression:

$$FC = n \cdot \bar{d} \cdot (f_1 \cdot \bar{s}^2 + f_2 \cdot \bar{s} + f_3) \cdot F \quad (10)$$

with: FC: Annual fuel consumption, in Euros.

$f_1$ ,  $f_2$  and  $f_3$ : Coefficients obtained from assimilating the fuel consumption curve to a second-degree polynomial using empirical data.

$F$ : Shadow price of fuel, in Euros per litre.

The relationship between speed and fuel consumption changes over time, due to changing vehicle characteristics. The values obtained for the coefficients  $f_1$ ,  $f_2$  and  $f_3$  reflect the reality of a precise period of time and need periodic recalibration.

[38] also consider that tyre wear and tear depends mainly on the roughness of the road, and to a lesser extent on vehicle speed. Tyre wear and tear can also be easily assimilated through regression from empirical data to a second-degree polynomial:

$$TC = n \cdot \bar{d} \cdot (t_1 \cdot \bar{s}^2 + t_2 \cdot \bar{s} + t_3) \cdot T \quad (11)$$

with: TC: Annual tyre costs, in Euros.

$t_1$ ,  $t_2$  and  $t_3$ : Coefficients obtained from assimilating the tyre wear and tear curve to a second-degree polynomial using empirical data.

$T$ : Shadow price of tyres, in Euros per tyre.

It must be pointed out that equations (10) and (11) are just one of many possibilities. It would be possible to use more complex curves, such as the ones proposed by specialized public institutions. An example would be the COPERT spreadsheets produced by the National Atmospheric Emissions Inventory from the United Kingdom. It is not expected that the results obtained would be significantly different.

Finally [38], conclude that maintenance and lubricant consumption seems to depend largely on road roughness, and not so much on vehicle speed. The depreciation of cars is mainly linked with time and, to a much lesser extent, with the type of usage.

##### 4.3. Accidents

Transport implies the risk of having accidents. Risk can be assessed through the combination of the probability of an accident taking place and the consequences of the accident once it occurs.

The probability of an accident depends to a great extent on the infrastructure conditions (its surface and geometry, but also the signalling), the weather, vehicle type and conditions (in particular safety systems such as airbags), and the travelling speed.

In theory, high speeds make the vehicle more difficult to control. There is, for instance, less time for the driver to react to an unexpected event and to steer the vehicle due to a decrease in traction [39]. Some recent studies that use aggregated sets of empirical data suggest, however, precisely the opposite, a negative speed-crash relationship [40]. In any case, most studies seem to agree that two main models relate speed and accidents, the exponential model and the power model [41]. The general form of the exponential model is the following:

$$A_a = A_b e^{\beta(\bar{s} - \bar{s}_b)} \quad (12)$$

with:  $A_a$ : Accidents per year after the speed limit change.

- $A_b$ : Accidents per year before the speed limit change.
- $s_b$ : Average speed before the speed change, in kph.
- $\beta$ : Exponent that depends on the type of accident (fatalities or injured road users for instance).

As for the power model, its general form is the following:

$$A_a = A_b \cdot \left( \frac{\bar{s}}{\bar{s}_b} \right)^e \quad (13)$$

with all the variables having been explained previously except for  $e$ , an exponent that depends on the type of road and the type of accident.

Although both the power model and the exponential model fit empirical data very well [42]. Nevertheless, according to Ref. [43], the exponential model fits individual data better when dealing with high-speed data points.

[22] found that a 10 mph speed limit increase in the USA resulted in 44.1% increase in fatal accidents.

Finally, the consequences of an accident increase with speed, since there is more kinetic energy involved.

$$E = \frac{1}{2} m \cdot s^2 \quad (14)$$

with: E: Kinetic energy, in Joules.

- m: Mass of the vehicle, in kilograms.
- s: Speed of the vehicle, in meters per second.

#### 4.4. Climate change emissions

Road transport that uses a combustion engine produces Green House Gases (GHG) emissions, which may contribute to global warming and various negative effects, for instance rising sea levels. The amount of GHG released depends on the type of vehicle and speed. The main GHG is CO<sub>2</sub>.

The relationship between vehicle speed and the level of GHG produced by a vehicle is well documented by car manufacturers and academia (see for instance Refs. [37,44,45]). From the empirical data provided in these studies, it is possible to obtain a GHG emissions curve that depends on average speed, using a regression with a second degree polynomial. The annual cost of GHG produced by light vehicle road transportation would be provided by the following expression:

$$GHG = n \cdot \bar{d} \cdot (g_1 \cdot \bar{s}^2 + g_2 \cdot \bar{s} + g_3) \cdot G \quad (15)$$

with: GHG: Annual cost of greenhouse gases produced by light vehicles, in Euros.

- $g_1$ ,  $g_2$  and  $g_3$ : Coefficients obtained from assimilating the greenhouse gases emission curve to a second-degree polynomial using empirical data.
- G: Shadow price of greenhouse gases, in EUR per gram.

#### 4.5. Pollution

Emissions produced by combustion engines used by road transport vehicles may have harmful effects on health (through the aspiration of pollutants released into the atmosphere), buildings, and other assets (by both soiling and degrading surfaces), crops, ecosystems and biodiversity. The amount and type of emissions depend on the type of vehicle and road, including speed.

The main pollutants released into the atmosphere by vehicles include carbon monoxide (CO), nitrogen oxides (NO<sub>2</sub>/NO<sub>x</sub>), volatile organic compounds, Ozone (O<sub>3</sub>), and particulate matter smaller than 10 μm in

diameter (PM<sub>10</sub>).

The relationship between vehicle speed and per-kilometre tailpipe emissions has been extensively studied and is U-shaped [37,44,36]. It is possible to assimilate this relationship through a regression to a second-degree polynomial.

$$PC = n \cdot \bar{d} \cdot (p_1 \cdot \bar{s}^2 + p_2 \cdot \bar{s} + p_3) \cdot P \quad (16)$$

with: PC: Annual cost of pollutants produced by light vehicles, in Euros.

- $p_1$ ,  $p_2$  and  $p_3$ : Coefficients obtained from assimilating the pollutant emission curve to a second-degree polynomial using empirical data.
- P: Shadow price of the pollutant, in Euros per gram.

Each type of pollutant (CO, NO<sub>x</sub>, HC ...) will have its polynomial coefficients and shadow prices. According to Ref. [22], a 10 mph increase in speed limits in the USA resulted in increases in the concentration of CO (+23%), NO<sub>2</sub> (+15%) and O<sub>3</sub> (+11%).

The relationship between speed and pollutant emissions depends on vehicle characteristics that change over time. Thus, the coefficients  $p_1$ ,  $p_2$  and  $p_3$  will depend to a large extent on the characteristics of light vehicles at a certain time.

#### 4.6. Noise, vibration and road wear and tear

Road transportation produces additional externalities besides the ones already described:

- Noise and vibration: According to the [46]; page 2), environmental noise is defined as “*unwanted or harmful outdoor sound created by human activities, including noise emitted by means of transport, road traffic ...*”. This may translate in turn into harmful effects for human health or annoyance that decreases the enjoyment of activities. The noise depends to a great extent on the road surface and geometry, road characteristics (tunnels, panels to prevent noise, etc.), as well as the type of vehicle and its speed.
- Road deterioration: Generally speaking, roads wear and tear once they are built, and thus require maintenance to meet certain quality standards. This deterioration depends on climate factors, as well as the type of vehicles that circulate on the road and their speed.

These externalities, however, in the case of light vehicles, are quite small in comparison with the rest of transportation costs – under 5% in Sweden and Norway [21]. It is thus suggested that they are not taken into consideration since it is very likely that they do not affect the outcome of the analysis.

#### 4.7. Signalling, communication and enforcement

These costs refer to the different systems that need to be changed to implement a new speed limit. They include, although not limited to: changes in vertical and horizontal road signs, communication campaigns in radio, television and other media. There are subtler changes such as updating navigation systems that include speed limits.

Enforcement costs also need to be considered. They refer to the costs of the necessary measures to ensure that new speed limits are respected by light vehicle users. Setting up higher speed limits probably would not require additional enforcement costs, but setting lower speed limits might require (at least initially) more supervision by the authorities to ensure that they are respected: additional police controls, more traffic radars, etc.

Although many of these costs are generally born by society, they do not depend on the new speed limit value itself.

### 5. Determining the optimum speed limit

Having identified all relevant costs associated with light vehicle road transportation, it can be concluded at this stage that said costs to society is provided by the following expression:

$$C_1(s) = \sum_{i=1}^N (TT_{1i}(s) + VOC_{1i}(s) + A_{1i}(s) + CC_{1i}(s) + AP_{1i}(s) + NV_{1i}(s)) + RD_1(s) + SC_1 \quad (17)$$

with:  $TT_{1i}$ : Cost of journey time with the new speed limit for vehicle i.

- $VOC_{1i}$ : Vehicle operation cost with the new speed limit for vehicle i.
- $A_{1i}$ : Accidents cost with the new speed limit for vehicle i.
- $CC_{1i}$ : Climate change cost with the new speed limit for vehicle i.
- $AP_{1i}$ : Air pollution cost with the new speed limit for vehicle i.
- $NV_{1i}$ : Noise and vibration cost with the new speed limit for vehicle i.
- $RD_1$ : Road deterioration cost with the new speed limit.
- $SC_1$ : Signalling and communication costs.
- s: average speed of light vehicles.

Applying derivatives to the above equation, and considering noise, vibration and road wear and tear as insignificant when compared to other costs, it would be possible to determine the optimum statutory speed limit.

$$\frac{dC_1(s)}{ds} = \sum_{i=1}^N \left( \frac{dT_{1i}(s)}{ds} + \frac{dVOC_{1i}(s)}{ds} + \frac{dA_{1i}(s)}{ds} + \frac{dCC_{1i}(s)}{ds} + \frac{dAP_{1i}(s)}{ds} \right) = 0 \quad (18)$$

Solving the above equation requires knowing the relationship between statutory speed limits and the average speed of the vehicles that use a particular road. There are currently very few empirical studies that could show some light on this issue. On the review carried out by Ref. [47] regarding the effects of speed limit enforcement on public health, a relationship is provided between statutory speed limits and the mean speed of traffic. The relationship was obtained through meta-data analysis and had an R-squared of 0.5404.

$$y = -0.0058x^2 + 0.2781x - 0.2343 \quad (19)$$

with: x: Change of speed limit (km/h).

y: Change of mean speed of traffic (km/h)

A study by Ref. [22] shows that a 10 mile per hour (mph) statutory speed limit increase in California (1996), Oregon (1987) and Washington (1996), with speed limits that ranged between 55 and 70 mph, had a 3–4 mph increase in average travel speed.

### 6. Application of the theoretical framework in two case studies from Spain

In this section, we applied the theoretical framework to two real situations, in which Spanish authorities modified speed limits. To do so, it would suffice to identify the different parameters in equation (17), solve the equation, and compare the results with the new speed limits established by the Authorities.

When selecting the case studies, we chose one that affects a freeway with an initial statutory speed limit of 120 kph and one that affects an urban highway with an initial statutory speed limit of 90 kph. The reason is that some parameters that need to be determined change

substantially depending on the type of road, such as those related to accidents and speed. Furthermore, since the equations to determine optimum speeds are nonlinear, the behaviour may change dramatically depending on the speed range used.

There are nevertheless some parameters that will remain the same

for both case studies. These are identified in the following Table 1:

The value of time is a key parameter in any CBA related to transport policy [48]. conducted a meta-analysis of the values of travel time in Europe that yielded for Spain the equivalent of 7.12, 6.23 and 13.84 EUR of 2020 per hour, depending on whether the purpose of the journey was “commuting”, “other” or “Employer’s Business Trips” on urban free-flow. A value of 7.00 EUR of 2020/hour has finally been adopted.

Severe injuries and light injuries were estimated to be the result of production losses and medical costs, which in turn were estimated as follows [5]:

- Production loss: 13% (severe injury) and 1% (light injury) of VOSL.
- Medical costs: 15% of production loss.
- Administrative costs: 18% of production loss.

Fuel consumption and gas emissions (of both GHG and pollutants) depend to a large extent on the fleet of light vehicles in Spain: how old they are on average, their power, how well maintained they are, etc. Although there are many fuel consumption-emission curves provided by auto manufacturers for specific models, unfortunately, we have not found any aggregate study for Spain. Thus, the coefficients of the polynomials that provide fuel consumption, GHG emissions and pollutant emissions depending on the speed of light vehicle were obtained by using empirical aggregate data provided by international studies [37,38,54,36]. Thus, the fuel consumption coefficients do not necessarily reflect the reality of the Spanish car fleet in 2011 (case study 1) and 2017 (case study 2). This study considers as a simplification that these coefficients have remained constant through the period of analysis. The same hypothesis has been adopted for pollutant emission coefficients.

The shadow price of fuel was obtained by using the market price of fuel in Spain and deducing taxes, which currently account for approximately 58% of the market price. Likewise, the average shadow price of a tyre was obtained from market prices deducing applicable taxes.

Finally, the question remains of the effects that a statutory speed limit change would have on the average speed of individual drivers. Ideally, data concerning a breakdown of vehicle speeds before and after statutory speed limits should be used. This would allow us to carry out a more precise analysis and to obtain important information commonly used in traffic engineering, such as the 85th percentile speed. Although for some roads there is a breakdown of speeds before statutory speed limit changes, there is very limited information regarding the effects in these speeds after said changes.

In the two case studies analysed, there is information available regarding the average speed before and after statutory speed limit changes. There is unfortunately no breakdown of this information. Thus, the analysis is carried out using statutory speed limits and the average speed of light vehicles.

#### 6.1. Case study 1: reducing the speed limit in Spanish highways to save fuel and improve the trade balance

The Central Government of Spain in 2011 limited the maximum speed on highways from 120 kph to 110 kph to save gasoline, to reduce the deficit in the international trade balance. This measure was reversed less than four months later [1]. perform empirical research of this case

**Table 1**  
General parameters for Spanish roads.

Parameter	Description	Units	Suggested value	Source
$V_T$	Value of time	EUR per hour	7.00	[48]
$A_D$	Statistical cost of a death in a traffic accident	Million EUR per fatality	4.5	[49]
$A_S$	Cost of a severely injured citizen in a traffic accident	EUR per injured	778,050	Self-Assessed based on data from [50,51] and methodology of [5]
$A_L$	Cost of a lightly injured citizen in a traffic accident	EUR per injured	45,000	Self-Assessed based on data from [50,51] and methodology of [5]
$f_1$	Coefficient of the second-degree polynomial that provides fuel consumption depending on vehicle speed	-	0.0000169	Self-Assessed with data from [52]
$f_2$	Coefficient of the second-degree polynomial that provides fuel consumption depending on vehicle speed	-	-0.002673	Self-Assessed with data from [52]
$F$	Shadow price of fuel	EUR per litre	0.546	Self-Assessed with market data
$t_1$	Coefficient of the second-degree polynomial that provides tyre consumption depending on vehicle speed	-	$10^{-8}$	Self-Assessed with data from [38]
$t_2$	Coefficient of the second-degree polynomial that provides tyre consumption depending on vehicle speed	-	$-5 \cdot 10^{-7}$	Self-Assessed with data from [38]
$T$	Shadow price of a tyre for a light vehicle	EUR per tyre	50	Self-Assessed with market data
$g_1$	Coefficient of the second-degree polynomial that provides CO <sub>2</sub> emissions depending on vehicle speed	-	0,0321	Self-Assessed with data from [37]
$g_2$	Coefficient of the second-degree polynomial that provides CO <sub>2</sub> emissions depending on vehicle speed	-	-5,3915	Self-Assessed with data from [37]
$G$	Cost of CO <sub>2</sub> emissions	EUR per T	104.7	[53]
$P_{NOX1}$	Coefficient of the second-degree polynomial that provides NOx emissions depending on vehicle speed	-	$8 \cdot 10^{-5}$	Self-Assessed with data from [54]
$P_{NOX2}$	Coefficient of the second-degree	-	-0.0077	

**Table 1 (continued)**

Parameter	Description	Units	Suggested value	Source
	polynomial that provides NOx emissions depending on vehicle speed			Self-Assessed with data from [54]
$P_{NOX}$	Cost of NOx emissions	EUR per T	8902	[53]

**Table 2**  
Particular parameters for Spanish freeways and highways.

Parameter	Description	Units	Suggested value	Source
$\bar{o}$	Average occupancy rate	Persons per vehicle and trip	1.5	[55]
$AD_b$	Deaths related to accidents before the speed limit change	Deceased per year	327	Spanish Ministry of Public Works, for the year 2016
$A_{sb}$	Severely injured people in accidents before the speed change	Severely injured per year	1120	Spanish Ministry of Public Works, for the year 2016
$A_{Lb}$	Lightly injured people in accidents before the speed change	Lightly injured per year	18,741	Spanish Ministry of Public Works, for the year 2016
$\beta_D$	Coefficient for deaths in highways	NA	0.08	[41]
$\beta_S$	Coefficient for severely injured in highways	NA	0.06	[56]
$\beta_L$	Coefficient for lightly injured in highways	NA	0.04	[56]
$n \cdot \bar{d}$	Annual distance covered by light vehicles	Veh Km per year	91,604,190,176	Spanish Ministry of Public Works, for the year 2017
$\bar{v}_b$	Average speed before the speed change	Kph	100.07	Self-estimation based on data from the Spanish Ministry of Public Works

study, analysing the results obtained by the government through this measure.

Table 2 below are included the specific parameters of Spanish highways and freeways, to determine the optimum speed limit.

The occupancy rate has been steadily declining since 1970 [57]. Although there are no official figures regarding the average occupancy rates of light vehicles on Spanish highways, a value of 1.5 was adopted, in line with the values provided by the European Union [55].

The Spanish Ministry of Public Works compiles statistics on aspects related to the use of the infrastructure it manages (directly or indirectly), including highways and freeways. These statistics include data such as the average number of vehicles per day that use the infrastructure and the number of victims in traffic accidents.

For the relationship between speed and accidents, an exponential model has been used. The reasons are the ones expressed by Ref. [43]: it fits better individual driver data and high-speed data points.

With these data, the most important transportation cost by far is time

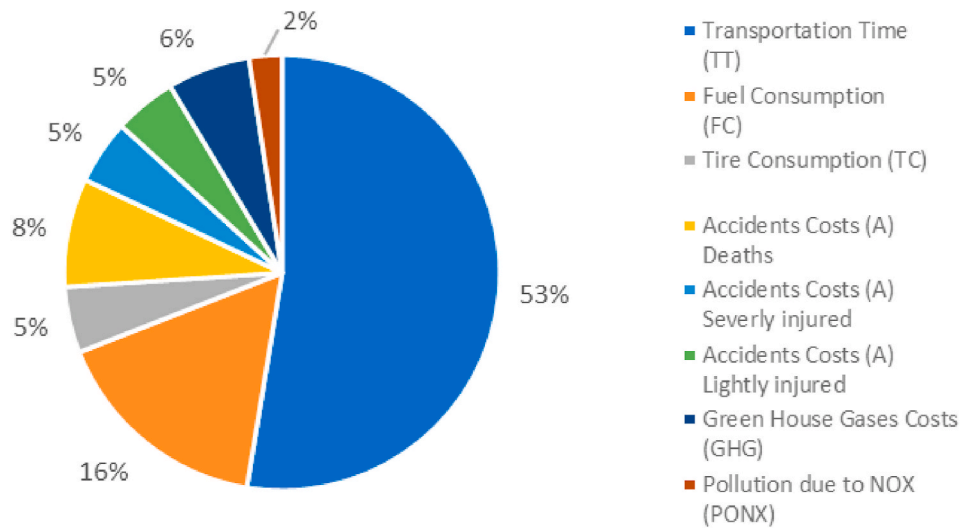


Fig. 2. Transportation costs in Spanish highways and tollways. Source: Self-elaboration.

Table 3

Relation between statutory speed limit changes and average speed changes. All data in kph. Source: Self-elaboration from data provided by the Ministry of Public Works and [47].

Statutory speed limit	Average light vehicle speed	Change in statutory speed limit	Change in average speed (real)	Change in average speed (predicted)
120	100.07	NA	NA	NA
110	98.34	-10	-1.73	-3.59
120	101.27	10	2.93	1.97

travel (55%), followed by fuel consumption (17%) and deaths (8%) (see Fig. 2).

There are consolidated data available regarding the average monthly speed of light vehicles in Spanish freeways. It is thus possible to determine the average speed changes for light vehicles that ensued after the statutory speed limit change, and that are shown in Table 3. These results are somewhat different from what would have been predicted by equation (19).

A new regression of changes in statutory speed limits and changes in average speed has been obtained (included in Annex 1).

Using the data in Tables 1 and 2 and applying equation (17), the optimum statutory speed on Spanish highways is around 70 kph. This

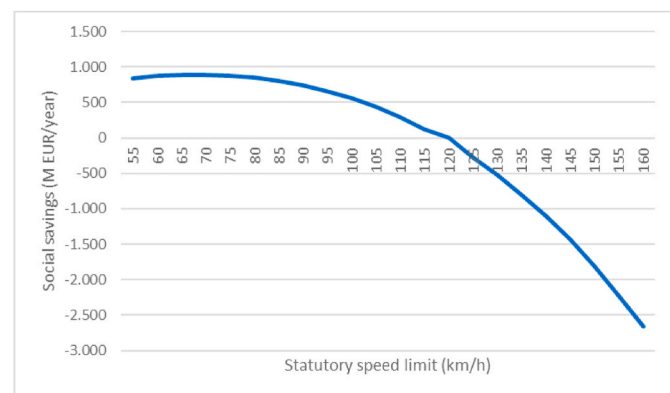


Fig. 3. Annual social savings from modifying the statutory speed limit of light vehicles on Spanish freeways and highways.

would mean decreasing statutory speed limits in 50 kph from current levels (see Fig. 3).

The conclusion for Case 1 would be that the decision by the Government to decrease the statutory speed limit on highways and freeways, once that all relevant transportation costs are considered, is a move in the right direction. Decreasing the statutory speed limit resulted in fuel consumption savings - in line with the results obtained by Ref. [1], which corroborated through an empirical analysis the fuel consumption and reduction in casualties. The annual savings in fuel consumption however were not as important as the initial estimates made by the government, and the main benefit obtained would be the reduction in casualties. Furthermore, the optimum statutory speed limit would be much lower than the one implemented. It is noteworthy however that the maximum annual savings that could be achieved by implementing the optimum statutory speed limit (900 million Euros of 2020 per year) are small when taking into account the total transportation costs (17.4 billion Euros of 2020 per year).

### 6.2. Case study 2: antipollution protocol for madrid M - 30 ring road

The Madrid local government in 2017 introduced as part of its anti-pollution protocol a decreased statutory speed limit on the M - 30 ring road, from 90 to 70 kph. This speed limit change only occurs on days when pollution levels are above predetermined thresholds [2]. perform an analysis of this particular case study, with a main focus on the environmental effects achieved by the reduction of speed limits.

It could be argued that this case study should be analysed as a variable or dynamic speed limits scenario. In as much as pollution costs remain constant and do not depend on the overall pollution level, the proposed theoretical framework is valid. Furthermore, it would be relatively easy to adapt the methodology proposed to take into consideration different pollution costs. In any case, since to the best of our knowledge, no such studies have been carried out for the M - 30 ring road, we conduct our study assuming that pollution costs remain constant - which allows us, for instance, to pass a judgement on statutory speed limits in the absence of high pollution scenarios.

In Table 4 below are given the main parameters of the M - 30 ring road.

Most of the data were obtained from the official website of Madrid Calle 30, the special purpose vehicle (SPV) in charge of operating the ring road. Unfortunately, the latest data available is from August 2015.

For the relationship between speed and accidents, both the exponential and power models were used, which provide similar results. The exponential model provides a more important reduction (increase) in

**Table 4**  
Specific parameters for M – 30 ring-road.

Parameter	Description	Units	Suggested value	Source
$\bar{o}$	Average occupancy rate	Persons per vehicle and trip	1.35	Ayuntamiento [58]
$AD_b$	Deaths related to accidents before the speed limit change	Deceased per year	0	Madrid Calle 30, for the year 2015
$A_{sb}$	Severely injured people in accidents before the speed change	Severely injured per year	336	Madrid Calle 30, for the year 2015
$A_{lb}$	Lightly injured people in accidents before the speed change	Lightly injured per year	468	Madrid Calle 30, for the year 2015
$e_D$	Coefficient for deaths in highways	NA	3.0	[42]
$e_s$	Coefficient for severely injured in highways	NA	2.0	[42]
$e_L$	Coefficient for lightly injured in highways	NA	1.1	[42]
$n$	Number of light vehicles affected by the change in the speed	Light vehicles using M – 30 ring road on a daily basis	1,233,333	Madrid Calle 30, average of years 2013–2015
$\bar{d}$	Average distance covered by a light vehicle	Km per year	2300	Madrid Calle 30, for the year 2015
$\bar{s}_b$	Average speed before the speed change	Kph	67.5	Self-Assessed based on data from the Spanish Ministry of Public Works, for the year 2016

the number of accidents than the power model as the statutory speed limit decreases (increases).

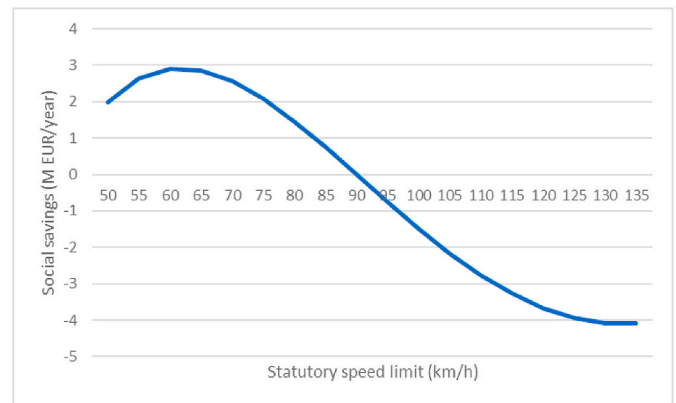
Unfortunately, there is no data available concerning the distribution of light vehicles average speed.

With these data, the main transportation cost is travel time (48%), followed by accidents with severe injuries (31%) and fuel consumption (10%) (see Fig. 4).

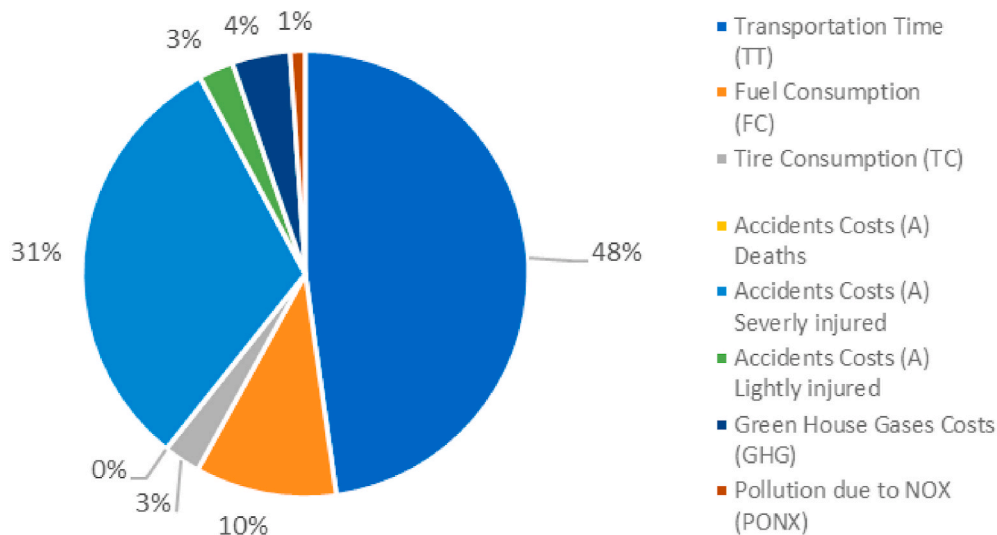
Madrid’s Municipal Government provides aggregated data regarding the average speed of vehicles circulating through Madrid Calle 30 daily. Thus, it is possible to determine the effects of statutory speed limit changes. These changes do not fit well the formula obtained by Ref. [47], and so a new regression has been carried out (Annex 2). The

**Table 5**  
Relation between statutory speed limit changes and average speed changes. All data in kph. Source: Self-elaboration from data provided by Madrid’s Municipal Government and [47].

Statutory speed limit	Average light vehicle speed	Change in statutory speed limit	Change in average speed (real)	Change in average speed (predicted)
90	66,63	NA	NA	NA
70	64,10	-20	-2,53	-0,97
90	65,65	20	1,56	0,18



**Fig. 5.** Annual social savings from modifying the statutory speed limit of light vehicles in M – 30 ring road.



**Fig. 4.** Transportation costs in Madrid Calle 30. Source: Self-elaboration.

results are shown in Table 5.

With the above data and using equation (17), the optimum statutory speed limit in Madrid Calle 30 is around 60 kph - with an average speed of 63 kph (see Fig. 5).

Following a reduction in Madrid Calle 30's statutory speed limit, the increased transportation time cost, increased fuel consumption cost and increased greenhouse gases cost is balanced by the decrease in accident costs.

The total cost associated with vehicle emissions (GHG or pollution) is quite low when compared to other transportation costs. In addition, the most recent trends show that vehicle engines are increasingly efficient, resulting in lower fuel consumption and decreased emissions of GHG and pollutants (see for instance Ref. [59]). With the available data, it seems very unlikely a scenario in which a reduction of the statutory speed limit would be justified due to GHG or other pollutants from light vehicles. These results are in contradiction with the findings obtained by Ref. [2], which conclude that the speed limitations have a significant impact on reducing pollution (14.4% for CO<sub>2</sub> and 16.4% for NO<sub>x</sub>) while not affecting travel time.

It is noteworthy that, even more than in the previous case study, the annual social gains or losses from increasing or decreasing the statutory speed limit would be almost irrelevant (between +3 million Euros and -4 million Euros) considering the total current transportation costs (830 million Euros).

The conclusion for Case 2 is that the decision by the local government to decrease the statutory speed limit on the M - 30 ring-road would be a move in the right direction, although the total savings achieved are insignificant and come mostly from accident reduction and not pollutant reduction.

## 7. Conclusions

The decision to modify the statutory speed limit on a road should probably be justified with technical analysis, such as a CBA. This analysis should, in turn, consider all the different costs associated with road transportation, and not just a few, as it seems to be usually the case. Even if only a few of these costs are going to be considered, the Authorities need to be mindful of which costs are the most relevant ones.

In practice, for the two case studies analysed in the present paper, it seems that these analyses might not have always been carried out:

- The reduction of speed limits on Spanish highways and freeways would be a move in the right direction - although the optimum

statutory speed limit would be around 70 kph. The main benefit from this measure however is an important reduction in accidents and not a reduction in fuel consumption. The estimated social savings from the reduction in deaths more than double the ones obtained through a decrease in fuel consumption. This measure was nevertheless very short-lived, signalling a probable absence of a comprehensive technical analysis and other factors that might also be at play, such as political pressure.

- The speed limit reduction on the Madrid Calle 30 ring road could also be justified. Although this measure indeed fosters a reduction in pollutant emissions, the main benefit is a decrease in accidents. These savings, however, are almost completely offset by the cost increase in transportation time and, to a lesser extent, in fuel consumption and CO<sub>2</sub> emissions.

Finally, it is noteworthy that the social savings obtained or lost due to limited changes in statutory speed limits are almost irrelevant when compared to total transportation costs. There is an automatic stabilization effect, in which an increase in some costs is offset by a decrease in other costs. This conclusion is in line with the results obtained by other researchers, for which the optimal speed limits in highways are close to indeterminate in the 70 km per hour to 110 km per hour range [60].

It is worth pointing out that the main weakness of the analysis explained in this paper, and its application to the two case studies presented, lies within the availability of the data needed. In particular, there isn't much data concerning the characteristics of the light vehicle fleet in Spain and its consumption and emission levels. Also, the changes introduced through a modification in statutory speed limits were considered at an aggregate level, since there is no information regarding how they affect drivers and the particular speed they had before the change.

Future research could focus on developing and updating specific speed-related functions for the main costs identified in this study, from empirical data, to validate the conclusions obtained in this paper.

## CRediT authorship contribution statement

**Vicente Alcaraz Carrillo de Albornoz:** Conceptualization, Methodology, Writing - original draft. **Juan Molina Millán:** Data curation, Investigation, Writing - review & editing. **Antonio Lara Galera:** Investigation, Resources, Writing - review & editing. **Belén Muñoz Medina:** Writing - review & editing.

## Annex 1. Relationship between statutory speed limit changes and average speed changes on Spanish highways

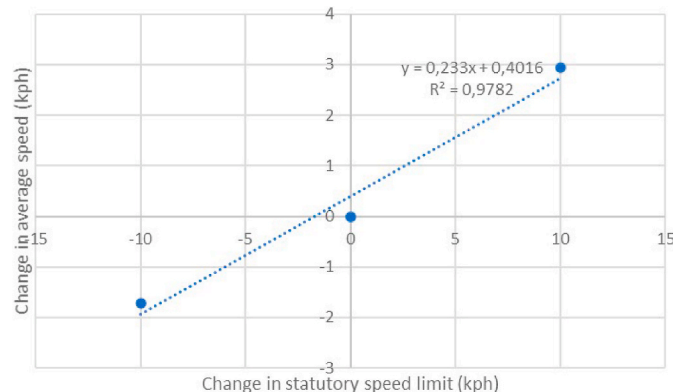


Fig. 6. Relationship between changes in statutory speed limits and average speed on Spanish highways. Source: Self-elaboration from data of the Spanish Ministry of Transportation, Mobility and Urban Agenda.

## Annex 2. Relationship between statutory speed limit changes and average speed changes on Madrid Calle 30

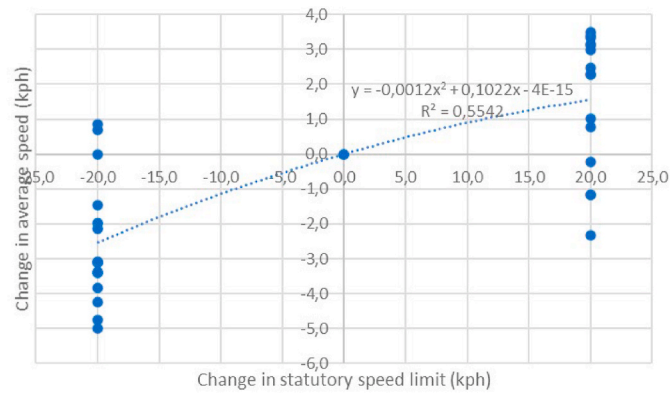


Fig. 7. Relationship between changes in statutory speed limits and average speed on Spanish Madrid Calle 30. Source: Self-elaboration from data of Madrid Municipal Government.

## References

- Castillo-Manzano JI, Castro-Nuño M, Pedregal-Tercero DJ. Temporary speed limit changes: an econometric estimation of the effects of the Spanish Energy Efficiency and Saving Plan. *Econ Modell* 2014;44:68–76.
- Pérez-Prada F, Monzón A. Ex-post environmental and traffic assessment of a speed reduction strategy in Madrid's inner ring-road. *J Transport Geogr* 2017;58:256–68.
- National Academies of Sciences, Engineering, and Medicine. *A guide for reducing speeding-related crashes*. Washington, DC: The National Academies Press; 2009. <https://doi.org/10.17226/14227>.
- Donnell E, Himes S, Mahoney K, Porter R. Understanding speed concepts. Key definitions and case study examples. *Transport Res Rec: Journal of the Transportation Research Board* 2009;2120:3–11.
- European Commission. *Guide to cost-benefit analysis of investment projects. Economic appraisal tool for cohesion policy 2014-2020*. Luxembourg: Publications of the European Union; 2015.
- Layard R, Glaister S. *Cost-benefit analysis*. second ed. United Kingdom: Press Syndicate of the University of Cambridge; 1994.
- Quah E, Toh R. *Cost-benefit analysis*. Routledge, Taylor and Francis Group, United Kingdom and United States of America; 1975.
- Mishan EJ, Quah E. *Cost-benefit analysis*. sixth ed. Routledge, United Kingdom and United States of America; 2021.
- De Palma André, Lindsey Robin, Quinet Emile, Vickerman, Roger. *A handbook of transport economics*. United Kingdom: Edward Elgar Publishing Limited; 2011.
- Demytyeva Maria, Verhoef Erik T. Miles, speed, and technology: traffic safety under oligopolistic insurance. *Transp Res Part B Methodol* 2016;86:147–62.
- Kröyer Höskuldur RG. "Is 30 km/h a 'safe' speed? Injury severity of pedestrians struck by a vehicle and the relation to travel speed and age. *IATSS Res* 2015;39(1): 42–50.
- Mostert Martine, Limbourg Sabine. "External costs as competitiveness factors for freight transport — a state of the art. *Transport Rev* 2016;36(6):692–712.
- Muscant Oren, Bar-Gera Hillel, Schechtman Edna. "Impact of speed limit change on driving speed and road safety on interurban roads." *transportation research record*. Journal of the Transportation Research Board 2015;2601:42–9.
- Tarko Andrew P. "Modeling drivers' speed selection as a trade-off behaviour. *Accid Anal Prev* 2009;41(3):608–16.
- Vernon Donald D, Cook Lawrence J, Peterson Katharine J, Dean Michael J. Effect of repeal of the national maximum speed limit law on occurrence of crashes, injury crashes, and fatal crashes on Utah highways. *Accid Anal Prev* 2004;36(2):223–9.
- Bel Germà, Rosell Jordi. Effects of the 80 km/h and variable speed limits on air pollution in the metropolitan area of Barcelona. *Transportation Research Part D*; 2013. p. 90–7.
- Bigazzi Alexander Y. Determination of active travel speed for minimum air pollution inhalation. *International Journal of Sustainable Transportation* 2017;11(3):221–9.
- Abir AKM, Burriss Mark W, Spiegelman Clifford. The value of travel time and reliability: empirical evidence from katy freeway. *Transport Res Rec: Journal of the Transportation Research Board* 2017;2606. <https://doi.org/10.3141/2606-10>.
- Börjesson Maria, Eliasson Jonas. Experiences from the Swedish value of time study. *Transport Res Pol Pract* 2014;59:144–58.
- Xu Hongli, Yang Hai, Zhou Jing, Yin Yafeng. A route choice model with context-dependent value of time. *Transport Sci* 2017;51(2):536–48.
- Elvik R. Optimal speed limits: limits of optimality models. *Transport Res Rec: Journal of the Transportation Research Board* 2002;1818:32–8.
- Benthem Arthur van. What is the optimal speed limit on freeways? *J Publ Econ* 2015;124:44–62.
- Gates T, Savolainen P, Kay J, Finkelman J. Evaluating outcomes of raising speed limits on high-speed non-freeways. MDOT Research Administration Project; 2015. Number: RC-1609B.
- Crouch RL. A framework for the analysis of optimal maximum highway speed limits and their optimal enforcement. *Accid Anal Prev* 1976;8(3):187–99.
- Hosseinlou MH, Kheyraadi SA, Zolfaghari A. Determining optimal speed limits in traffic networks. *IATSS Res* 2015;39:36–41.
- Montella A, Punzo V, Chiaradonna S, Mauriello F, Montanino M. "Point-to-point speed enforcement systems: speed limits design criteria and analysis of drivers' compliance. *Transport Res C Emerg Technol* 2015;53:1–18.
- Karafiatis MG, Golias I. Effects of road geometry and traffic volumes on rural roadway accident rates. *Accid Anal Prev* 2002;34(3):357–65.
- Miaou SP, Lum H. Modeling vehicle accidents and highway geometric design relationships. *Accid Anal Prev* 1993;25(6):689–709.
- Transportation Research Board. *Highway capacity manual 6th edition: a guide for multimodal mobility analysis*. Washington, USA: The National Academies of Sciences, Engineering, and Medicine; 2016.
- Calthrop Edward, Proost Stef. Road transport externalities. *Environ Resour Econ* 1998;11:335.
- Santos Georgina, Behrendt Hannah, Maconi Laura, Shirvani Tara, Teytelboym Alexander. Part I: externalities and economic policies in road transport. *Res Transport Econ* 2010;28(1):2–45.
- Verhoef Erik. External effects and social costs of road transport. *Transport Res Pol Pract* 1994;28(4):273–87.
- American Association of State Highway and Transportation Officials. *A manual of user benefit analysis for highways*. third ed. AASHTO; 2010.
- Caltrans. *Life-Cycle benefit-cost analysis - economic valuations*. California Department of Transportation, Division of Transportation Planning, Office of Transportation Economics; 2007.
- Litman TA, Doherty E. *Transportation cost and benefit analysis: techniques, estimates and implications*. second ed. Victoria, Canada: Victoria Transport Policy Institute; 2009.
- Samaras Z, Ntziachristos L. Average hot emission factors for passenger cars and light-duty trucks". Deliverable 7 of the MEET Project. Greece: Aristotle University Thessaloniki; 1998. p. 112. LAT Report No. 9811, <http://www.inrets.fr/infos/cost319/index.html>.
- André M, Hammarström U. Driving speeds in Europe for pollutant emissions estimation. *Transport Res Part D* 2000;5(5):321–35.
- Archondo-Callao R, Faiz A. Estimating vehicle operating costs. World bank technical paper 234. Washington D.C: The World Bank; 1994.
- Wong JY. *Theory of ground vehicles*. fourth ed. Hoboken, NJ: John Wiley & Sons; 2008.
- Imprialou MIM, Quddus M, Pitfield DE, Lord D. "Re-visiting crash-speed relationships: a new perspective in crash modelling. *Accid Anal Prev* 2016;86: 173–85.
- Elvik R, Vadeby A, Hels T, van Schagen I. Updated estimates of the relationship between speed and road safety at the aggregate and individual levels. *Accid Anal Prev* 2019;123:114–22.
- Elvik R. A re-parameterisation of the Power Model of the relationship between the speed of traffic and the number of accidents and accident victims. *Accid Anal Prev* 2013;50:854–60.
- Elvik R. A comprehensive and unified framework for analysing the effects on injuries of measures influencing speed. *Accid Anal Prev* 2019;125:63–9.
- Joumard R, André M, Vidon R, Tassel P, Pruvost C. « Influence du cycle de conduite sur les émissions unitaires de polluants des voitures particulières. » INRETS Report, No. LTE 9902. 1999 [Bron, France].
- Sjödén A, Perrson K, Andréasson K, Arlander B, Galle B. On-road emission factors derived from measurements in a traffic tunnel. *Int J Veh Des* 1998;20(1–4):147–58.

- [46] European Parliament and the Council. Directive 2002/49/EC relating to the assessment and management of environmental noise. 2002.
- [47] Elvik R. Speed limits, enforcement, and health consequences. *Annu Rev Publ Health* 2012;33:225–38.
- [48] Wardman M, Chintakayala VPC, de Jong G. Values of travel time in Europe: review and meta-analysis. *Transport Res Pol Pract* 2016;94:93–111.
- [49] Viscusi WK, Masterman CJ. Income elasticities and global values of a statistical life. *J Benefit-Cost Anal* 2017;8(2):226–50.
- [50] Ine. Encuesta de Hogares y medio ambiente 2008. España: Instituto Nacional de Estadística, Ministerio de Economía; 2009.
- [51] Ine. Plan estadístico nacional 2017-2020. España: Instituto Nacional de Estadística, Ministerio de Economía; 2017.
- [52] Sobrino N, Monzon A, Hernandez S. Reduced carbon and energy footprint in highway operations: the highway energy assessment (HERA) methodology. *Network Spatial Econ* 2014;16(1):395–414.
- [53] European Commission. Handbook on the external costs of transport. Luxembourg: Publications of the European Union; 2019.
- [54] Ntziachristos Leonidas, Samaras Zissis. Speed-dependent representative emission factors for catalyst passenger cars and influencing parameters. *Atmos Environ* 2000;34:4611–9.
- [55] European Environmental Agency. Term 2016: transport indicators tracking progress towards environmental targets in Europe. Luxembourg: Publications Office of the European Union; 2016.
- [56] Elvik R. *Fart og trafikksikkerhet. Nye modeller. Rapport 1296*. Oslo: Transportøkonomisk institutt.; 2014.
- [57] Schafer Andreas. The global demand for motorized mobility. *Transport Res Pol Pract* 1997;32(6):455–77.
- [58] de Madrid Ayuntamiento. Plan de movilidad urbana sostenible de la ciudad de Madrid. Madrid: Madrid Municipal Government; 2014.
- [59] Hu Kejia, Chen Yuche. “Technological growth of fuel efficiency in European automobile market 1975–2015. *Energy Pol* 2016;98:142–8.
- [60] Elvik R, Christensen P, Amundsen A. Speed and road accidents. An evaluation of the Power Model. Oslo, Norway: Institute of Transport Economics TOI; 2004.

Dr. Vicente Alcaraz Carrillo de Albornoz is an applied economics professor at Madrid’s Polytechnic University. His research focuses on public infrastructure. He has experience in investment banking and management consulting, having undertaken projects in Latin America, Europe and South-East Asia. Over the last decade he has focused on public procurement and PPPs, acting as an advisor to the public and private sector in transactions exceeding 14 billion EUR. Mr. Alcaraz holds a PhD and a Master’s of Science in Civil Engineering from Madrid’s Polytechnic University, a Master’s of Science in Business and Economics from HEC (Paris, France) and a Master’s in Infrastructures, Public Services and Facilities Management from UPM.