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A novel adaptive vehicle speed recommender fuzzy system for autonomous vehicles on conventional two-lane roads

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Abstract

This paper presents an intelligent speed adaption system for vehicles on conventional roads. The fuzzy logic based expert system outputs a recommended speed to ensure both safety and passenger comfort. This intelligent system includes geometrical features of the road, as well as subjective perceptions of the drivers. It has been developed and checked with real data that were measured with an instrumental system incorporated in a vehicle, on several two-lane roads located in the Madrid Region, Spain. Along with the road geometrical characteristics, other input variables to the system are external factors, such as weather conditions, distance to the preceding vehicle, tire pressure, and other subjective criteria, such as the desired comfort level, selected by the driver. The expert system output is the most suitable speed for the specific road type, considering real factors that may modify the category of the road and thus, the appropriate speed. This information could be added to the adaptive cruise control of the vehicle. The recommended speed can be a very useful input for both, drivers and the autonomous vehicles, to improve safety on the road system.

KEYWORDS

adaptive cruise control, expert system, fuzzy logic, industry 4.0, intelligent speed recommender, knowledge, two-lane roads, vehicle speed

1 | INTRODUCTION

Today society is facing a great challenge in the widespread introduction of autonomous vehicles. This is a key sector in the so-called "fourth revolution" of industry, boosted by the boom of virtual sensors. We are on the verge of successfully implementing the technology to achieve autonomous vehicles, albeit many more aspects will have to be worked out: insurance, allotment of accountabilities in case of accidents, sharing modes and more. This is one of the potentially more relevant instances of the industry 4.0, which aims for fully automated cyber-physical systems (CPS) and an augmented data exchange that, in this case, can be defined as V2X (Vehicle to everything), meaning both vehicle-to-vehicle or vehicle-to-infrastructure (Mekala et al., 2021).

A likely scenario is a fleet of autonomous vehicles that may be boarded by one or more persons. Once the destination is set, a comfort velocity will be required, a decision by the people travelling as to what accelerations are acceptable. These will be dictated by the urgency of the trip ("Are we risking losing the plane if we do not reach the airport ASAP?") and personal choices ("We have ample time, and we desire to have a conversation while travelling and having tea and biscuits"). In the first example, the vehicle will have to choose a speed as high as possible maintaining safety standards, and sharp accelerations. In the second, all manoeuvres will have to be calm, and accelerations kept to a minimum, such as in commercial airline aviation, where the plane controls shift through many positions to avoid having uncomfortable experiences for the passengers.

If, in this scenario, the vehicle goes on a conventional two-lane road, a more complex strategy must be in place to decide the vehicle speed, considering road geometry, meteorology, desired comfort, other vehicles in the same road section and the need or not to adjust the speed to allow for new vehicles coming in from intersections and interchanges.

Indeed, the speed at which vehicles travel is a very important factor both in safety and comfort. Speed reduction is considered as one of the major causes in contributing to improving road safety, since excessive speed is a relevant factor in many accidents. Speed may be inadequate for two main reasons: first, drivers do not always respect the speed limits imposed by road signs; second, sometimes the state of the roads or weather conditions make it unadvisable to travel at the maximum allowed speed, although this is a choice that must ultimately be made by the driver. That is why appropriate road geometric design and state of the infrastructure are important issues in the evaluation of any road and, particularly, in rural highways, to attain a smooth and safe traffic operation (Gibreel et al., 1999).

In this paper, and with the aim of improving driving safety, an intelligent expert system is proposed. This fuzzy logic based system recommends the driver a suitable speed while travelling on interurban roads, considering the infrastructure and other external and internal factors. The intelligent recommendation system incorporates the driver subjective knowledge, used to adapt vehicle speed to the own perception of the road conditions, and not dictated merely by road signing, although legal maximum speed will always represent a limit that drivers are fined for exceeding. Speed choice is strongly influenced by road environment and drivers' assessment of safe speed level at a specific location. In addition, with the fuzzy system this speed is smoothed and therefore, acceleration rate is reduced and comfort improved, as shown in simulation results. The system output could be added to the existing adaptive cruise control (ACC) in automated vehicles to achieve a closer human-like behaviour in selecting speed.

In order to implement the recommender system here proposed, an instrumented system based on LIDAR technology would be sufficient to collect the necessary information. The speed is then calculated and, therefore, no other communications are necessary. This increases its robustness and availability. The recommended speed could be displayed to the driver with a visual and/or audio signal if the vehicle exceeds the recommended speed. The driver can either modify the speed or enter it into the vehicle's own cruise control system, acting as an adaptive speed system based on road geometry and external conditions. In any case, the vehicle will apply the speed chosen by the ACC system, except if the recommended computed speed is lower.

This intelligent speed model has been applied to two-lane roads, where, in some cases, the signs are assigned to geometrical conditions that may have changed. These conventional roads belong to the Madrid Region, Spain. Real road data have been used. The results show that the decision-making system suggests more conservative speeds in some sections, which increases traffic safety, reducing the accident risk.

In addition, introducing the human perception in automated vehicles will result in an easier transitions between the existing fleet and automated vehicles. This could be especially import for two-lane roads, that are the most prevalent road type in the network, and its speeds are higher than in urban streets, but its configuration is more complex than that of a freeway. While freeways and urban streets are receiving most of the efforts (Pozanco et al., 2021), two-lane roads are being somewhat left behind in this drive.

The structure of the rest of the paper is the following. Section 2 presents briefly the motivation and discusses some relevant related works. Section 3 defines the speed types, their characteristics and other subjective and objective factors that have an influence. Section 4 presents the fuzzy expert system that obtains the recommended speed in an adaptive way. Simulation results are discussed in Section 5. Finally, the paper ends with the conclusions and future works.

2 | BACKGROUND AND RELATED WORKS

The traditional methods for calculating the maximum recommended speed of a vehicle on interurban roads are based on the interaction of vehicle dynamics with road geometry and physical characteristics. Models of operating speed profiles calculate a certain operating speed (speed at which drivers circulate) on the road are based on continuous or discrete models of the road layout (Pérez-Zuriaga et al., 2012). These models generate a speed based on geometry without considering any external factors. However, speed should be determined based on three factors: the geometry of the road (radius, camber, etc.); the degree of comfort desired by the driver and companion travellers; and third, the urgency level desired or required at a specific trip.

Over the last few decades, autonomous vehicles have been greatly developed, equipped with ADAS (Advanced Driver Assistance Systems) and with previously existing functionalities such as cruise speed and new ones, such as an anti-collision, blind spot warning, lane departure warning, automatic parking assistance, and driver drowsiness detection, among others (Hidalgo et al., 2020; Lattarulo et al., 2020). Within the EU, from 2022, new cars should use what is called Intelligent Speed Adaption (ISA), that is, the vehicle must recommend speed limits. However, this does not rule out the possibility of selecting an excessive speed for a certain road stretch and set of circumstances, if the road pavement is deteriorated, tire pressure is not adequate, or road signs are poorly visible. That is why this work proposes a complementary way to supplement ISA and ADA systems, aiming at improving driver safety and comfort.

In the road design process, speed variation along the road segment is an important issue to consider in adapting road geometry to vehicle performance and drivers' expectations. Despite this, the works that have demonstrated interest in including the road geometric characteristics to adapt the speed of traffic are not very extensive. In Gibreel et al. (1999), a comprehensive literature review of highway geometric design consistency mainly on two-lane rural highways in North America and Europe is presented. But these solutions generally use secondary information (GPS, road lateral signs…). In addition, they are relatively arbitrary, as there are currently many competing models without the prevalence of one over the others being settled. These research papers have generally aimed at modifying road geometric standards, considering a statistically conservative standard vehicle and driver, rather than taking the individual drivers into account.

Some scientific works have studied how road geometry affects driving. For example, in Yan et al. (2013) a study of road geometry variables for adaptive cruise control is carried out. In Andersen et al. (2016), an analysis of the relationships between speed and road characteristics and speed and driver features is presented for secondary rural two-lane roads. The results show a primarily influence from road and shoulder width, the extent of road markings and the section lengths on speed. In Pérez-Zuriaga et al. (2010), different factors than condition the speed chosen by drivers on conventional road straight stretches are analysed. These authors use Global Positioning System (GPS) devices to capture data and propose speed models. They also include speed models for horizontal curves of different radius.

A method to determine speed limits, taking into account the road geometry and vehicle characteristics is presented in Jiménez et al. (2008). It is based on a mathematical vehicle model and a detailed digital map that contains every piece of data that may be relevant from a safety point of view. This proposal was tested on real driving conditions and results show that drivers usually reduce speeding on sharp bends and traffic becomes more homogeneous.

Different factors have been analysed to assess road design consistency, such as free-flow speed distribution (García-Jiménez et al., 2016). In this paper, the authors study some statistics of the speed in curves and transitions. The work by Llopis-Castelló et al. (2018) also states that operating speed is closely related to geometric design consistency. The authors drew from the study that the radius of the horizontal curve and the grade at the point of curvature have both a significant influence on heavy vehicle speeds.

In Ben-Bassat and Shinar (2011), the combined effects on driving (speed and lane position) of three roadway design elements, shoulder width, guardrail existence and curvature radius are studied. Other subjective measures, such as perceived safe driving speed and estimated road safety were included. The results show a significant effect of roadway geometry on both objective and subjective decisions. Shoulder width had a significant effect on actual speed, on lane position, and on perceived safe driving speed, but only when a guardrail is present. An increase in the width of the shoulders induces a higher operating speed, while a narrowing of the shoulders causes a decrease in speed (Liu et al., 2016). The shoulders are also a clear influence when they are paved, inducing a higher driver speed than unpaved shoulders. How lane and shoulder widths affect operating speed has also been studied (Garber & Ehrhart, 2000; Ibrahim et al., 2018; Melo et al., 2012; Rosey et al., 2009; Vey & Ferreri, 1968). According to these authors, lane width is the most commonly used variable in discrete models. A wider lane induces drivers to feel safer in their driving, as they are allowed more freedom to manoeuvre, thus increasing operating speeds.

Similarly, Hansen et al. (2007) analysed the influence of two types of variables: geometric and road environment on the desired speed. The considered variables of the first type were lane and shoulder widths and shoulder type. As for the second type, the presence of sidewalks, distance to the building face, access density and types of land use were analysed. The most relevant variables in this study were shoulder width, speed limit, distance to building face and land use.

In Weigel et al. (2006), a sensor fusion method is proposed to combine information from a vision sensor, a radar system, digital maps, GPS data and an odometrical sensors to produce a single common description of road geometry ahead of the vehicle. This information was used to calculate the risk of a given scenario and a given speed. Hazoor et al. (2021) proposed an intelligent speed adaptation system based on sight distance. In poor visibility conditions, the system advises the driver when driving at an excessive speed.

The effects of the road infrastructure and some road geometrical factors on driver behaviour have been commented in Montella et al. (2015). Authors analysed driver behaviour in terms of speed choice and deceleration or acceleration. They develop some models to predict operating speed in curves and transitions. Results show that the drivers' speed is not constant along curves, and the maximum speed reduction takes place in the tangent-to-curve transitions.

3 | SPEED AND ROAD FACTORS

As a starting point, speed should be considered to be closely linked to road design, since it is a determining factor in the road design process. The Highway Capacity Manual (2022) suggests adjustments to free-flow speed based on lane width, lateral visibility, number of lanes and number of interchanges, parameters that influence operating speed but are somewhat difficult to measure and/or quantify. The geometric design of roads has traditionally been based on the project speed and the specific speed for each road element, assuming that the vehicles circulated at this speed or lower. However, it has been proven that this does not usually happen, and that operating speeds are most frequently very different between drivers.

Traditional road speed calculation models are based on the interaction of vehicle dynamics with road geometry. These calculations develop continuous or discrete models from existing conditions. We can mention, for instance Castro et al. (2013), Kanellaidis et al. (1990), Lamm et al. (1990) and Passetti and Fambro (1999). These models consider homogeneous sections with horizontal curves, length of tangents (or straight segments), the road access density (incorporations and intersections) per unit of length, etc. Fitzpatrick and Collins (2000) reported that a higher density of accesses leads to a lower operating speed.

Ahead visibility has an important influence on operating speeds (Pérez-Zuriaga et al., 2010). Sections with large visibility distances will have higher operating speeds than similar sections with less visibility, where drivers tend to slow down in order to also decrease the required braking distance from any obstacle on the road. Moreover, lateral visibility performs a less important weight on operating speed and has been less studied than frontal visibility. Additionally, studies have concluded that it does affect the operation speed.

On the other hand, orography (known as "terrain") also influences traffic, causing the drivers to select a certain desired speed for the journey according to the geometric characteristics of the road (succession of curves, grades, etc.) and their own driving capabilities, considering the accelerations subjected to the vehicle (Pérez-Zuriaga et al., 2012).

Some studies have also been conducted to determine the influence of meteorology (Hamdar et al., 2016; Lamm et al., 1990) on operating speeds. In most cases, the effect of light or heavy rain, and even the effect of snowfall, has been studied. The intensity of these phenomena implies a greater reduction of the operating speed, since the driver perceives a considerable risk (Ibrahim & Hall, 1994). Some atmospheric phenomena such as foggy weather, icy, wet pavement, make drivers pay more attention to address road challenges in that weather conditions.

3.1 | Speed and human factor

A series of objective and subjective factors may be considered to estimate the speed at which one wants to circulate. Some may depend on the driver: age, risk perception, urgency of the trip, distractions, etc.; others depend on the vehicle status, tire-pavement, friction, etc. (Martín et al., 2016; Medina & Tarko, 2005; Zhang et al., 2021).

The variables related to individual drivers are the most difficult to identify and estimate, and these are causing the residual variability in the operating speeds prediction models. These variables are mainly associated with psychology (DGT, 2017; Waard et al., 1995) and the particular conditions of each driver. Drivers constitute a rather abstract and diverse group, with some factors that refer to the person characteristics (personality, attitude, motives, etc.) and others to their actual circumstances, such as age, sex, presence of accompanying persons, previous history of accidents and offences, attitude towards traffic rules and, in particular, the speed limit, purpose of the journey, pleasure derived from driving, risk assessment, value assigned to time saved, costs associated with the journey, etc. (Godley et al., 2004; Rudin-Brown et al., 2014; Santos & López, 2012). Despite these studies, the results have been unclear since many factors are subjective or merely difficult to quantify.

The desired speed is not the same for every driver (Fitzpatrick et al., 2001). The concept of driving comfort is also difficult to define. It is known that in circular curves, vehicles and their occupants experience centripetal force and acceleration, which, if a certain threshold is exceeded, causes the vehicle occupants to experience discomfort they would prefer to avoid. But there are other factors that can also reduce the driving comfort degree.

3.2 | Speed and road geometric factors

The identification of high risk road sections is one of the main goals of any successful road safety management process. This process may be defined as the methodical search for locations with higher number of accidents than other similar roads, mainly caused by local risk factors (Elvik et al., 2009). The effects of the mean and standard deviation of speed, traffic flow per lane, shoulder and lane width, and other road characteristics such as radius or slopes, the camber, and carriageway dimensions have been studied in some works (Chang & Chen, 2005; Garber & Ehrhart, 2000; Persaud et al., 2000; Vogt & Bared, 1998).

In particular, the calculation of the operating speed taking into account the road geometric is crucial. The relationship between speed and the geometry of the road can be developed as follows. When a vehicle moves over a curve of radius R (m), at a uniform speed V (m/s), it experiences a centrifugal force in the direction of the centre of the curve, equivalent to Kraemer et al. (2003):

$$Fc = ma_c \tag{1}$$

The centrifugal acceleration (m/s^2) is given by:

$$a_c = \frac{V^2}{R} \tag{2}$$

Then:

$$Fc = \frac{P.V^2}{g.R} \tag{3}$$

where $P = mg$ is the weight (N) of the vehicle and g is the gravity acceleration (m/s^2).

This centrifugal force is counteracted by the following forces:

- Friction between the wheels and the road surface
- Raising the outer edge with respect to the inner edge (camber). The camber tilts the vehicle, and its weight can be broken down into a component normal to the road plane and one parallel to it. The equation of balance in the parallel direction to the inclined plane is as follows (Figure 1):

$$T + P \cdot \sin\alpha = Fc \cdot \cos\alpha \tag{4}$$

The friction force, T, is equal to the sum of the normal components of P and Fc multiplied by the friction coefficient f between tire and pavement, expressed as:

$$T = f.(P \cdot \cos\alpha + Fc \cdot \sin\alpha) \tag{5}$$

Substituting T in (4) and Fc in (4) and (5) we obtained:

$$f.\left(P \cdot \cos\alpha + P \cdot \sin\alpha \cdot \frac{V^2}{gR}\right) + P \cdot \sin\alpha = P \cdot \cos\alpha \cdot \frac{V^2}{gR} \tag{6}$$

Dividing (6) by P and $\cos\alpha$:

$$f.\left(1 + \tan\alpha \cdot \frac{V^2}{gR}\right) + \tan\alpha = \frac{V^2}{gR} \tag{7}$$

The tangent (α) is equal to the slope of the road, that is, the camber or cross slope of the curve, ρ:

$$f + \rho = \frac{V^2}{g \cdot R}(1 - f \cdot \rho) \tag{8}$$

The values of the friction coefficient f are between 0.069 and 0.18, and the cross slope, ρ, varies between 2% in conventional roads and 8% in highways (FOM/273/2016, 2016). Thus, its product can be neglected in comparison to P and expression (8) becomes:

$$\rho = \frac{V^2}{g\,R} - f \tag{9}$$

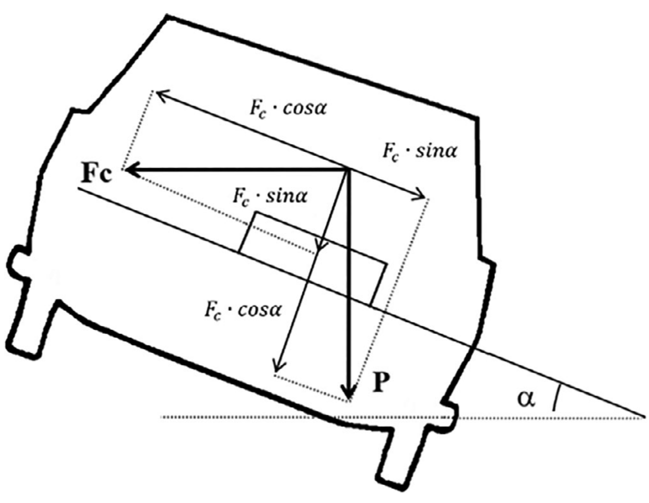

FIGURE 1 Vehicle on a curve (Kraemer et al., 2003)

Replacing g by its value and expressing the speed in m/h, the last equation becomes:

$$\rho = \frac{V^2}{127 \cdot R} - f \tag{10}$$

This equation allows the calculation of the desired cross slope ρ (%) as a function of the radius of curvature R (m), the speed V in km/h and the coefficient of lateral friction, f.

For a given design speed, a radius is assigned according to the maximum desirable lateral friction and a normalized transverse slope. The radius associated with this boundary condition is defined as the minimum radius. Curves with radius greater than this minimum value should use a super-elevation to counteract centripetal acceleration (NCHRP, 2000).

The formula for calculating the minimum radius with standardized cross slope is then:

$$R = \frac{V^2}{127(0.01\rho + f)} \tag{11}$$

This expression will be used to calculate the specific speed of the vehicle (Section 4.1).

As this equation indicates, the minimum radius depends on the normalized transverse slope and the maximum transverse slope friction. This transverse slope is generally determined by drainage needs. The maximum lateral friction to be used on depends on the method used to distribute the camber and lateral friction. If a method makes generous use of camber, the level of lateral friction should be limited to a relatively small value. The conservative use of camber implies that a large amount of side friction is accepted by the driver and assumes that camber will only be provided when the side friction demand exceeds the maximum design side friction factor (NCHRP, 2000). In general, greater speed reductions would occur if the radius used with a standardized transverse slope is reduced.

To show an example, some of these geometric features of the two-lane road M-509 in Madrid Region are shown in Figure 2. The cross slope and the gradient (both in ‰ in this figure to better show their values) and the curvature radius (m) are represented. Large values of the radius represent straight road sections.

4 | INTELLIGENT SPEED ADAPTION MODEL

In this work we hypothesize that speed can be determined by three factors: (i) road geometry, that is, the radius of curvature, considered jointly with or without cross slope; (ii) driver and passengers desired comfort; and (iii) the level of safety of each particular vehicle travelling on the road.

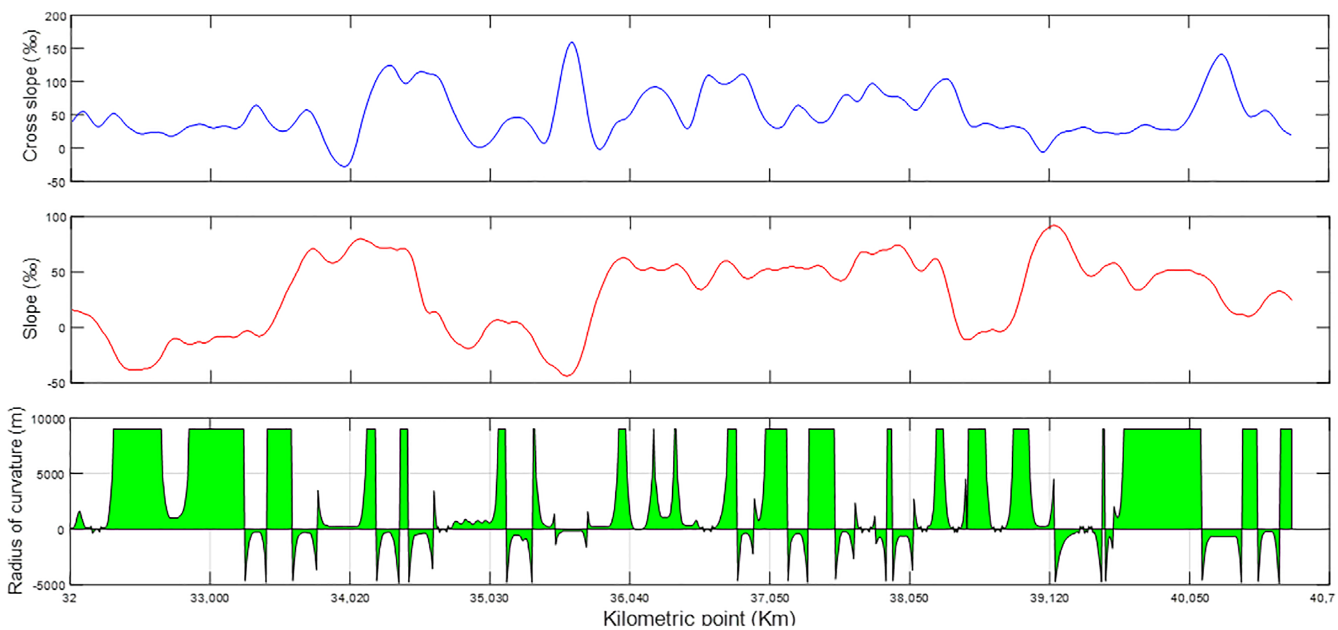

FIGURE 2 Geometric features of M-509 two-lane road

Each driver has a different perception of safe speed. Furthermore, the same driver may perform differently even for the same journey, depending -for instance- on the urgency felt by the driver. Additionally, depending on weather conditions, for example, larger lane widths and longer visibility lengths may be desired for a speed to be considered safe and comfortable by a driver.

The speed recommender here developed addresses some of these subjective perceptions of the driver and includes several factors such as weather, external and vehicle conditions, distance ahead to the following vehicle, a comfort factor chosen by the driver, and the main geometric road features. The intelligent speed adaption model is made up of different modules that are interrelated (Figure 3). Out of the seven subsystems, five of them receive external inputs, which are: specific speed estimation, fuzzy module of road geometry, speed adaption module, fuzzy module of environment and vehicle conditions, and speed adaption to external environment. There is a module that outputs the recommended speed. In addition, a filter smooths out the speed, reducing acceleration rate to increase comfort.

As it is possible to see in Figure 3, some of the subsystems are defined using fuzzy logic. Thus, they have fuzzy inputs that are fuzzified using some fuzzy sets. The knowledge that summarizes the performance of each module is represented by fuzzy rules. The product has been used to implement the implication. The output is obtained applying the centre of area defuzzification strategy.

Each subsystem is described below.

4.1 | Specific speed calculation subsystem

The specific speed is defined as the maximum speed in a road element that maintains both comfort and safety, with wet pavement and tires in good condition, without considering other restrictions such weather, traffic, or legal rules.

The behaviour of a vehicle in a circular curve is considered to be a rigid solid in transverse equilibrium, which runs through the curve at a constant speed, regardless of the effect of the suspension system (FOM/273/2016, 2016). According to this model (11), the specific speed V (km/h) is:

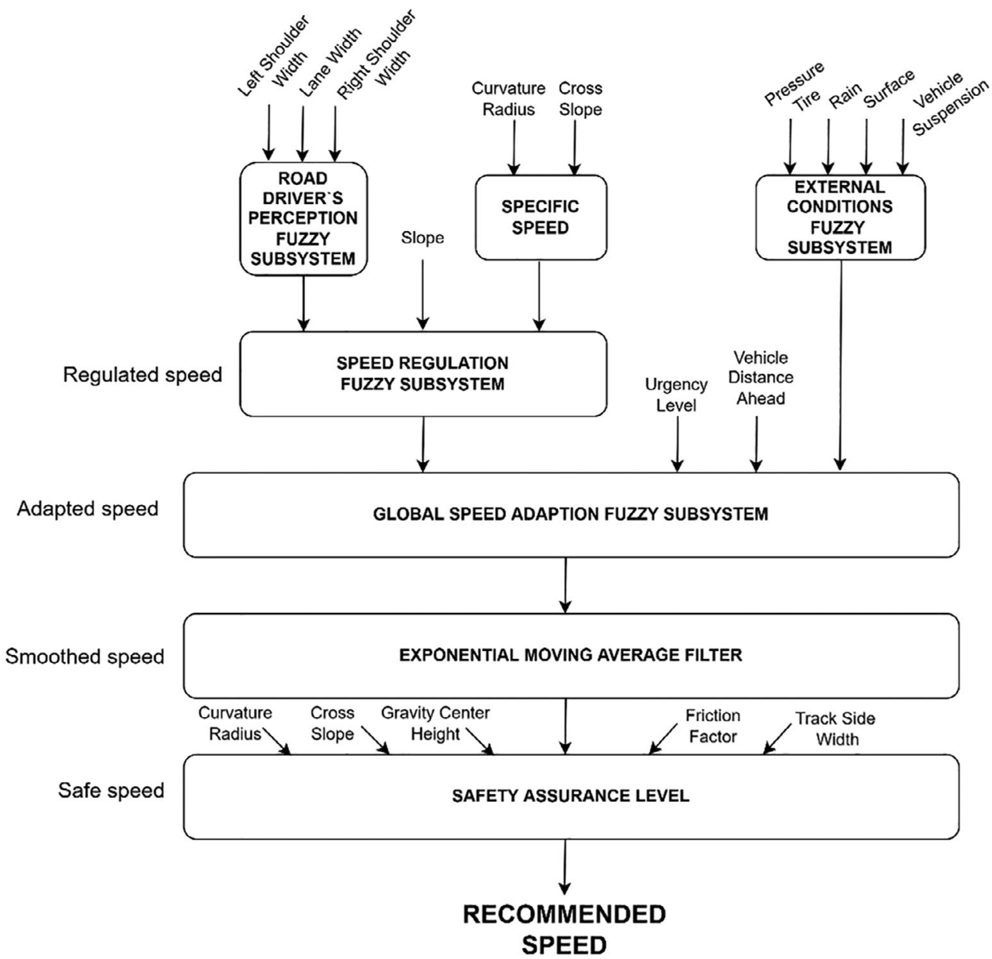

FIGURE 3 Speed recommendation expert system

$$V = \sqrt{127R(f + 0.001\rho)} \quad (12)$$

where R (m) is the radius of the curve, ρ (%) is the cross slope, and f is the maximum mobilized transverse friction.

In this system, the inputs are the radius and the cross slope. The radius R_{min} is the minimum permissible radius in the design of a circular curve. The maximum cross slope is 7% for speeds up to 100 km/h, which increases to 8% for higher speeds. The maximum moving transverse friction, f, is the friction coefficient mobilized when a vehicle is driven at maximum speed in a curve limited by the vehicle own slip resistance. The value of the maximum transverse coefficient f_{max} obtained applying Table 1, according to the specific speed V, which in turn depends on the radius R.

Then, applying Equation (12) the specific speed is obtained, which is the output of this system.

4.2 | Road driver's perception based on road geometry

It is a fact that drivers feel more comfortable on wider roads and tend to accelerate within the speed limits (Godley et al., 2004). Thus, the perception of the geometric features of the road has an influence on the driver's desired speed. This fuzzy module represents this driver's perception. The inputs are the lane and shoulders width (0–60 dm) and lane width (0–160 dm). Three fuzzy sets have been assigned (Narrow, Medium, Wide). In Figure 4, left, the right shoulder width fuzzy sets are shown and in Figure 4, right, the corresponding fuzzy sets for lane width.

The driver's perception that has been used to define the fuzzy rules and the output of this system are based on the following reasoning. On roads with very small or non-existent shoulders, drivers tend to slow down, just like if the road were narrow. And vice versa. The output is how the driver adapts the speed to the road geometry. This output has been normalized between 0 (low speed, L), 5 (medium speed, M) and 10 (high speed, H) (Figure 5, right). It does not mean the speed is low or high, it depends on other factors, such as that the speed may be limited to a lower value. It is a complement that shows the desire of the driver to go faster or slower depending on how the road characteristics are perceived.

4.3 | Speed regulation

Speed regulation is the fuzzy module in charge of obtaining the speed considering the slope of the road and the outputs of the two previous defined fuzzy subsystems, specific speed and driver's road perception. The third input, the slope, is defined between −400 and 400 (‰) by three triangular fuzzy sets, Negative, Medium, Positive (Figure 6, left).

Considering that a road with a high-negative slope makes the vehicle gains more speed, the driver will try to reduce it, and vice versa. Uphill the driver tends to keep the speed, and if possible, to set it to the maximum allowed value. This regulated speed also considers the driver's road perception and road geometrical features as explained in the previous subsystems. Eventually, it is limited to the posted speed, which maximum value is 90 km/h in conventional two-lane roads. The regulated speed output of the vehicle can be: low, medium, or high (Figure 6, right).

TABLE 1 Maximum transversal friction as a function of the specific speed, under wet road conditions

V (km/h)	40	50	60	70	80	90	100	110	120	130	140
R_{min} (m)	50	85	130	190	265	350	450	550	700	850	1050
f_{max}	0.180	0.166	0.151	0.137	0.122	0.113	0.104	0.096	0.087	0.078	0.069

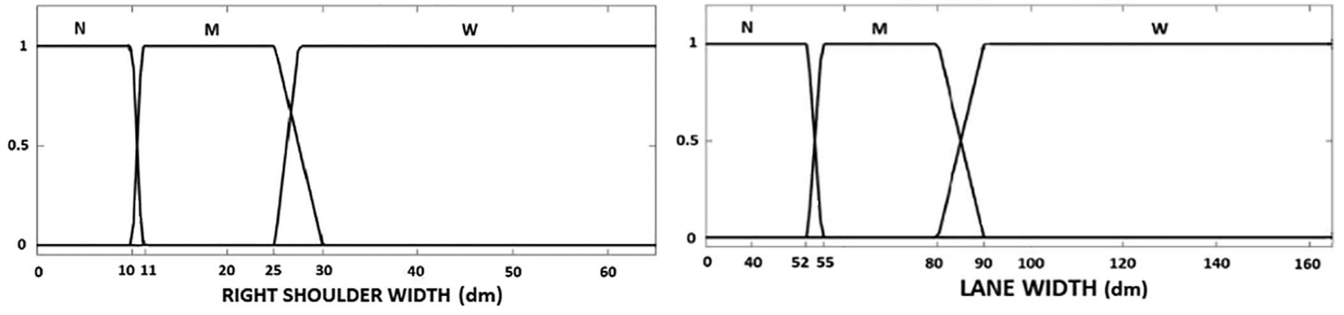

FIGURE 4 Fuzzy input variables: Right shoulder width (left) and right-side free lane width (right)

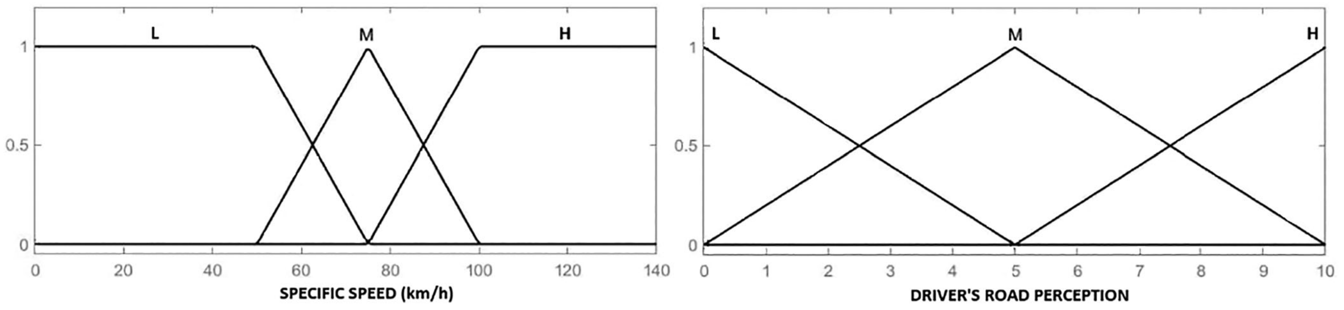

FIGURE 5 Fuzzy sets of the specific speed (left) and driver's road perception (right)

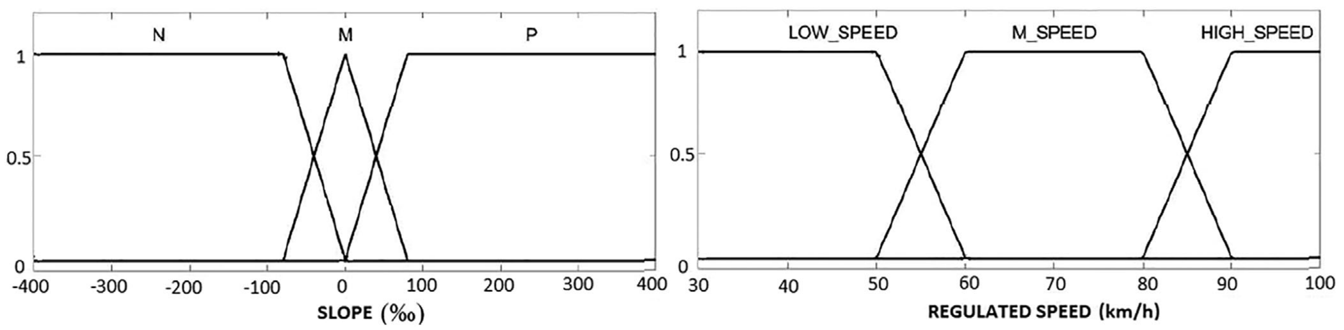

FIGURE 6 Fuzzy sets of slope (left) and regulated speed output (right)

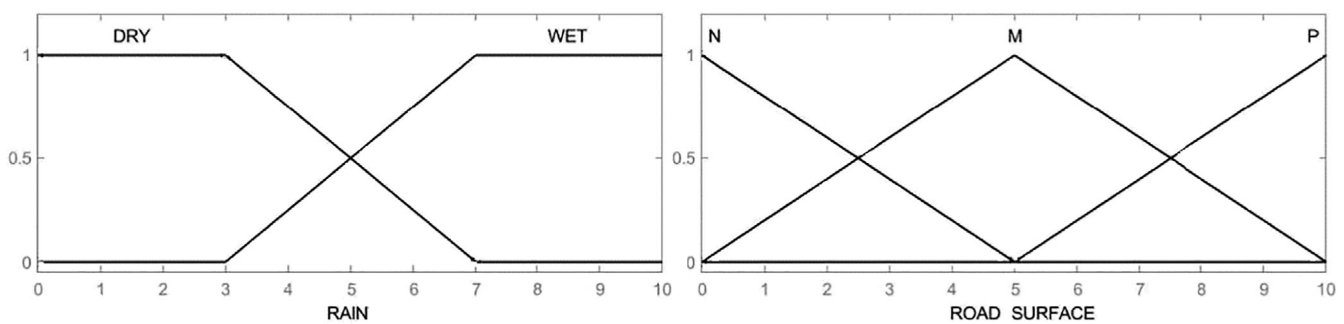

FIGURE 7 Fuzzy sets of weather (left) and surface condition (right) inputs

4.4 | External conditions fuzzy subsystem

The expert system has a module that evaluates external conditions and determines how they affect the recommended speed of the vehicle. It has as inputs weather (rain), tire conditions, vehicle suspension and pavement status. Indeed, a pavement with potholes, gravel, etc., makes driving at certain speeds less safe due to the poor tire grip. Similarly, driving on a wet and thus, probably slippery road may be very dangerous. These variables are represented by fuzzy sets dry and wet (Figure 7, left), for the weather, and using three values: 0 (Negative), 5 (Medium) a 10 (Positive) (Figure 7, right) to rate the pavement condition.

The vehicle's suspension makes it less grippy on the road and dangerous to drive at relatively high speeds, as well as having a negative impact on the comfort of the vehicle's passengers. Two fuzzy triangular sets describe whether the vehicle suspension is bad or good (Figure 8, left).

Poor tire maintenance makes the grip between the pavement and the tire weaker, therefore, tires in poor condition can lead to risky driving situations. The tires conditions are described by two trapezoidal fuzzy sets, bad or good (Figure 8, right).

The output gives a global evaluation of the environmental conditions, normalized between 0 and 10, which takes values 0 (negative), 5 (medium) and 10 (positive). This system makes it possible to reflect the driver's attitude when environmental conditions worsen, or the road surface is in poor condition.

4.5 | Global speed adaptation fuzzy module

The global speed adaptation fuzzy module estimates the safe and comfortable speed in relation to the road geometry and from environmental and vehicle conditions. It uses previous subsystems outputs and two new inputs. The latter are the distance of the vehicle ahead, defined between 0 and 200 (m) by two trapezoidal fuzzy sets, Near or Far (Figure 9, left) and the level of urgency, defined by the fuzzy sets Calm, Relaxed, Normal, Urgent, Proper Emergency and Declared Emergency (Zhang et al., 2018), as showed in Figure 9, right.

When driving in a relaxed mode, lower speed is selected, therefore accelerations to which the vehicle and occupants are subjected are lower (greater comfort). Besides, when a vehicle is circulating near the car ahead, the speed is reduced. The adapted speed that is the output of this system can be: very low, low, medium, high or very high (km/h) (Figure 10).

This would be the final proposed speed but then we have to check if there is any problem of overturning with that vehicle speed.

4.6 | Exponential moving average filter

This adapted speed is smoothed by reducing the acceleration in order to increase comfort, but trying to keep the same speed value. An exponential moving average filter is applied to calculate the final speed. According to eco-driving principles, more efficient driving consists of accelerating

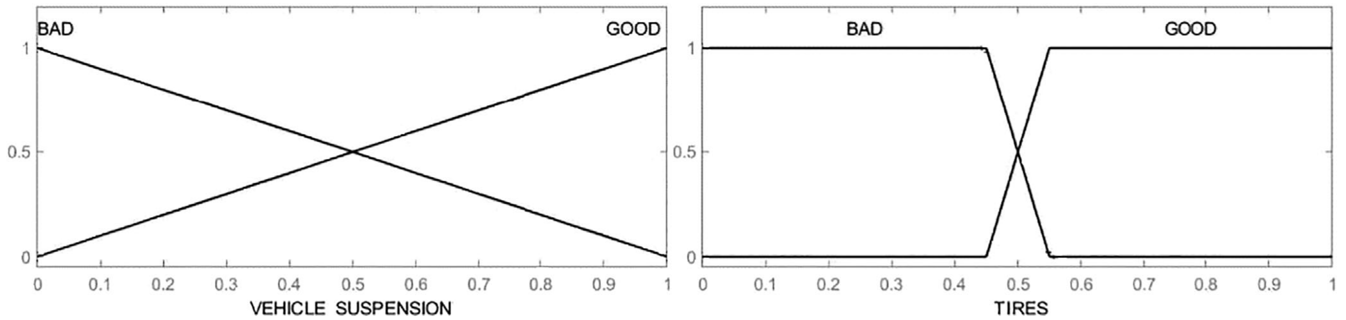

FIGURE 8 Fuzzy sets of vehicle suspension (left) and tire condition (right)

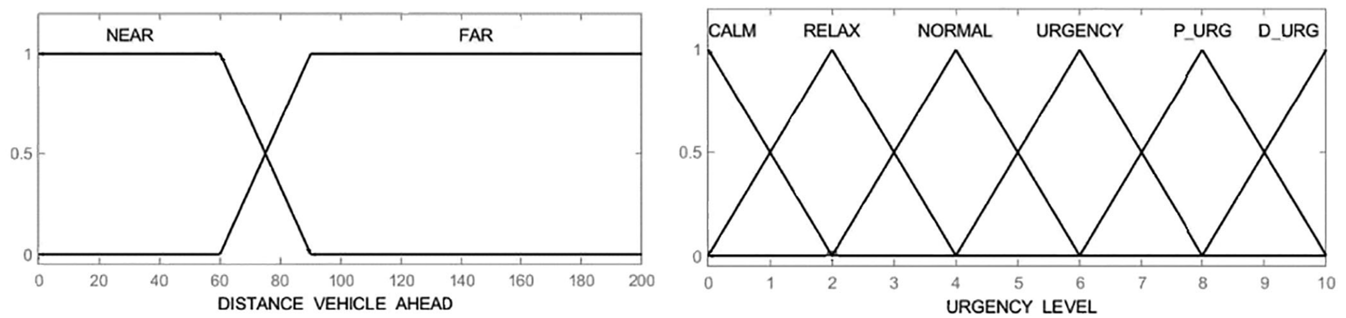

FIGURE 9 Fuzzy sets of distance to vehicle ahead (left) and urgency level (right)

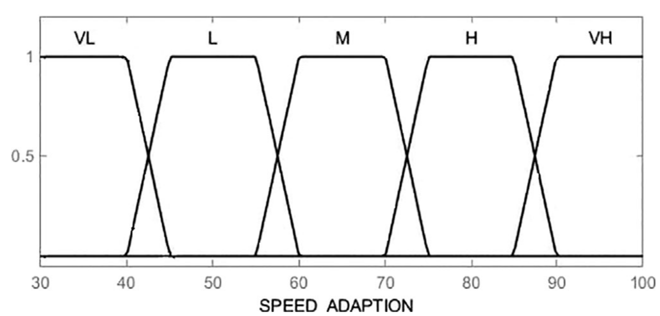

FIGURE 10 Fuzzy sets of adapted speed

and braking smoothly, driving without accelerating while in gear and trying to stay in neutral for as little time as possible. The single exponential moving average filter is formulated as follows:

$$\overline{X} = \begin{cases} Y_1 \, t = 1 \\ \alpha Y_1 + (1-\alpha) \cdot S_{t-1} \, t > 1 \end{cases} \tag{13}$$

where α is the degree of weighting decrease, between 0 and 1, so older observations are discounted more quickly when the value is higher, and it gives more weight or importance to recent data. This technique allows quickly adaptation to the predicted fluctuations in recent data.

4.7 | Safety assurance level

Finally, the speed may be reduced to a minimum critical velocity whether the smoothed speed is still higher than this value to ensure that slipping or overturning does not occur. That is, the acceleration rate is limited by the curvature radius. This is due to the fact, experimentally proved, that for instance a loaded truck rolls over at a speed of 25 km/h on a 20 m curvature radius (Elvik et al., 2009), only 5 km/h higher than the calculated speed. Therefore, the drive may not feel the danger. This applies mainly to heavy vehicles, but for smaller cars, the critical speed is usually very close to the regulated one.

The forces acting on a vehicle travelling through a curve (Figure 11) are its weight, the centrifugal force (3), and the frictional force, calculated as *f.m.g* where *m* is the mass, *g* the gravity acceleration and *f* is the coefficient of friction.

To avoid a vehicle sliding laterally, the frictional force must be greater than the centrifugal reaction, $f.m.g > m.v^2/R$. Therefore, the so called critical speed for sliding, v_{sl} (km/h) is:

$$v_{sl} = \sqrt{fgR} = \sqrt{\frac{R(f+\rho)}{(1-f\rho)}} \tag{14}$$

And the expression of critical speed for rollover (overturning), v_{ov} (km/h) is:

$$v_{ov} = \sqrt{egR/_{2h}} = \sqrt{\frac{R\left(h \cdot \rho + \frac{e}{2}\right)}{\left(h - \left(\frac{e}{2}\right) \cdot \rho\right)}} \tag{15}$$

where ρ is the cross slope, *R* is the curvature radius (m), *f* is the friction coefficient between wheels and surface (Table 1), *h* is the height to centre of gravity, and *e* is wheel track width, that is the rollover threshold (Gunay, 2022). The particular case with no cross slope (horizontal) causes both equations to produce the same result. In this work, the *e* value taken as reference is 1.524 m and the *h* value is 0.66 m for a standard car (Lohith et al., 2013).

4.8 | Adaptive cruise control approach

The system output is proposed as an aid to the Adaptive Cruise Control (ACC) of a vehicle. Particularly, for the car following approach (Figure 12), where the vehicle (ego car) is equipped with an ACC and a sensor that measures the distance to the previous vehicle in the same lane (lead car)

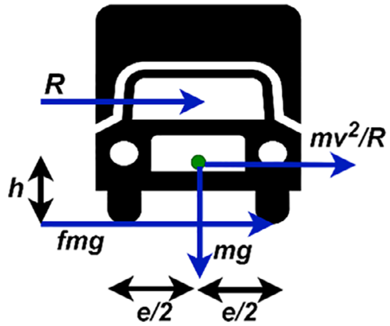

FIGURE 11 Forces acting on a vehicle rotating (without camber) (Gunay, 2022).

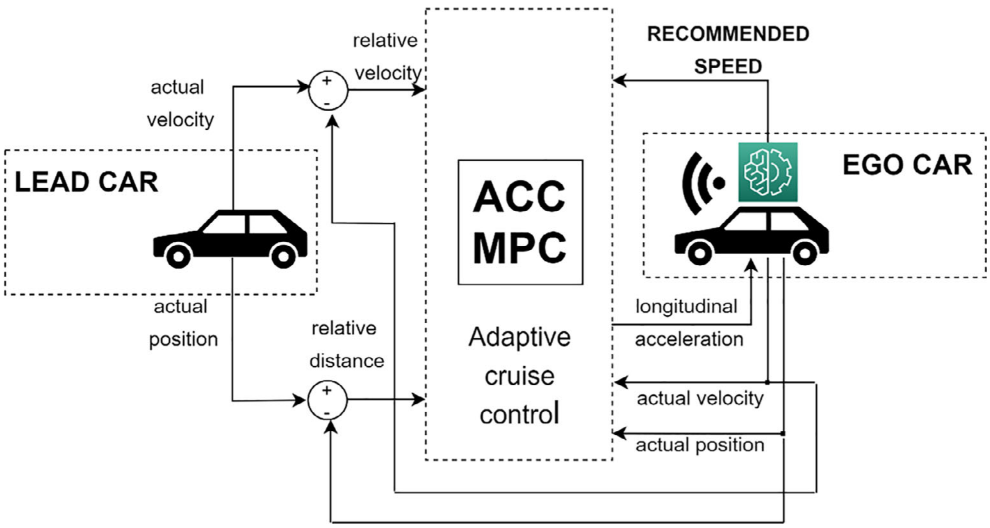

FIGURE 12 Recommended speed adaptation integrated in the adaptive cruise control approach.

TABLE 2 Data collected sample of M-509 road

Kilometre point	Mileage post (m)	No. of lanes	Carriage width (dm)	Left shoulder width (dm)	Lane width 2 lanes (dm)	Right shoulder width (m)	Curvature radius (m)	Cross slope (‰)	Slope (‰)
32	130	2	9.5	8	7.5	1.2	1110	51	15
32	140	2	8.6	8	6.6	1.2	1540	53	14

and the relative distance of the lead car. The "ego vehicle" or "ego car" is a term widely used in the literature as vehicle under test. The ACC system switches from speed control to spacing control when the lead car is too close. And vice versa, the control system switches from distance control to speed control if the lead car is far away. This way the ego vehicle travels at the suggested speed to keep a safe distance. This aid is part of the EU policy for new vehicles (ETCS, 2021).

The safe distance is equal to 10 m. The adaptive cruise control system outputs an acceleration control signal for the ego car. According to the physical limitations of the vehicle dynamics, the acceleration is constrained to the range -3 to 2 (m/s^2) (Treiber & Kesting, 2013).

The integration of the expert system with the ACC makes the vehicle apply the speed selected by the ACC system except if the obtained recommended speed is lower.

5 | SIMULATION AND DISCUSSION OF RESULTS

An example of the real data here used is shown in Table 2. The data have been collected by the Coordination and Information Center of Transport, Madrid Region, Spain, for the M-509 road every 10 m. The features measured are road name, mileage post, number of lanes, additional lanes, lane and shoulders width, radius of curvature, camber and slope.

Conventional roads, which do not have separate carriageways, can be grouped into several types. The Highway Capacity Manual is the world most widely used document to assess road capacity and level of service (LOS), although with adaptations and local versions for different countries. The Manual starts by dividing road facilities into two large classes, uninterrupted and interrupted flow. Uninterrupted flow means without stop signs in the main road or traffic lights, whereas interrupted flow means where the vehicle in the main road is expected to stop at a certain time and place (with traffic lights or stop signs). In addition, Spanish conventional roads are classified in interurban (higher speed), suburban (lower speeds than interurban) or accessibility roads, with even lower operating speed than interurban and suburban roads. A fourth type encompasses urban roads.

The road we are working with is the M-509, that goes from Majadahonda and Villanueva del Padrillo, in Madrid Region. Its type is intercity/interurban. This means that the maximum speed is 90 km/h.

But this classification may be no longer appropriate due to the degradation of the road, which may cause changes in some of its geometric characteristics (Barreno et al., 2021). This is relevant because speed limit is usually set based on the road design features. Therefore, it is important to update the classification of the road type.

In the simulations, the speed recommendation obtained with the expert system is shown with other road characteristics. The obtained speed considers the real conditions of the road geometry and not only the road type assigned by design. In addition, different inputs regarding weather and driver conditions have been included in the simulation scenarios.

Simulations of different scenarios have carried out with Matlab/Simulink software. The following figures show the results obtained for one of the roads, M-509. The upper graph shows the dimensions of the right (red) and left (green) shoulders in dm. The second graph shows the lane width (dm). The third graph represents the instantaneous speed (km/h) recommended by the system (blue) and vehicle speed (cyan) applied by the adaptive cruise control; the fourth graph is the vehicle acceleration (m/s^2). Bottom graph shows the vehicle jerk (m/s^3). The jerk or jolt is the rate at which an object's acceleration changes with respect to time. Therefore, it is important to avoid sudden jerks of the vehicles to enhance comfort.

Figure 13 shows the results obtained by the expert system with normal driving, good pavement conditions and good weather for the M-509 road.

The variations in speed (3rd graph) are associated with two issues. First, with the radius and cross slope; if the radius of curvature is very large then the road, in practice, will require subtle steering wheel turns and thus low perceived centripetal accelerations will happen. Under these conditions, the speed is expected to be high. A radius is considered to be large if it exceeds 350 m in two-lane conventional roads (minimum radius of curvature to reach 90 km/h, Table 2). Second, variations in speed are also affected by the shoulder and lane widths. If the road is narrow, the speed is reduced. For a normal driving level, the system determines a speed of 80 km/h, close to the legally permitted maximum speed (90 km/h). On the other hand, the acceleration variations (4th graph) are small, and thus the jerk (bottom graph) is practically zero in the analysed section, which indicates that there are no swerves during normal driving, which results in comfort during the journey. This speed ensures safety and comfort driving.

Besides, as it will be also shown in the rest of the figures, the acceleration rate generally decreases over time as the driver's desired speed is approached. Not all studies agree, but it appears that a comfortable acceleration rate would be in the range of 1.5–2.0 m/s^2. In general, the acceleration obtained by the system is in the region defined above. Another way of defining comfort during driving is the rate of change with respect to the acceleration, that is, the jerk. In this case, the values of the jerk are close to zero, as no strong accelerations occur during the vehicle's trip.

Figure 14 represents a comparative between recommended speed, specific speed and estimated speed (high, medium or low speed) for the M-509 road with normal driving, good pavement and good weather conditions. In the 1st graph, the speed estimated for that specific road section from its geometry is represented. If the lane width is considered to be medium or wide, and some of the shoulder widths are medium or wide, a high speed will be estimated. But with narrow shoulders and medium lane width, medium speed is then recommended. If the lane is narrow, a low speed will be estimated. In the second graph, the specific speed can be seen. The speed reduction observed in the third graph (between kilometre points 38 and 39) is due to the fact that lane width is medium and the shoulder widths are very narrow, therefore the system determines a medium speed (1st graph). In the second graph, specific speed is also represented. Before the mentioned interval, the specific speed is higher, then it is reduced by the system, adapting it to the real road geometry, and giving the recommended speed (3rd graph).

Figure 15 represents the speed obtained with the speed recommendation system for the M-509 road with a normal driving level, good pavement condition and rain. As expected, the speed is reduced by the bad weather conditions compared to Figure 13. Indeed, it is reduced around

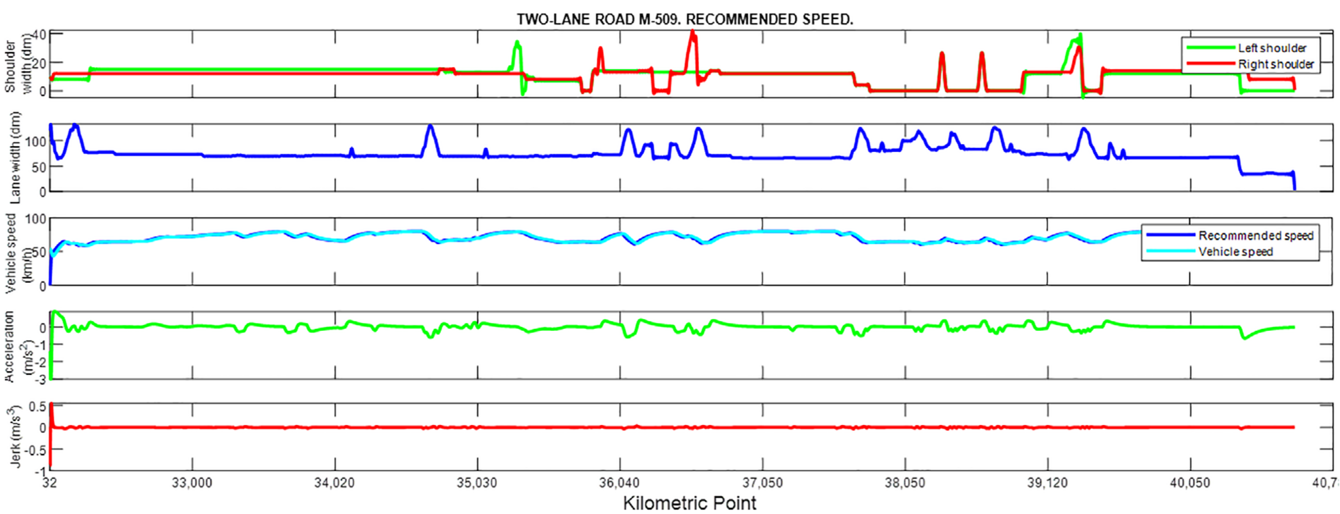

FIGURE 13 Recommended and vehicle speed, acceleration, and jerk for a car travelling on the M-509 road with normal driving, good pavement and good weather conditions

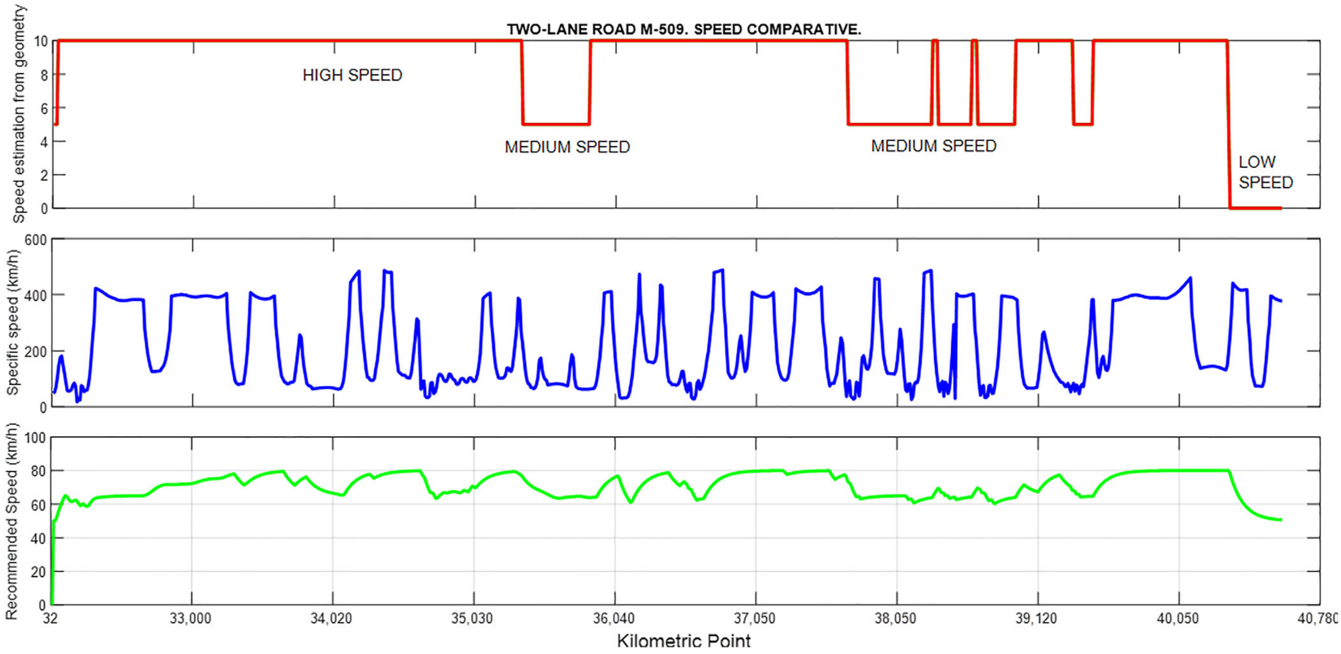

FIGURE 14 Speed estimation from geometry, specific speed, and recommended speed for the M-509 road with normal driving, good conditions of the pavement and good weather conditions

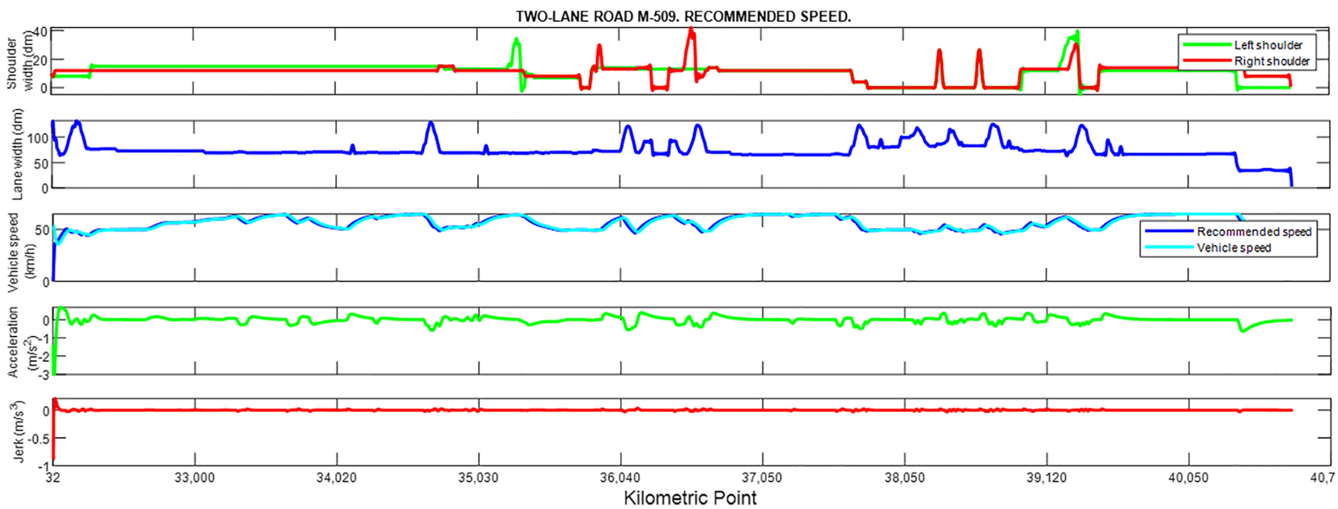

FIGURE 15 Recommended and vehicle speed, acceleration, and jerk for the M-509 road with normal driving level, good conditions of the pavement and rain

20 km/h along the road section with respect to the maximum speed allowed for that road (90 km/h). The acceleration variations are small, and the jerk shows also small variations, which results in comfort during travel.

Figure 16 represents a calmly driving, good condition of pavement and good weather on the M-509 road. The speed is low as a result of these conditions. In this case, the speed is reduced to 50 km/h along the road section with respect to the maximum value of 90 km/h due to the relax driving mode. The acceleration and jerk variations are very small since the speed is practically constant.

Figure 17 shows the results obtained by the speed expert system with declared emergency driving level, good pavement conditions and good weather for the M-509 road. The speed recommended by the intelligent system is high, according to the situation. The speed is limited only by the curvature radius and lane and shoulder widths to ensure safe driving, which is a condition that it is always applied. Acceleration variations are higher at some mileage points and the jerk also shows some significant variations due to the driving mode.

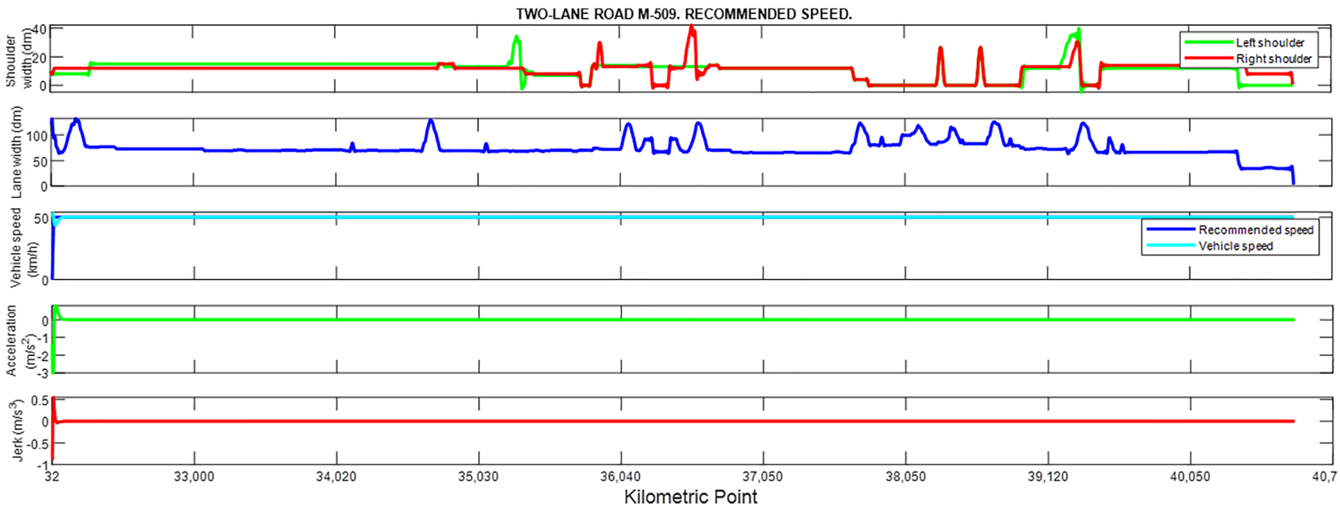

FIGURE 16 Recommended and vehicle speed, acceleration, and jerk for the M-509 road with calm driving, good pavement conditions and good weather

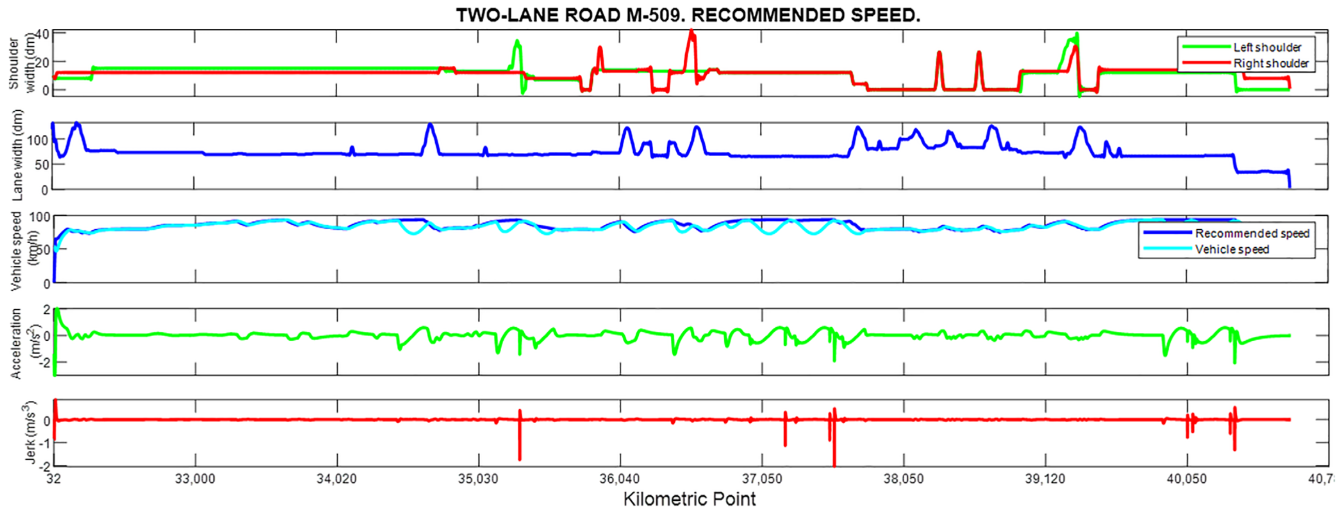

FIGURE 17 Recommended and vehicle speed, acceleration, and jerk for the M-509 road with declared emergency driving level, good conditions of the pavement and good weather conditions

6 | CONCLUSIONS AND FUTURE WORKS

In this work, a fuzzy logic-based speed recommendation expert system for conventional roads has been designed and developed according to actual road geometric characteristics and other factors such as pavement condition, driver comfort or prevailing weather. Conventional two-lane roads make up much of the road network, and many trips start or finish in such facilities. The final aim of this work it to contribute with a tool that can be implemented in vehicles as an aid to the already existing ACC to improve efficiency while enhancing safety and maintaining the desired level of comfort in each trip.

The intelligent speed adaption system output can be used by the driver as reference or included in the car ACC using the model predictive control approach these systems are based on. The recommender system calculates the vehicle operating speed along the road and complements it with other factors that influence the velocity, mainly from the point of view of the driver. For instance, the subjective perceptions of some geometric road characteristics (lane and shoulder widths, distance from the vehicle ahead …) as well as other environmental variables are dealt with. This way, driver's subjective perceptions, experience, and level of urgency, are taken into account. In addition, the system always adjusts the recommended speed to the legal one based on the identification of the type of road according to its geometric characteristics.

The intelligent system calculates the speed in an adaptive way, considering the actual changes in the geometric features of the road and the driving mode chosen by the user. The obtained results are interesting and useful to complement other driver assistance systems installed in the vehicle and may be used in autonomous vehicles. The proposed system could work cooperatively with other driver assistance systems that are based on road-sign recognition cameras and GPS-linked speed limit databases, taking a joint decision on the speed limit to be set for the vehicle.

Other factors that are currently beginning to be measured by intelligent sensors, such as group permeability to faster vehicles, wheel-pavement interaction, etc., could be introduced as future works regarding automated vehicles. It could be also used to generate verification maps for existing road speed signs, and as a tool to detect possible less safe road sections in safety audits, for example.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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