



Smart Roads Geometric Design Criteria and Capacity Estimation Based on AV and CAV Emerging Technologies. A Case Study in the Trans-European Transport Network

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Abstract

Smart roads, AV and CAV are emerging technologies that represent the new paradigm of mobility. To support the public and private road operators better prepare themselves to implement these technologies in their respective existing or planned infrastructures, there is an urgent need to develop an integrated analysis framework to evaluate the impact of these novel systems on road capacity and safety in function of different market penetration levels of AVs and CAVs. The research focuses on novel smart road geometric design and review criteria based on the performance of AVs and CAVs. The case study of one of the first planned smart roads in Italy has been analysed.

Keywords Smart roads · AVs · CAVs · Design criteria · Capacity estimation

1 Introduction

Smart roads represent the new paradigm of mobility and aim at being more sustainable, safe, innovative and inclusive, thus modifying the traditional relationship between vehicles, users and infrastructure/environment. Smart roads are digitalized infrastructures increasingly compatible with the new technologies employed in light and heavy vehicles, with specific regard to the more recent Autonomous Vehicles (AVs) and connected and automated vehicles (CAVs). CAVs can monitor multiple vehicles ahead by the vehicle-to-vehicle (V2V) communication.

Basically smart roads adopt cooperative intelligent transportation system technologies (C-ITS) in order to enable the communication and cooperation both among all the vehicles and among the latter and road facilities.

Lately, by means of the C-Roads Platform, many road operators and technical authorities have joined together to harmonise the deployment actions of C-ITS in the European countries. The main objective is the deployment of interoperable cross-border C-ITS services for road users, especially the so-called “Day 1 - C-ITS service”.

In addition to the essential C-ITS technologies, one or more of the following systems can be implemented in smart road Environment (SRE) [1]:

- *Lanes dedicated to AVs and CAVs* travelling isolated or in platoons;
- *Internet of Things (IOT)*: sensors for monitoring traffic flows, structures (bridges, viaducts, road safety barriers etc.), weather and air pollutants;
- *Ramp-metering systems*;
- *Hard Shoulder Running (HSR) systems*;
- *Variable Speed limits (VSL)*;
- *Green Islands (GIs)*: a multi-technological site (e.g. one for each 20–30 km highway segment) for generating energy from renewable sources (i.e. photovoltaic cells, mini-wind turbines, etc). GIs allow for a road or highway segment to be power-supplied, thus lowering operating costs. Each Green Island can be equipped with power recharge points, drone areas for landing and take-off used to survey the traffic streams and deliver the first-aid kit like, for instance, portable defibrillators;
- *Electric priority lanes* (lanes only for electric vehicles (EVs) [2] equipped with wireless recharge technologies);
- *Charge vehicles system on specifically assigned lanes*;
- *Piezoelectric devices to generate electrical energy*: piezoelectric crystals are placed about 5 cm below the asphalt pavement surface. The piezoelectric crystals

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Table 1 Summary of existing relevant studies (adapted from [7])

Study	Focus and application	Approach
Shladover [9]	CAV platooning capacity implications	mathematical formulation
Vander Werf et al. [10]	CV impacts on traffic flow capacity	Monte-Carlo simulation
Tientrakool et al. [11]	partially AV impact on highway capacity	numerical simulation
Fernandes et al. [12]	CAV platooning capacity implications	traffic simulator (SUMO)
Shladover et al. [13]	CV impact on highway	traffic simulator (AIMSUN)
Milanes et al. [14]	CV impact on traffic flow stability	Empirical study
Arnaout et al. [15]	V2V impact	agent-based
Friedrich [16]	CAV impact on traffic flow condition	mathematical formulation
Hussain et al. [17]	CAV freeway lane management	mathematical formulation
Talebpour et al. [18]	CAV impact on shockwave formation	integrated simulation framework
Chen et al. [19]	AV impact on operational capacity	mathematical formulation
Ghiassi et al. [20]	CAV impact on highway capacity	Markov-chain analysis
Ye and Yamamoto [21]	CAV impact on traffic flow condition	numerical simulation
Olia et al. [22]	AV and CAV impact on highway capacity	traffic simulator (Paramics)
Abdulsattar et al. [7]	CAV impact on highway capacity	agent-based
Guerrieri et al. [8]	CAV impact on highway capacity	mathematical formulation

became slightly deformed when vehicles travel across the road and produce electrical current [3];

- *Programmable wireless digital traffic sign systems;*
- *Static weighing to weigh-in-motion (WIM), virtual WIM and High speed weigh-in-motion (HS-WIM);*
- *Smart intersections* that allow reducing fatal collisions and enhancing safety at road intersections. Using intelligent cameras, object recognition and V2X the connected vehicle can warn the driver of a pedestrian crossing, even when they are not directly within line of sight [3];
- *Smart street lights with sensors-added* used for a variety of purposes, including [3] (a) gunshots, terrorists and riots detection, (b) air quality monitoring, (c) EV charging points, (d) traffic congestion monitoring, (e) people crowd monitoring, (f) public safety monitoring, (g) roadside parking monitoring, and (h) trash and littering monitoring;
- *Road safety barriers equipped with an accidents monitoring system (AMS)* able to detect the impacts against the barriers in real-time (e.g. NDBA safety barrier [4]).

The exchange of several types of information (i.e. position, speed, acceleration and highway alignment parameters) between the vehicles by V2V, V2I and V2X systems will enable the CAVs to anticipate the forthcoming accident risk in surroundings traffic stream resulting in accident-free and smooth driving under complex traffic environment [5].

Machine Learning (ML), Deep Learning (DL), Neural networks and in general Artificial Intelligence (AI) are highly used to increase the success rate of the emerging transportation technologies [6].

To support the public and private road operators better prepare themselves to implement C-ITS, AV, CAV technologies and smart roads in their infrastructures network, there is an urgent need to develop an integrated analysis framework to evaluate the impact of these novel systems on road capacity and safety [7].

At present, neither technical standards nor guidelines on geometric design criteria for such new digitalized infrastructures are available.

In [8] it has been formalised some novel highway design criteria founded on the performance of AVs and CAVs.

In addition, these criteria allow assessing whether an existing highway could be used by CAVs safely.

Instead, numerous studies have investigated the potential impact of CAVs on highway capacity. Generally, two different types of approach are used [7]: (i) microscopic traffic simulations; (ii) analytical models. Table 1 shows a summary of some of the most relevant literature. All the research results showed an increase in highway lane capacity in the range 180%–500% (Fig. 1) with correlated remarkable environmental benefits [23, 24].

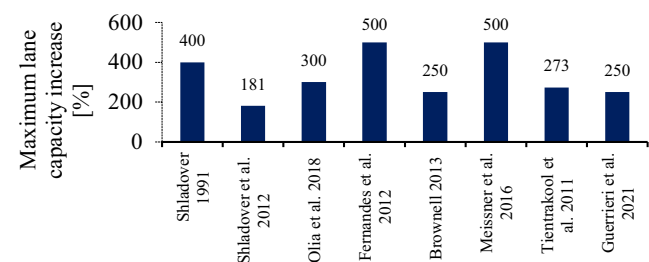


Fig. 1 Highway lane capacity increase due to smart road, AV and CAV technologies in accordance with recent research

CAVs are still at the theoretical and experimental phases of development. In the near future different market penetration levels (MPLs) of CAVs are expected. In accordance with MPLs, different penetration rates η of AVs and CAVs in the total highways traffic volume are plausible in the coming decades as follows:

- Market penetration level 1 (MPL1): only manually driven vehicles ($\eta = 0$);
- Market penetration level 2 (MPL2): mixed traffic flow comprising of both manually driven vehicles and CAVs ($0 < \eta < 1$);
- Market penetration level 3 (MPL3): only CAVs ($\eta = 1$).

Obviously, new highways will need to be designed specifically for CAVs and existing highways will need to be able to be travelled by CAVs safely.

In this research the design and review criteria (formalised in [4]) founded on the performance of emerging AV and CAV technologies are used for the design review of the existing Italian A19 motorway that will be one of the first smart roads in Italy. In addition, the expected increase in motorway capacity is estimated.

The methodological approach from this research and the results of the analyzed case study may represent one of the first tools to include the emerging CAV technologies in the decision processes concerning the novel digitalized-infrastructure planning and designing.

The remainder of the article is structured as follows: as the first section introduced the main research objectives, Sections 2 and 3 present the proposed Design criteria and capacity model for smart roads considering the effect of AVs and CAVs. In Sections 4, the proposed models are applied to the Italian A19 motorway and the results are discussed in detail.

Table 2 Horizontal and vertical design criteria in function of the market penetration levels of AVs and CAVs

Horizontal and vertical design criteria	MPL1 ($\eta = 0$)	MPL2 ($0 < \eta < 1$)	MPL3 ($\eta = 1$)
Straights -Maximum length	$L_{s,max} = 22 \cdot V$	$L_{s,max} = 22 \cdot V$	∞
Straights -Minimum length	$L_{s,min} = 6 \cdot V$	$L_{s,min} = 6 \cdot V$	$\begin{cases} L_{s,min} = \frac{V}{3} \\ L_{s,min} \geq 30 \text{ m} \end{cases}$
Minimum radius equation	$\frac{V^2}{R} = 127 \cdot (q_t + f_t)$	$\frac{V^2}{R} = 127 \cdot (q_t + f_t)$	$\frac{V^2}{R} = 127 \cdot (q_t + f_t)$
Horizontal curves -minimum length	$S_{v,min} = 2.5 \cdot \frac{V}{3.6}$	$S_{v,min} = 2.5 \cdot \frac{V}{3.6}$	$\begin{cases} S_{v,min} = \frac{V}{3} \\ S_{v,min} \geq 30 \text{ m} \end{cases}$
Ratio between the radii of consecutive horizontal curves	must fit within the “Good design area” of the “radii tulip” abacus [27] (cfr. Fig. 9)	must fit within the “Good design area” of the “radii tulip” abacus [27] (cfr. Fig. 9)	must fit within the “Good design area” of the “radii tulip” abacus [27] (cfr. Fig. 9)
Transition curves (Clothoids paramters)	$A1 = 0.021 V^2$ $A2 = \sqrt{\frac{R \cdot B_r \cdot (q_f - q_i)}{\Delta i_{max}}}$ $A3 = R/3$ $R \geq A \geq (A1, A2, A3)$	$A1 = 0.021 V^2$ $A2 = \sqrt{\frac{R \cdot B_r \cdot (q_f - q_i)}{\Delta i_{max}}}$ $A3 = R/3$ $R \geq A \geq (A1, A2, A3)$	$A1 = 0.021 V^2$ $A2 = \sqrt{\frac{R \cdot B_r \cdot (q_f - q_i)}{\Delta i_{max}}}$ $A \geq (A1, A2)$
Crest vertical curves	$R_v = \frac{SSD_{(TV)}^2}{2 \cdot (h_1 + h_2 + 2 \cdot \sqrt{h_1 \cdot h_2})}$ if $SSD_{(TV)} < L$ $R_v = \frac{2}{\Delta i} \cdot \left(SSD_{(TV)} - \frac{h_1 + h_2 + 2 \cdot \sqrt{h_1 \cdot h_2}}{\Delta i} \right)$ if $SSD_{(TV)} > L$ $h_1 = 1.10 \text{ m}$ $h_2 = 0.10 \text{ m}$	$R_v = \frac{SSD_{(TV)}^2}{2 \cdot (h_1 + h_2 + 2 \cdot \sqrt{h_1 \cdot h_2})}$ if $SSD_{(TV)} < L$ $R_v = \frac{2}{\Delta i} \cdot \left(SSD_{(TV)} - \frac{h_1 + h_2 + 2 \cdot \sqrt{h_1 \cdot h_2}}{\Delta i} \right)$ if $SSD_{(TV)} > L$ $h_1 >> 1.10 \text{ m}$ $h_2 = 0.10 \text{ m}$	For AV $R_v = \frac{SSD_{(AV)}^2}{2 \cdot (h_1 + h_2 + 2 \cdot \sqrt{h_1 \cdot h_2})}$ if $SSD_{(AV)} < L$ $R_v = \frac{2}{\Delta i} \cdot \left(SSD_{(AV)} - \frac{h_1 + h_2 + 2 \cdot \sqrt{h_1 \cdot h_2}}{\Delta i} \right)$ if $SSD_{(AV)} > L$ For CAV $R_v = \frac{SSD_{(CAV)}^2}{2 \cdot (h_1 + h_2 + 2 \cdot \sqrt{h_1 \cdot h_2})}$ if $SSD_{(CAV)} < L$ $R_v = \frac{2}{\Delta i} \cdot \left(SSD_{(CAV)} - \frac{h_1 + h_2 + 2 \cdot \sqrt{h_1 \cdot h_2}}{\Delta i} \right)$ if $SSD_{(CAV)} > L$ $h_1 >> 1.10 \text{ m}$ $h_2 = 0.10 \text{ m}$ $R_s \geq 0.129 \cdot V^2$
Sag vertical curves	$R_s = \frac{2}{\Delta i} \cdot \left(SSD^{(L)} - (TV \frac{h_v + SSD^{(L)} \cdot (TV \cdot \theta)}{\Delta i}) \right)$ $h_v = 0.5 \text{ m}$		

Finally, research conclusions, limits and prospective future studies are given in Section 5.

2 Smart Road Geometric Design Criteria

In this section are given some smart road design criteria founded on the potential performance of AVs and CAVs [8]. They were obtained by modifying those traditionally employed in highway engineering in function of the so-far known potential performances of AVs and CAVs.

In accordance with Market penetration levels of CAVs three types of smart roads use have been analyzed in this research, taking into account different penetration rate η values of CAVs in the total highways traffic volume:

- MPL1: only manually driven vehicles ($\eta = 0$);
- MPL2: mixed traffic flow comprising of both manually driven vehicles and CAVs ($0 < \eta < 1$);
- MPL3: only CAVs ($\eta = 1$).

Clearly, smart roads with a mixed traffic (i.e. $0 < \eta < 1$) must ensure good safety standards as traditional road ($\eta = 0$) for considering the human factors effect deriving by traditional vehicles.

Thus the design standard of the smart roads specified for the MPL2 must be the same as those of traditional roads (i.e. MPL1).

Traditional vehicles (TVs), Autonomous Vehicles (AVs) and connected and automated vehicles (CAVs) have different reaction delay (RD) values. In fact for TVs the reaction delay is equal to the perception-reaction time (PRT) that is correlated to Human Factors and users behaviour in Transportation Systems [25, 26]. Instead for AVs and CAVs the reaction delay is the sum of sensing, computing, communication and actuating delays and depends only by the vehicles performance.

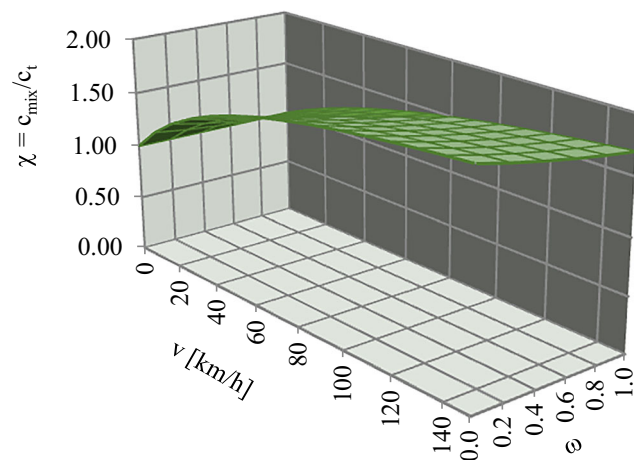


Fig. 2 Lane capacity increase χ in function of v and ω ($l_m = 7.5$ m)

In this research the following reaction delay (expressed in seconds) are considered:

- Traditional vehicles (TVs): $RD = (2.8 - 0.01 \cdot V)$, being V the vehicle speed expressed in km/h;
- Autonomous Vehicles (AVs): $RD = 0.15$ s;
- Connected and automated vehicles (CAVs): $RD = 0.30$ s.

As it is well known the stopping sight distance (SSD) can be calculated using the following equation [25]:

$$SSD = \frac{V \cdot RD}{3.6} + \frac{V^2}{25.92 \cdot g \cdot (f_e \pm i)} \tag{1}$$

In which SSD is expressed in m, V is the vehicle instantaneous speed in km/h, PRT is the perception-reaction time in seconds, f_e is the longitudinal friction coefficient, i is the grade of the road.

Equation (1) allows calculating the stopping sight distance for each vehicle type using the corresponding reaction delay as follows:

- $SSD_{(TV)}$: stopping sight distance for Traditional Vehicle ($RD = (2.8 - 0.01 \cdot V)$);
- $SSD_{(AV)}$: stopping sight distance for Autonomous Vehicles ($RD = 0.15$ s);
- $SSD_{(CAV)}$: stopping sight distance for connected and automated vehicles ($RD = 0.30$ s).

Table 2 shows the summary of the smart road design criteria used in this research, including the design of straights, horizontal circular curves, transition curves (clothoids), crest vertical curves and sag vertical curves.

Since the research is focused on the A19 Italian motorway the design criteria of Table 2 are partially obtained in accordance with the present Italian Guidelines for the Design of Roads and Highways [28].

For more details the interested reader may consult [8].

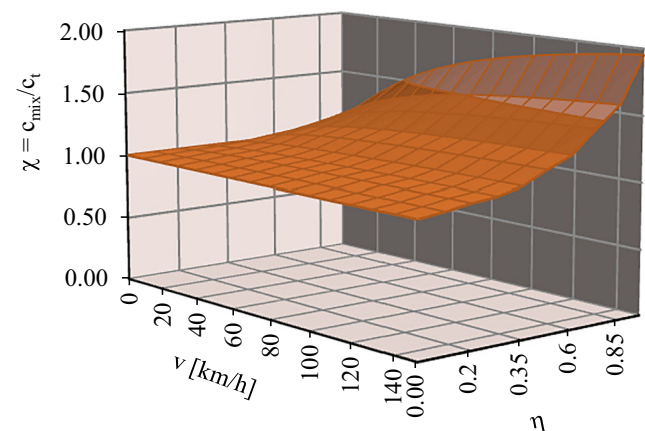


Fig. 3 Lane capacity increase χ in function of v and η

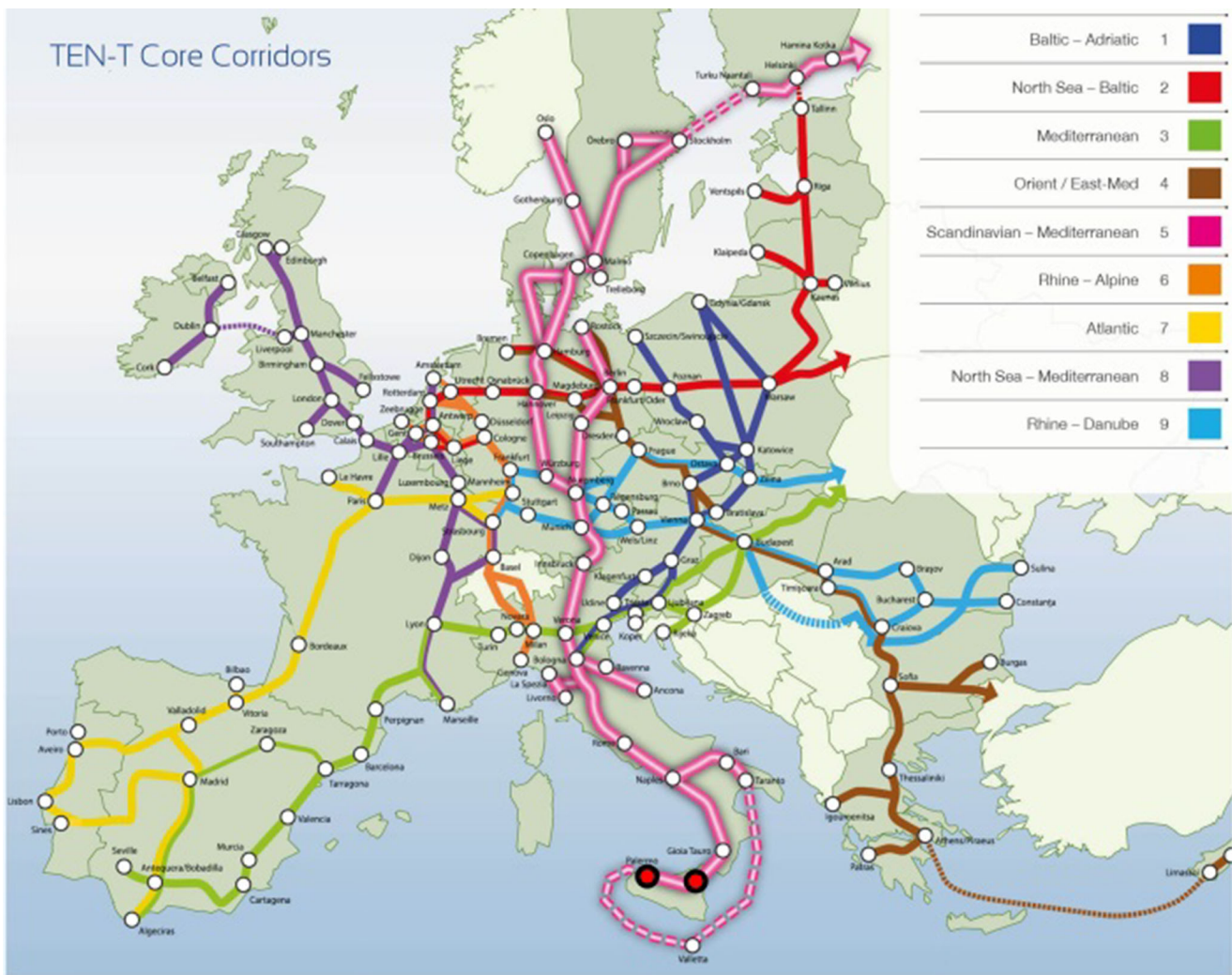


Fig. 4 TEN-T road network - the A19 motorway links the cities of Palermo and Catania (red points)

The models of Tab. 2 have been implemented in the new software “Smart Roads Safety Analysis Software. v.2021a” developed in Matlab environment and applied in this research.

3 A Closed-Form Model for Estimating the Highway Lane Capacity Increase Due to AVs and CAVs

As is well known, the fundamental traffic flow relationship links the macroscopic flow variables, i.e. flow q , vehicle density k and space mean speed v , to each other with a state equation. In a homogeneous traffic stream the vehicle density k is equal to the reciprocal of the mean space gap between pairs of vehicles into the stream [29, 30]:

$$k = \frac{1}{h \cdot v + l} \tag{2}$$

Being h the mean time headway, v is the space mean speed and l is the intravehicular space distance.

In accordance with [8, 16, 30–32] if the highway is in capacity condition for the sake of safety the following mean time headway values can be considered for traditional vehicles (TVs), Autonomous Vehicles (AVs) and connected and automated vehicles (CAVs) [8, 16]:

- mean time headway for TVs: $h_t = 1.15$ s;
- mean time headway for AVs and CAVs: $h_a = 0.5$ s.

Table 3 Main characteristics of straights (A19 motorway)

Straights				
N°	L_{min} [m]	L_{max} [m]	$V_{p,min}$ [km/h]	$V_{p,max}$ [km/h]
169	56	2652	96	140

Table 4 Main characteristics of horizontal circular curves (A19 motorway)

N°	R _{min} [m]	R _{max} [m]	V _{p,min} [km/h]	V _{p,max} [km/h]	S _{v,min} [m]	S _{v,max} [m]
169	100	2657	96.39	140.0	29.83	2657.04

The highway lane capacity is the flow value that is quite likely not to be overcome in a given highway section. In capacity conditions the mean vehicle speed is the so called critical flow speed v_c . Consequently, in capacity condition $v = v_c$. Equation (2) enabled to estimate the capacity c_t for a traffic stream of only Traditional Vehicles and the capacity c_a for a stream made up of only Autonomous Vehicles (AVs) and connected and automated vehicles (CAVs) as follows:

$$c_t = \frac{v}{h_t \cdot v + l} \tag{3}$$

$$c_a = \frac{v}{h_a \cdot v + l} \tag{4}$$

The ratio χ between the two capacities is:

$$\chi = \frac{c_a}{c_t} = \frac{h_t \cdot v + l}{h_a \cdot v + l} \tag{5}$$

The traffic variable χ represents the potential increase in highways lane capacity due to the introduction of the emerging AV and CAV technologies respect to the corresponding lane capacity in case of traffic streams formed only by TVs (current technology).

The following mean values can be adopted for l :

- passenger car $l = l_{car} = 7.5$ m (4.5 m mean vehicle length + 3 m minimum safety distance to the vehicle ahead);

- heavy vehicle $l = l_{truck} = 21$ m (18 m mean vehicle length + 3 m minimum safety distance to the vehicle ahead).

If mixed traffic stream condition occurs, denoting with ω the heavy vehicle share in the total highway traffic volume, for the scenario of market penetration level MPL1 ($\eta = 0$) the relationships (3), (4) and (5) can be rewritten as follows [16]:

$$c_t = \frac{v}{(1-\omega) \cdot (h_t \cdot v + l_{car}) + \omega \cdot (h_t \cdot v + l_{truck})} \tag{6}$$

$$c_a = \frac{v}{(1-\omega) \cdot (h_a \cdot v + l_{car}) + \omega \cdot (h_a \cdot v + l_{truck})} \tag{7}$$

$$\chi = \frac{(1-\omega) \cdot (h_t \cdot v + l_{car}) + \omega \cdot (h_t \cdot v + l_{truck})}{(1-\omega) \cdot (h_a \cdot v + l_{car}) + \omega \cdot (h_a \cdot v + l_{truck})} \tag{8}$$

In accordance with Eq. (8), Fig. 2 shows the highway lane capacity increases χ in function of traffic mean speed v and for several heavy traffic share ω values.

Consider now the market penetration levels MPL2 ($0 < \eta < 1$) and MPL3 ($\eta = 1$), being $\eta > 0$ the lane capacity is a function of the penetration rate η of AVs and CAVs in the total highways traffic volume [16]:

$$c_{mix} = \frac{v}{\eta \cdot v \cdot h_a + (1-\eta) \cdot v \cdot h_t + l} \tag{9}$$

For the future market penetration level MPL2 ($0 < \eta < 1$) there will be a simultaneous presence of TVs, AVs and CAVs

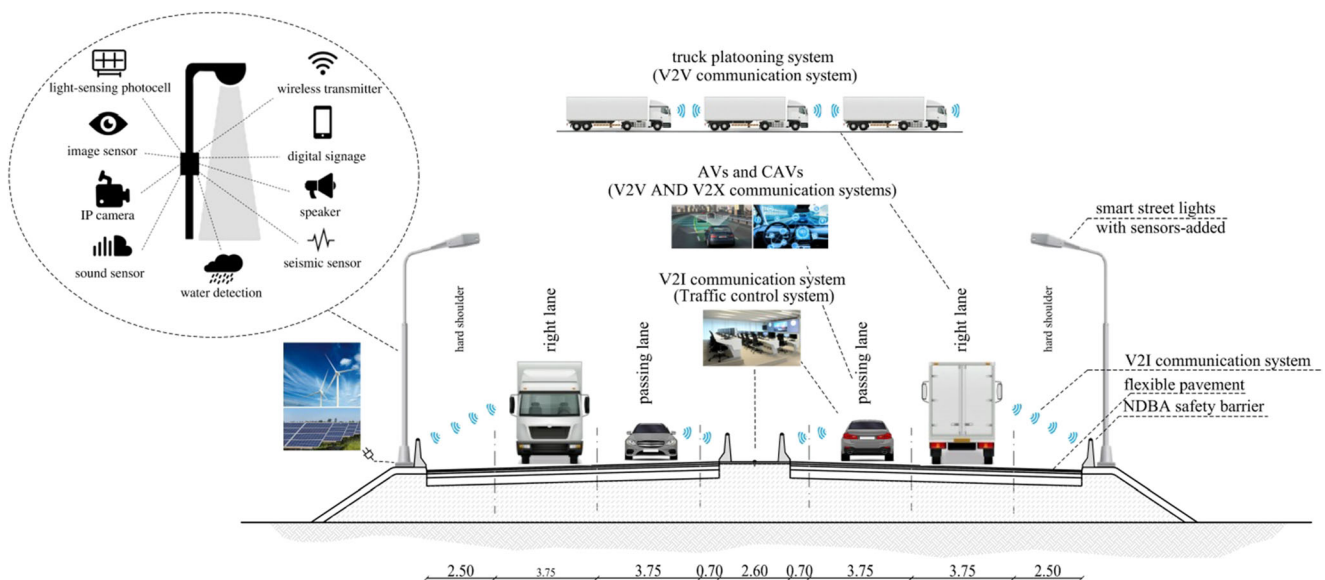


Fig. 5 A19 motorway current cross-section with exemplification of some of the planned technological devices

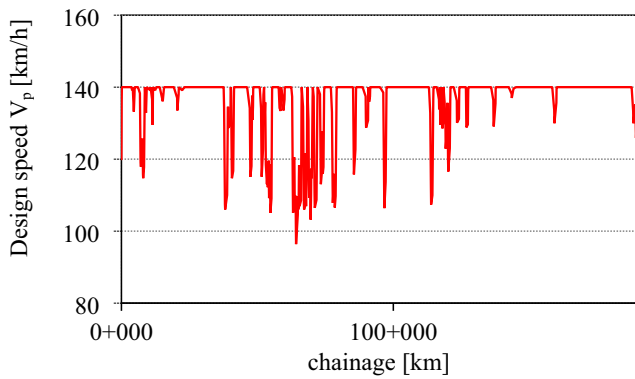


Fig. 6 Design speed diagram (A19 motorway)

therefore the vehicle pairs following one another in a certain traffic stream will be made up of a random combination of successive Traditional vehicles (TVs), Autonomous Vehicles (AVs) and connected and automated vehicles (CAVs).

In this research, depending of vehicle pairs combination, the following headways have been taken into account:

- vehicle pair TV- TV: $h_t = 1.15$ s;
- vehicle pair AV- AV, CAV- CAV, AV-CAV, CAV-AV: $h_a = 0.5$ s;
- vehicle pair AV-TV, CAV-TAV: $h_{a,t} = 0.9$ s.

It is worth underlining that it has been assumed $h_{a,t} > h_a$ to preclude AVs or CAVs from travelling too close to TVs, thus disturbing the human driver of a given TV.

By denoting here with l_m the mean vehicle length, the lane capacity can be evaluated by the following equation:

$$c_{mix} = \frac{v}{\eta^2 \cdot v \cdot h_a + \eta \cdot (1-\eta) \cdot v \cdot h_{a,t} + (1-\eta) \cdot v \cdot h_t + l_m} \quad (10)$$

The ratio $\chi = c_{mix}/c_t$ between the lane capacity with mixed traffic rate η and the lane capacity with only traditional vehicles is:

$$\chi = \frac{h_t \cdot v + l_m}{\eta^2 \cdot v \cdot h_a + \eta \cdot (1-\eta) \cdot v \cdot h_{a,t} + (1-\eta) \cdot v \cdot h_t + l_m} \quad (11)$$

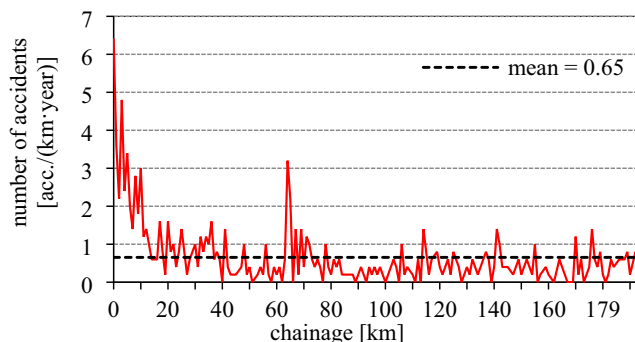


Fig. 7 Number of accidents per km and per year

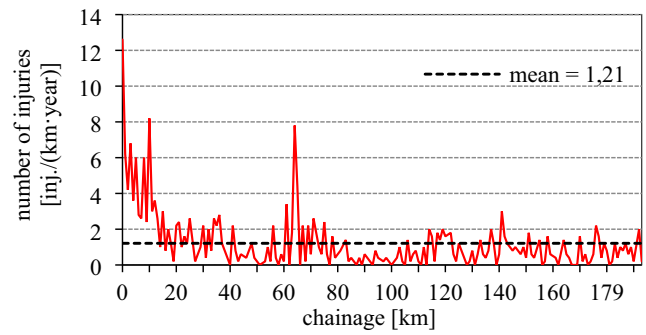


Fig. 8 Number of injuries per km and per year

As shown in Fig. 3 with the proposed traffic model (i.e. Friedrich model [16]) the highway lane capacity increases in proportion to the penetration rate of AVs and CAVs and decrease with the increase of the heavy vehicle share in the total highway traffic volume (Fig. 2).

4 The Case Study of the A19 Italian Motorway

The Italian road operator ANAS SpA in the year 2016 has launched the smart road program which involves an investment of 160 million euros for the technological modernization of the following Italian strategic infrastructures:

- the A2 “Autostrada del Mediterraneo”;
- the Rome ring road A 90 and the A91 Rome-Fiumicino motorway;
- The motorway “Orte – Mestre”;
- the A19 motorway ‘Palermo- Catania”.

In brief, the main objective of the “smart road project” is to develop digitalized infrastructures able to provide infomobility data and connectivity services. In the first phase traffic and environmental information conditions will be provided to users through innovative systems such as “wi-fi in motion” and the new DSRC (Dedicated Short Range Communications) standard.

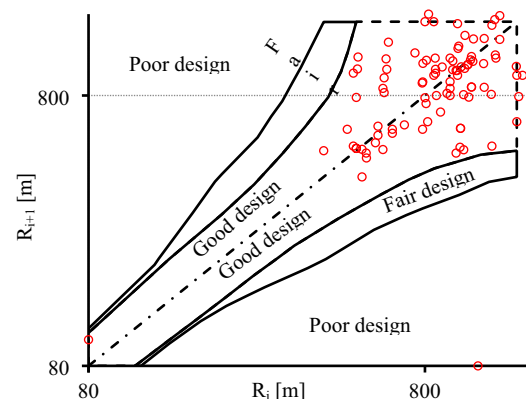


Fig. 9 Ratio between the radii of consecutive horizontal curves

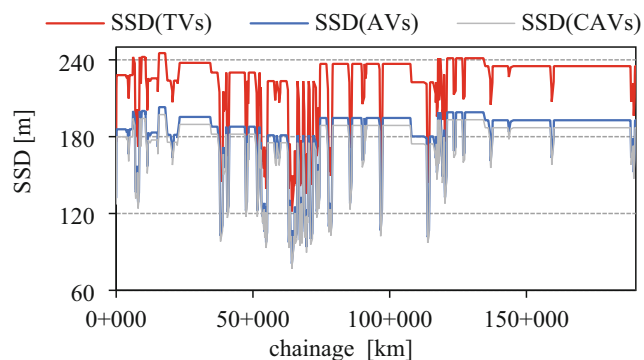


Fig. 10 Stopping sight distance profile for TVs, AVs and CAVs (direction 1: from km 0 to km 197)

The Italian A19 motorway, involved in the Italian “smart road project” belongs to the Trans-European Transport Network (TEN-T), specifically to the Helsinki–La Valletta corridor. This motorway connects the two metropolitan cities of Palermo (PA) and Catania (CT) (Fig. 4) and the cities of Caltanissetta (CL) and Enna (EN) where more than 2.8 million residents are concentrated overall, equal to over 50% of the inhabitants of the Sicily region. The study forecasts the analysis of safety and capacity implication due to the potential implementation of emerging AV and CAV technologies into the existing A19 motorway.

4.1 Safety Evaluation

The comprehensive geometric data on straights and circular curves of the A19 motorway are shown in Tables 3 and 4 respectively. The horizontal curves radii ranging from a minimum of 100 m to a maximum of 2657 m. The grade values are modest for the entire infrastructure ($0\% \leq |i| \leq 3.7\%$).

Currently the A19 motorway is 197-km long. It has two lanes (3.75-m wide each) in each direction and right-hand hard shoulders, each 2.50 m-wide; the mean wide of the central reservation is 4.00 m (see Fig. 5).

Figure 6 shows the design speed diagram deduced for the analyzed motorway. Several researchers have used speed (design speed V_p and operating speed V_{85}) as surrogate measure to evaluate road consistency and safety [33–35].

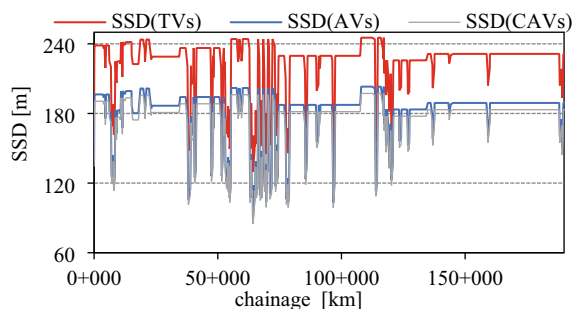


Fig. 11 Stopping sight distance profile for TVs, AVs and CAVs (direction 2: from km 197 to km 0)

Table 5 Locations of counting sections

Counting section	Location
km 6+283	Bagheria (PA)
km 10+900	Altavilla Milicia (PA)
km 80+100	Resuttano (CL)
km 92+112,	Alimena (PA)
km 112+500,	Enna (EN)
km 157+300	Catananuova (EN)
km 188+848	Misterbianco (CT)

In accordance with the Italiana road and highway design guidelines [28], the design speed profile allows evaluating the consistency of highway alignment elements. A good consistency ensures safe driving conditions at the desired speed on the entire highway segment, while the inconsistency is manifested when drivers must slow down below the desired speed to safely connect to the next road element [36]. Therefore, its knowledge is crucial because it allows assessing the potential heterogeneity of the alignment also in case of existing roads. For the A19 motorway the design speed values are in the range 96.39–140.00 km/h, but the speed variation between consecutive geometric elements (e.g. tangent to curve and curve to curve) is always below 10 km/h.

In order to deeply understand the current safety conditions of the A19 motorway before implementing smart road, AV and CAV technologies, crash occurrences have been analyzed collecting ANAS Spa reports. Crash data covered a time period of 5 years (2012–2016).

In this interval of time crash count was 634, the mean number of accidents and injuries per year and kilometer were 0.65 and 1.21 respectively.

The data pointed out that accidents more frequently occurred in the motorway segments next to the City of Palermo (km 0, Figs. 7 and 8) where high traffic flow values have been recorded (AADT = 76.289 veh/day, see Tab. 6).

The analyses show that the horizontal and vertical overall alignment of the A19 motorway is in compliance with the design and the review criteria discussed in Sect. 2. For instance, Fig. 9 demonstrates that the ratio between the radii of consecutive horizontal curves almost always falls in the good design zone of the “radii tulip” abacus [27, 37]. Only some straights are shorter than the minimum values shown in Tab. 2. However “short” straights may generate only potential comfort issues for users and not safety issues. In fact AVs and CAVs will be capable to regulate their acceleration, deceleration and speed in function of the motorway alignment using the information and exchange data between the existing infrastructure and vehicles thanks to the emerging V2I and I2V communication systems [38–40]. Also the research results demonstrate that Autonomous Vehicles and connected and

Table 6 Traffic variables of the basic segments

N°	Basic segments	Length [m]	AADT [veh/day]	DHV [veh/h]	PHF	q [veh/h]	FFS [km/h]	q* [veh/h]	v _c [km/h]	k [veh/km]	c [veh/h]	LOS
1	Palermo - Villabate	5410	76,289	3814	0.8	2427	110	1450	78	31.2	2350	F
2	Villabate - Bagheria	6238	34,011	1717	0.8	1094	99	1615	99	11.0	2295	C
3	Bagheria - Altavilla Milicia	4662	31,433	1752	0.8	1178	95	1675	95	12.4	2275	C
4	Altavilla Milicia - Resuttano	69,200	5613	293	0.8	196	98	1630	98	2.0	2290	A
5	Resuttano - Alimena	12,012	7501	382	0.8	268	104	1540	104	2.6	2320	A
6	Alimena - Enna	20,388	11,285	578	0.8	417	89	1765	89	4.7	2245	A
7	Enna - Enna 2	10,585	15,104	766	0.8	539	96	1660	96	5.6	2280	A
8	Enna 2 - Catenanuova	34,215	15,170	793	0.8	559	108	1480	108	5.2	2340	A
9	Catenanuova - Misterbianco	31,548	19,243	990	0.8	639	102	1570	102	6.3	2310	A
10	Misterbianco Catania	3452	29,242	1755	0.8	1150	104	1540	104	11.1	2320	B

automated vehicles will necessitate shorter stopping sight distances (SSD) than those required by traditional vehicles. In fact, Figs. 10 and 11 clarify that in each motorway direction and section it results:

- $SSD_{(AV)} < SSD_{(TV)}$;
- $SSD_{(CAV)} < SSD_{(TV)}$.

The previous conditions on the stopping sight distances may help to remove various existing speed limits in particular infrastructure segments (generally used to visibility obstacles) with consequent benefits in terms of travel time (TT) reduction and Level of Service (LOS) improvement.

4.2 Capacity Estimation

The prominent counting section chosen to carry out the traffic analyses are given in Table 5. The examined traffic data were collected from 1th January to 31 th December 2015.

Table 6 shows for each of the ten homogeneous basic segments in which the A19 motorway has been subdivided the traffic parameters in terms of Annual Average Daily Traffic (AADT), peak hour factor (PHF) and Design Hourly Volume (DHV). Each basic segment is characterized by a constant AADT value.

The Free flow speed (FFS) of the motorway segments were measured directly by the counting sections of Tab. 5. By means of the HCM model [41] the Speed-Flow curve $v = v(q)$ for each basic segment has been estimated using the following Equations:

$$\begin{cases} v = FFS \\ \text{if } q < q^* \text{ with } q^* = 3100 - 15 \cdot FFS \end{cases} \quad (12)$$

$$\begin{cases} v = FFS - \left[\frac{1}{28} \cdot (23 \cdot FFS - 1800) \cdot \left(\frac{q + 15 \cdot FFS - 3100}{20 \cdot FFS - 1300} \right)^{2.6} \right] \\ \text{if } q^* < q \leq c \text{ with } c = 1800 + 5 \cdot FFS \end{cases} \quad (13)$$

Figure 12 illustrates the Speed-flow curves with the representation of LOS limits for each basic segment. The lane capacity ranging from a minimum of 2275 veh/h to a maximum of 2350 veh/h depending on the motorway basic segment (Tab. 6), instead the critical speed v_c values fall in the field $v_c = 78-108$ km/h depending on the basic segment. As shown in Table 6 the levels of service are good for the entire motorway (LOS A-LOS C) except for the first basic segment (Palermo-Villabate) where oversaturation phenomena have been detected (LOS F). These results can be considered reliable not only for the existing configuration of the A19 motorway but also for the case of market penetration level 1 (only TVs and $\eta = 0$).

A quantitative estimation of the effects deriving by the implementation of emerging smart road, AV and CAV

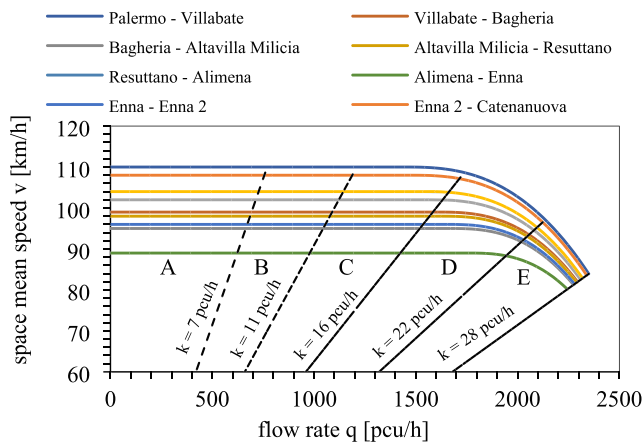


Fig. 12 Speed-flow curves with representation of LOS limits for each basic segment of the A19 motorway

technologies on capacity of each motorway segment can be assessed using the proposed model in Sect. 3.

As explained in Sect. 2, the expected lane capacity increase is a function of penetration rate η of AVs and CAVs in the total traffic volume.

Eq. (10) can be applied to estimate, for each basic segment of Tab. 6, the potential capacity value with mixed traffic c_{mix} and the ratio $\chi = c_{mix}/c_t$ between such a potential capacity and that estimated in the present traffic conditions (c_t) or in case of market penetration level 1 (i.e. TVs, therefore $\eta = 0$). Figure 13 shows the typical diagrams of the variable χ as a function of the penetration rate η of AVs and CAVs for the all the basic segments.

As expected, lane capacity increase more and more with the increase of the penetration rate η . It is worth pointing out that for $\eta = 1$ (i.e. MPL3) the infrastructure will be used only by AVs and CAVs. In this particular traffic flow condition ($\eta = 1$), the potential lane capacity values ranging from a minimum of 4336 veh/h to a

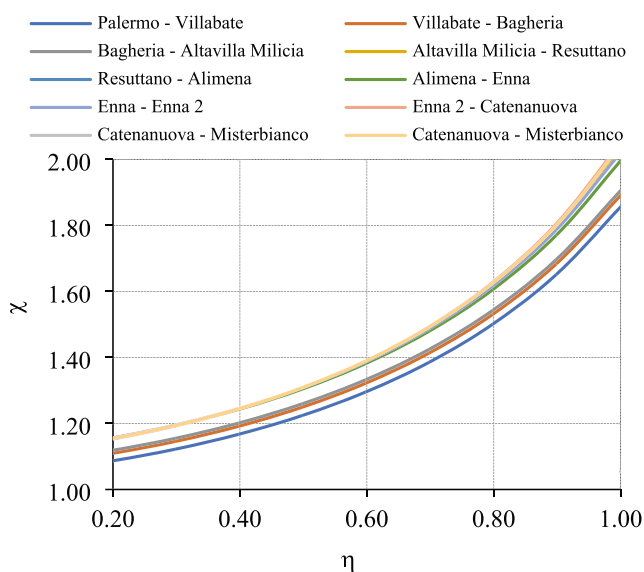


Fig. 13 Ratio χ as a function of η for each basic segment of the A19 motorway

maximum of 4800 veh/h (Fig. 14) against the current capacity range of 2275 veh/h - 2350 veh/h ($\eta = 0$). Therefore, the expected potential percentage improvement in the lane capacity may reach values in the range 186%–205% respect to the current lane capacity ($\eta = 0$), depending on the motorway basic segment.

5 Conclusions

Smart road, Autonomous Vehicles (AVs) and connected and automated vehicles (CAVs) are emerging technologies that allow increasing road capacity, and safety. In particular, smart roads are digitalized infrastructures well-matched with AVs and CAVs tanks to the V2V and V2I communication systems.

To support the public and private road operators better prepare themselves to implement these emerging technologies in the existing roads and highways, there is an urgent need to develop an integrated analysis framework to assess the influence of the already mentioned technologies on road capacity and safety in function of market penetration (MP) levels of AVs and CAVs. In this regards, three different modes of smart roads use have been analyzed in this research, considering different penetration rates of CAVs in the total highways traffic volume:

- MPL1: only manually driven vehicles ($\eta = 0$);
- MPL2: mixed traffic flow comprising of both manually driven vehicles and CAVs ($0 < \eta < 1$);
- MPL3: only CAVs ($\eta = 1$).

In this article some novel highway geometric design and review criteria established taking into account the performance of emerging AV and CAV technologies are used for the design review of the existing Italian A19 motorway that will be one of the first smart roads in Italy. Nowadays the A19 motorway is part of the Trans-European Transport Network TEN-T (specifically the Helsinki–La Valletta corridor). The proposed highways and road design criteria are partially based on the Italian Guidelines for the Design of Roads and Highways and may represent a useful support tool for decision making.

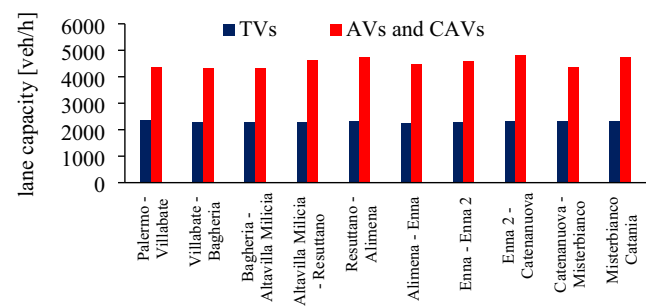


Fig. 14 Estimated lane capacity for each basic segments in the current traffic conditions (only TVs) and for the MPL3 (only AVs and CAVs)

The proposed criteria have been implemented in the new software “Smart Roads Safety Analysis Software. v.2021a” developed in Matlab environment and used for analyzing the A19 motorway.

Although the A19 motorway was built several decades ago, the analyses concerning its geometric alignment show that the infrastructure is in compliance with the proposed highway geometric design and review criteria except for only some geometric elements (straights). In addition, the research results demonstrate that AVs and CAVs will necessitate shorter stopping sight distances (SSD) than those required by traditional vehicles (TVs), therefore many existing speed limits in particular motorway segments (as in the case of the A19) could be removed when Market Penetration Level MPL3 ($\eta = 1$) will be concretely achieved with consequential benefits in terms of travel time reduction and LOS improvement.

Also the research focuses on the comparative analysis of the current motorway capacity and the future capacity due to the implementation of smart road, AV and CAV merging technologies.

First, the A19 motorway was subdivided in ten homogeneous basic segments characterized by a constant AADT value. Then, the Speed-flow curves with the representation of LOS limits for each basic segment have been deduced starting from a sample of traffic data collected from 1st January to 31st December 2015.

Instead, the estimation of the effects deriving by the implementation of emerging smart road, AV and CAV technologies on capacity of each motorway segment was obtained by the Friedrich model.

As predictable, the motorway lanes capacity growth increasing of the penetration rate η of AVs and CAVs in the total highways traffic volume. For instance for $\eta = 1$ (i.e. MPL3) the potential lane capacity values ranging from a minimum of 4336 veh/h to a maximum of 4800 veh/h, depending on the basic segment, against the current capacity range of 2275 veh/h – 2350 veh/h ($\eta = 0$, i.e. MPL1). Then, in accordance with the main results of the present research, for the case of MPL3, the expected potential percentage improvement in the lane capacity may reach values up to 205% respect to the current lane capacity.

In conclusion, the study aims to cover the research gap in the field of smart roads geometric design and capacity estimation. It is worth underlining that the results of this study are affected to the hypotheses assumed in the proposed and adopted closed-form models in particular as concern the potential performances of AVs and CAVs. Therefore, the closed-form models from this research and the main results of the analyzed case study may represent only one of the first tools to include the emerging Smart road, AVs and CAVs technologies in the decision processes concerning the novel digitalized-road planning and designing.

More reliable mathematical models could be considered in future researches as well as the study of the effect of emerging technologies on other geometric design parameters of smart

roads (e.g. the lane widths which may be smaller than those currently used) and the sustainability of such innovative transportation systems.

List of Abbreviations and Nomenclature A , clothoid parameter; A_1 , clothoid parameter (dynamic criterion); A_2 , clothoid parameter (slope criterion); A_3 , clothoid parameter (optical criterion); AV, autonomous Vehicle; B_p , carriageway width; c_p , lane capacity for traffic stream of only TVs; c_{av} , lane capacity for traffic stream of only AVs and CAVs; CAV, connected and automated vehicle; Δi , total grade change; Δ_{imax} , denotes the maximum gradient edge of the clothoid arc; f_l , longitudinal friction factor; f_s , side friction factor; FFS, free flow speed; h_1 , height of driver's eye point; h_2 , target point (object) height; h_v , vehicle headlights height; η , penetration rate of CAVs respect to the total traffic volume; k , vehicle density; LOS, level of service; $L_{s,max}$, maximum straight length; $L_{s,min}$, minimum straight length; MPL, market penetration level of AVs and CAVs; q , traffic flow; q_p , circular curve superelevation; q_f , superelevation at the end of the clothoid; q_b , superelevation at the beginning of the clothoid; θ , vehicle headlights divergence; R , horizontal circular radius; R_c , minimum crest radius; R_s , sag vertical curve design; RD, reaction delay; SSD, the stopping sight distance; $S_{v,min}$, minimum length of the circular horizontal curve; TT, travel time; V , vehicle speed; v , vehicle space mean speed; v_c , critical speed (of traffic flow); V_p , design speed

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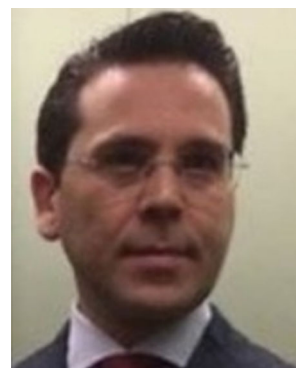
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