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Rethinking the main road design concepts for future Automated Vehicles Native Roads

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Abstract

Road design standards/guidelines are based on internationally valid concepts. They include requirements concerning alignment, sight distance, speed, friction, cross-sections. Those requirements are based on three main factors related to: drivers, physics, and comfort. The introduction of automated vehicles in the market will likely have a great impact on the road and transport design, management, operation and safety. In particular, the concept of road design and the related standards and guidelines may be modified, since some driver-based requirements may lose their significance in case of self-driving vehicles.

In this article, basic International road design concepts are reviewed, with specific focus on rural roads. The review aims at classifying the design concepts into the three categories: driver-, physics-, and comfort-based. Based on this classification, the applicability of traditional road design concepts to Automated Vehicles Native Roads -AVNRs- (roads specifically designed for automated vehicles) is discussed, by also taking into account results from simulations performed for the possible design of AVNRs.

As a result of the study, concepts/requirements concerning road design consistency and discrepancies between design, operating and posted speeds, may be not more necessary in case of AVNR design. Concepts/requirements related to tangent and curve lengths and sight distances may significantly change as well. Some minor modifications were discussed for cross-sectional elements (e.g. reduction of lane widths), and design speeds. The essentially physics-based design elements and requirements, such as curves, grades, road friction, sight distance (based on road geometry), transition curves and shoulders, should still be considered for the AVNR design instead, as well as comfort-based requirements.

Keywords: Automated Vehicles Native Roads, road design standards, road automation, vehicle automation.

1. Introduction

Vehicle automation is a groundbreaking and complex issue for transport development. The path towards the complete automation is composed of several steps, which are rapidly progressing. The National Highway Traffic Safety Administration (NHTSA)

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identifies five levels of vehicle automation (based on SAE, 2016), ranging from no automation (level 0) to full automation (level 5). Christensen et al. (2014) associate different applications to those levels: e.g. Anti-lock Brake Systems (level 0), cruise control (level 1), driving assistant(level 2), parking systems (level 4), robot shuttle (level 5).

The presence of automated vehicles (AVs) in the traffic flow will depend on several factors related to their actual future costs and benefits. Litman (2017) estimates that they could be available for driving on public roads in around 2020, being most of circulating vehicles in 2050s. However, there are several technical and social issues to address. Firstly, the development of safe self-driving vehicles, and the implementation of sensors/wireless for connecting vehicles and infrastructures (see e.g. Lu et al, 2014; Liu et al., 2019) is necessary. The social acceptance of AVs is another crucial matter: Piao et al. (2016) reported that only a quarter of a surveyed sample think that AVs are safer than traditional vehicles and only half of them will consider to use available AVs. Moreover, relationships between transport and land may be heavily modified. Zakharenko (2016) e.g. estimates that an increased availability of AVs may have a potential impact on travel distances, parking, economic activities, rent prices, urban sprawl, thus modifying cities.

Among the possible technologies including the implementation of AVs, vehicle platooning was proposed for reducing transport, environmental and safety costs (see e.g. SARTRE or PATH projects). Tsugawa (2014) estimated that an autonomous platoon of 3-4 trucks on a dedicated lane, with only one driver in the first truck, could pursue energy saving goals by combining adaptive cruise control and vehicle-to-vehicle communication systems (Cooperative Adaptive Cruise Control, CACC, Nowakowski et al., 2010).

One of the most important effects of full driving automation may be the reduction in road accidents (see e. g. Fagnant and Kockelman, 2015). In fact, since human factors may contribute to about 90 % of road crashes (see e.g. Treat et al., 1979),reducing possible human errors through automation may lead to a huge reduction in crashes. Litman (2017) estimates that safety benefits related to AVs in terms of reduced traffic risk could be revealed between 2040s and 2060s, when they will be largely widespread on roads.

The potential for road safety improvements due to automation derives from advanced scanning systems for recognizing obstacles; communication systems with other vehicles (V2V: Vehicle-to-Vehicle) and the infrastructure (V2I: Vehicle-to-Infrastructure, I2V: Infrastructure-to-Vehicle communications); safety systems such as adaptive cruise control, lane guidance, braking systems (some of them already widely implemented). An equipment composed of those elements will likely prevent human errors in the complete self-driving stage. However, there are intermediate automation stages, in which drivers will still play active roles and/or a switch from automatic to manual may be required (see e.g. Svensson et al., 2013), inducing possible problems (Rudin-Brown and Parker, 2004).

It should be stated that even road safety may significantly improve, other hazards for public safety may arise from vehicle automation. For example, Gora and Rüb (2016) highlighted that the connection between vehicles could suffer from distorted, missing and overabundant data. Vehicles could be exposed to hacking attacks or software breakdowns (Mousavian et al., 2017). Therefore, security issues may arise, replacing traditional safety matters, but representing important challenges to overcome (De la Torre et al., 2018).

2. Research questions

A brief presentation of current and future vehicle automation issues was reported above. As shown, the main focus of previous research was generally dedicated to developing technologies and systems for allowing the safe and secure guidance of AVs, essentially related to IT (Information Technology) and mechanical/electrical engineering.

However, AVs will still likely travel on roads. At the same time, they should be readable by vehicles and provided with all the necessary digital infrastructures for the safe transit of AVs (Svensson et al., 2013; Meyer and Beiker, 2014). Hence, in parallel with vehicle automation, the role of road infrastructure may be transformed as well. The development and implementation of road digital technologies, including sensors and connection facilities, is one important part of this transformation process.

On the other hand, there is another less frequently studied aspect, worthwhile of being investigated. It concerns the compatibility of the current road design geometric standards (considering traditional vehicles), with the transit of Automated Vehicles (AVs). Current road geometric standards may still be valid for AVs, if theymay recognize driving risks, through sensors, scanning and connection systems, quicker or equal than traditional users.

Nevertheless, considering the design process of a road/lane specifically born for the travelling of AVs: an “AV-Native Road (AVNR)”, other matters arise. In fact, in this case, different rules and control systems could be used. Geometric standards of AVNRs should be thought at first for AVs, considering their capabilities. However, the research body still lacks ofcomprehensive detailed studies focused on road design perspectives (see e.g. Washburn and Washburn, 2014; McDonald, 2017; Kwok and Hassan, 2017).

The philosophy underlying to most of International road design standards and guidelines is highly dependent on drivers’ human factors. In a full automated road environment, driving could potentially change its definition as a “task” requiring attention, in particular for familiar drivers (Colonna et al., 2016a, Intini et al., 2016, 2017). In fact, drivers will become only passengers, as in trains or planes. This may potentially influence the current road geometric design philosophy, leading to possible changes.

Hence, in this article, the following research questions are addressed:

- Which road geometric standards mainly governed by driver factors may be modified for AV-Native Roads (AVNRs)?
- Which modifications and/or innovations may be introduced in the design conceptsfor AVNRs?

The answers to these research questions are provided throughout the article, starting from a review of the main traditional geometric requirements, useful for the further analysis of potential changes in case of ANVR design. There are different road types (i.e. divided/undivided, two-lane/multi-lane), elements (i.e. segment/intersections) and environments (i.e. urban/rural/transition). Due to the impossibility of treating all these aspects in one single article, the exploratory analysis conducted here is limited to rural road segments. In fact, road designers have more degrees of freedom in choosingrural than urban road layouts. Hence,the rural environment matches more efficiently the inquiry into possible modifications of general road design aspects. Moreover, the futureuse of asphalt pavements is considered as still valid for AVNRs. If road materials will change, the road design concepts treated here may still be actual, even if all requirements involving friction may numerically change, still being conceptually valid.

3. Review and classification ofroad design requirements

The review of road geometric requirementsis based on internationally valid principles. Hence, it does not refer to specificstandards, since requirements may largely differamongregions. However, some specific documents are referenced where appropriate.

Different design aspects were inquired, concerning horizontal and vertical alignments, sight distances, speeds, friction and cross-sections. For each aspect inquired, the following classification is adopted, useful for the discussion about design of AVNRs:

- Physics-based, if design provisions are essentially based on physical considerations (vehicle statics/dynamics), allowing the safe vehicular travelling.
- Driver-based, if design provisions are needed forallowing drivers to correctly navigate roads, operate correct decisions, and being not surprised by road features.
- Comfort-based, if design provisions aim at ensuring acceptable driving comfort.

Some design aspects may be classified in two or more categories (e.g. both driver and comfort-based), since there may be several different requirements for the same aspect, even varying among different sources. Clearly, road design aspects related to driver-based requirements are those mostly targeted for possible modifications in case of AVNRs.

3.1 Horizontal alignment

The horizontal alignment design relies on fundamental concepts forbasic elements (tangents and curves), transition between basic elements and consistency requirements.

*Length of tangents.*Both minimum and maximum tangent lengths may be required. In case of a very short tangent included between curves, users may misperceive the actual alignment and choose inappropriate trajectories. Hence, minimum tangent lengths can be set, based on design or operating speeds (see e.g. MdE/SITRA, France (1994) or MIT, Italy (2001))Maximum lengths may be required to avoid speeding, drivers' distraction and/or fatigue instead (see e.g. CSIR, South Africa (2000), MdE/SITRA, France (1994), FGSV, Germany (2008), MIT, Italy (2001)), and they are often based on design speeds. The requirementsfor minimum and maximum tangent lengths are essentially driver-based. In fact, perception (for minimum length), distraction and speeding tendencies (for maximum length) are driver-related issues. However, the maximum length requirement has also clear comfort-related implications. In fact, for vehicles driven by humans, the monotony of a very long tangent may cause fatigue, being responsible for discomfort too.

*Length of curves.*A minimum curve length is usually required. The curve length can influence crash occurrence(see e.g. Harwood et al., 2000, Crash Modification Factors in: AASTHO; 2010). This influencedepends on curveradius, lengthand the presence of spiral transition curves. For a given radius, the longer is the curve, the safershould be the outcome, as based on the considered studies. This can be explained by the difficulty for drivers in perceiving a very short curve, possibly leading to incorrect maneuvers or errors. Hence, minimum lengths, a clear driver-based requirement,are often set as follows:

$$L_{C,min} = S\, t_{min} \tag{1}$$

where:$L_{C,min}$ = minimum length of curves (m);
S = Design or Operating speed (m/s);
t_{min} = minimum time necessary for correctly perceiving the curve (i.e. few seconds) (s).

<u>*Radius of circular curves.*</u>Horizontal curves are a crucial part of road alignment design, since they may be more hazardous than tangents for several reasons (Findley et al., 2012). Crash rates may rapidly increase at sharp curves, e.g. with radius <250 m (see Elvik, 2013, Oltham et al., 2009). Requirements for the main curve parameter, the radius of curvature, derive from the equilibrium of forces acting on vehicles in curve sections:

$$R_{limit} = \frac{S^2}{g\,(i_t+f_t)} \tag{2}$$

where:R_{limit} = Radius of curvature corresponding to the limit conditions (m);
S = Speed (m/s);
g = gravity acceleration constant;
i_t = cross slope (-);
f_t = side friction coefficient (-).

For givenS and f_t(which reflects the tire-pavement interaction), Eq.2 provides the radius of curvature R in the limit conditions. If the maximum available side friction is used, and the cross slope is equal to the maximum value allowed by local standards, then the radius obtained from Eq.2 is the minimum possible radius for that speed. Hence, the minimum possible radius (R_{limit}) largely varies as a function of speed, cross slope and side friction (e.g. from about 50 meters for low speeds and high cross slopes to about 1500 m for high speeds and flat cross sections).Curve design is then limited by the minimum radius (R_{limit}), which is an entirely physics-based rule, depending on the forces actingin Eq.2. However, the presence of super-elevation may have a positive impact on comfort of drivers, since the lateral acceleration can partially be compensated by the vehicle weight. For the same reason, sharp curves may cause discomfort in case of inappropriate speeds.

<u>*Transition curves.*</u> The transition between tangents and curves is often made with spiral transition curves. They are usually suggested or required for three main reasons:

- Allowing drivers approaching at curves through correct trajectories close to the lane centerline (extremely difficult without a transition element) and speeds;
- Reducing the effect of a sudden lateral acceleration due to the circular curve;
- Allowing the gradual shift of cross-section slopes between tangents and curves.

Hence, if transition curves are present, general positive effects on safety may be achieved (Harwood, 2000; AASHTO, 2010). To meet the above explained conditions, spiral transition curve design should usually be compliant with the following requirements (e.g. AASHTO (USA), 2011, MIT, Italy (2001)): minimum/maximum total length; adequate length of spiral sub-elements (in which the super-elevation occurs); prescriptions for other geometric parameters.Hence, the need for transition curves in road design can be deemed:

- User-based, since they may allow drivers to correctly perceive the transition curve and then approach curves through appropriate near-centerline trajectories;
- Comfort-based; since they gradually introduce to lateral accelerationsin circular curves (limited by correcting design parameters);
- Physics-based, since they allow a gradualtangent-to-curve cross slope variation (even if the same effect could alsobe reached in the terminal part of tangents) and a gradual variation of vehicle trajectories and approaching speeds (deceleration).

Road design consistency. Road design consistency is defined as the "*conformance of a highway's geometric and operational features with driver expectancy*" (Wooldridge et al., 2003). It follows that subsequent road elements should not be largely different, aiming at meeting drivers' expectations, by avoiding surprises. This concept is strictly related to the "*self-explaining roads*", ideally inducing safe behaviours through their own features (Theeuwes and Godthelp, 1995). Horizontal design consistency is mainly obtained by:

- Avoiding sudden sharp curves after long tangents;
- Provide subsequent curves with radii not largely different one with each other.

These requirements are often included in road standards (see e.g. French (MdE/SIDRA, 1994), Italian (MIT, 2001), German (FGSV, 2008) standards). For example, French standards require a radius ofat least namely 200, 300 mafter a tangent more than 0.5, 1.0 km long.The requirement concerning subsequent radius may be summarized as follows:

$$R_{following} > k(R_{previous})\, R_{previous} \qquad (3)$$

where:$R_{following}$ = radius of the following curve;
$R_{previous}$ = radius of the previous curve;
k = coefficient generally depending on the radius of the previous curve, otherwise fixed.

Horizontal design consistency requirements are mainly user-based, since they aim at correctly meeting drivers' expectations, and avoiding dangerous surprises. However, design consistency may also involve physics and comfort factors. In fact, in particular for subsequent curves, high differences between radii (i.e. sharp radius after a large radius) should be controlled to allow appropriate decelerations.This specific matter was already taken into account while considering transition curve requirements. On the other hand, consistent layoutsmaybe harmonious and less stressful from a comfort-based perspective. However, the consistency requirements listed above are mainly safety-related and based on human perception (user-based rather than physics/comfort-based).

3.2 Vertical alignment

The vertical alignment design relies on fundamental concepts for basic vertical elements (grades), vertical curves, horizontal-vertical consistency requirements.

*Grades.*Usually, requirements for both maximum and minimum longitudinal slopes are set.A minimum gradient is usually required to ease water drainage from the pavement (e.g. in the order of 3-5 ‰, see WSDOT, USA, 2010).This is clearly physics-based, not depending on interactions with drivers.Whereas, the maximum uphill/downhill slope is usually decreased starting from physics-constrained limits(based on the friction coefficient and other boundary conditions). Hence, maximum longitudinal slopes are usually set considering the road importance/context and the design speeds (i.e. from 3-5 % for high-speed freeways to 10-12 % for local roads, see ITE, 2016; Polus et al., 1998). Requirements for maximum longitudinal slopes are mainly physics-based, since vehicles are physically impeded on very high grades (in both travelling uphill and succeeding in braking downhill). However, the strictly physics-based requirement is usually prudentially lowered. Hence, also comfort-based and driver-based aspects arise. In fact, drivers' comfort is increased by limiting uphill slopes, since the effect of slowing down behind heavy vehicles may be reduced. Dangerous downhill braking may be impeded as well through limited slopes, through a physics-based mechanism. However, limiting downhill slopes may also prevent high speeds, which may increase safety in case of braking. For this aim, this requirement may be deemed as marginally driver-based too.

*Radius of vertical curves.*Vertical radii should be mainly designed for meeting sight distance requirements (treated in detail later in this article). In fact, the unobstructed line of sight is dependent on the vertical curve shape.Hence, in order to provide the required stopping or passing sight distance to vehicle drivers, a minimum radius is usually set. Alternatively, the vertical curve length(as in: AASHTO, 2012), or the length K for a 1 % of change of grade, given previous and subsequent grades may be set (as in UK standards: HA/SEDD/NAW/DRDNI, 2002). In sags, requirements takealsointo account the inclination of headlights, crucial for nighttime visibility(a separate discussion should be dedicated to road lighting for AVNRs indeed). Besides sight distance requirements (usually stricter), minimum radii (or lengths) should also ensure that parts of vehicles other than tires should not get in contact with the pavement: physics-based requirement. Moreover, some standards require a limitedvertical radius for comfort-based reasons, to avoid high vertical acceleration, as explained through Eq. 4 (k value varies e.g. between 0.01 and 0.05, see DTMR, Queensland, Australia, 2013), depending on road importance.

$$R_{minimum,comfort-based} = \frac{S^2}{k\,g} \tag{4}$$

where:$R_{minimum,comfort\text{-}based}$ = minimum radius allowed for comfort-based reasons (m);
S = design speed (m/s);
g = acceleration of gravity(m/s^2);
k = coefficient determining the vertical acceleration allowed for comfort-based reasons.

*Consistency of vertical and horizontal alignments.*Several standards/guidelines provide that the vertical alignment should be designed in coherence with the horizontal alignment, to avoid coordination problems (e.g. DTMR (Queensland, Australia, 2013)). Vertical and horizontal curves should be harmonized, aiming at not alteringdrivers' perception of road layouts (see Campbell et al., 2012; Vitkiene and Puodziukas, 2014). For example, horizontal curves upon sag vertical curves areexperimentally associated with inappropriate reactions due to perception errors(Bella, 2015). The requirements and/or recommendations for ensuring a proper horizontal/vertical coordination are clearly user-based. In fact, they aim at preserving the correct visual drivers' perception of different road elements, by fostering them to adopt the correct trajectories and safe behaviours.

3.3 Sight distance

A fundamental road design conceptconcerns providing adequate sight distance (SD) to drivers, commensurate to the required distance needed for: stopping, overtaking, other maneuvers. This requirement is summarized as follows (see e.g. Campbell et al., 2012):

$$Available\ (unobstructed)\ SD \geq Required\ SD = D(PRT) + D(MT) \qquad (5)$$

where:D(PRT) = T_{PR}(S)S = Distance run duringthe Perception-Reaction Time (PRT), needed to notice and react to the obstacle/target(e.g. vehicle to overtake, freeway exit);

D(MT) = Distance corresponding to the Maneuvering Time (MT) needed for each type;

T_{PR}(S) = Perception-Reaction Time (s), depends on the maneuver type, as a function of speed S or fixed (e.g. usually around 2 s for stopping, even if itactually variesbetween 1.5 s to more than 5 s: Campbell et al., 2012, Fambro et al., 1997, Lerner et al., 1995);

S = travelling speed (m/s).

The basic equation for computing D(MT) in case of stopping is reported as follows:

$$D(MT, stopping) = \frac{S^2}{2\,(f_L + i_L)\,g} \qquad (6)$$

where: S = travelling speed before starting to brake (m/s);

g = acceleration of gravity (m/s^2);

f_L = available longitudinal friction coefficient (-);

i_L = longitudinal slope (-).

D(MT) refers to braking maneuvers, since usually the distances for overtaking and other maneuvers are set as based on fixed times (see e.g. Green Book (AASHTO, USA, 2011), MIT, Italy, 2001)). In fact, Eq.5 can be used to compute the total required sight distances. In this case T is the sum of the perception-reaction and maneuvering times, which relies on empirical data (e.g. about 10 s for speed/path/direction changes on rural roads). The influence of the considered factors on the total stopping sight distance (SSD) (even if other factors may be considered, such as resistances to motion) is represented in Fig. 1.

Requirements for sight distance are evidently both physics- and driver-based. In fact, they consider both physics relationships (maneuvering distance) and drivers' perception and reaction. In particular, human factors were highlighted as highly influential on sight distance requirements. Curves corresponding to PRT = 0 s in Fig. 1 represent the physics requirements for SSD (Eq. 6). However, even in excellent friction conditions (Fig. 1:f_L = 0.8), SSD greatly increases (e.g. more than doubled for PRT = 2.5 s, particularly notable for high speeds). Considering that the PRT may be increased for taking into account particular road conditions (and actuallysome drivers, e.g. having impaired visual, could anyway require more PRT), the influence of human factors can be considered as determinant for sight distance requirements. In fact, it is numerically more important than physics factors for high PRT times, at least in level sections.

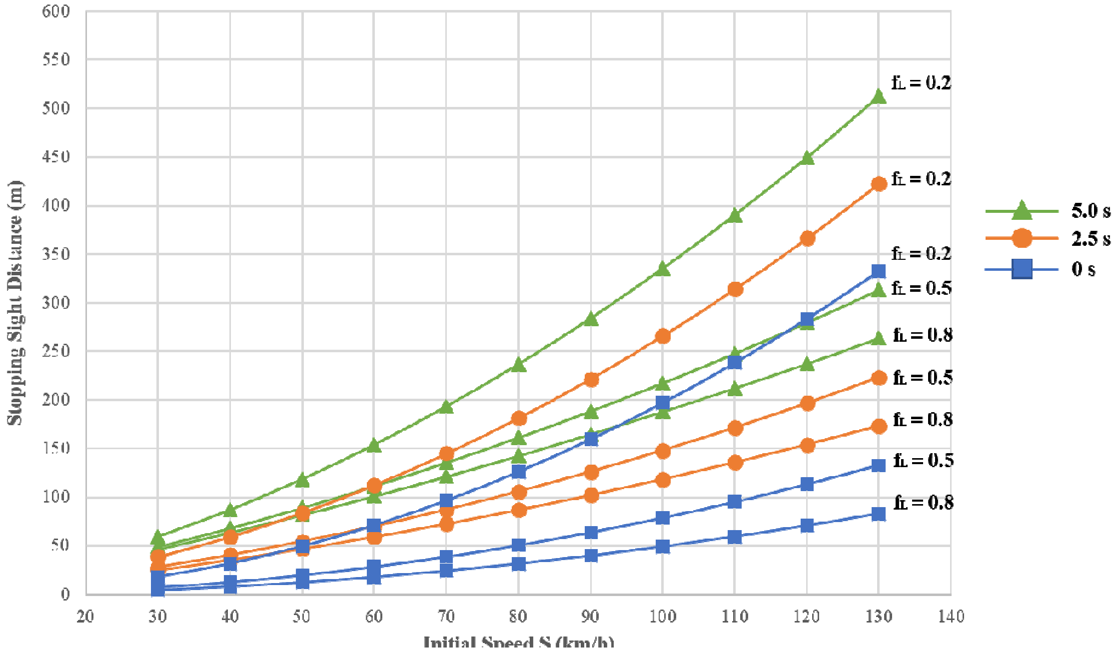

Figure 1: Stopping sight distance (SSD) for different values of initial speeds, Perception-Reaction Times (PRT), and longitudinal friction f_L, considering a level tangent section.

3.4 Design, posted and operating speeds

Road design implies posting and/or suggesting safe speeds to drivers. Ideally, the road layout and its related design speeds should suggest the correct safe speeds to follow (concept of self-explaining road, Theeuwes and Godthelp, 1995). However, this condition could not be easily achieved, and inconsistencies arise with respect to operating speeds.

Design speeds. The design speed (S_D) is usually set by standards/guidelines according to the road types and contexts. Most of the geometric elements are designed according to the associated S_D (see e.g. Eq.1, 2, 4, 5, 6). Clearly, since those speeds are assigned according to the specific features of each road element, then a single driver ideally following design speeds for each road element should be safe.Moreover, other design requirements concern the coherence among design speeds of subsequent elements such as for geometric consistency (i.e. avoiding large discrepancies, as a general principle used in some countries, see e.g. MIT, Italy, 2001; Krammes and Garnham, 1998; Fitzpatrick et al., 2003). The need for setting design speeds according to different road categories depends on a mix of driver, comfort and physics-based concepts. The prevailing concept among them depends on the type of provision/recommendation set by the specific document. Some guidelines such as the Green Book (AASHTO, USA, 2001) recommend:

- minimum $S_D$for high-speed roads (i.e. 80 km/h).Driving on primary roads designed with low-speed standards may cause discomfort: comfort-based concept.
- maximum $S_D$for low-speed roads (i.e. 70 km/h). High S_D may be associated to high-standard elements (to which drivers may adapt),not suitable on low-level roadswith low-standard elements (e.g. sharp curves): driver-based concept.

However, other standards (e.g. MIT, Italy, 2001) set$S_D$intervals (between minimum and maximum S_D) for each road category. In this case, the recommendations concern setting:

- maximum $S_D$for high-speed roads (e.g. 120 km/h). It can be unsafeto use design speeds considerably higher than maximum posted speeds: driver-based and physics-based concept. In fact, in case of great speed differences between a very high maximum S_D and a low S_D, a safe deceleration could be impeded.
- minimum $S_D$for low-speed roads (e.g. 40 km/h). This may be needed for ensuring suitable standards for the mostcritical elements, by not severely limiting speeds(i.e. min.$S_D$relates to the min. curve radius): driver/comfort-basedconcepts. To some extent, it is also related to avoiding excessive decelerations (physics-based).

<u>*Operating speeds*</u>. The actual average drivers' travel speed (i.e. the operating speed S_O, usually measured through the 85th percentile speed S_{85}) may be substantially different than the design speed S_D. A good design practice implies that operating speeds should not be considerably different (i.e. higher) than safe design speeds (e.g. Fitzpatrick et al., 2003). In fact: "*Drivers do not adjust their speeds to the importance of the highway, but to their perception of the physical limitations of the highway and its traffic*" (AASHTO, 2001). In other words, they do not know the design speeds.For this reason, the S_O-$S_D$difference ($S_O$can be predicted through models, see e.g. Discetti et al., 2011;Dell'Acqua 2015; DTMR, Queensland, Australia, 2000) should stay within given thresholds (see Lamm's criterion, 1999).The criteria for checkingS_O-$S_D$differences are determined by guidelines, even if rarely being mandatoryprovisions. However, theyare considered here,given the crucial need for limiting real operating speeds, clearly related to safety (Elvik, 2013; Nilsson, 2004; Aarts and Van Schagen, 2006). Those criteriamay be deemed as driver-based: they aim atensuring thatdrivers' perceptionsmeet design predictions.

<u>*Posted speeds*</u>. Posted speeds are set for safety reasons,based on regulations and road features. While design, posted and operating speeds should ideally converge (see also ITE, 2016), some other practical considerations are needed (Donnell et al., 2009). Drivers are more prone to abide by plausible speed limits. Hence, speed limits can be set close to S_{85} (Milliken et al., 1998), that is near the upper limit of a range of anticipated S_O(Donnell et al., 2009, see Fig. 2). Clearly, as stated above, anticipated $S_O$should be coherent with S_D(better if lower). Hence, setting speed limits is essentially driver-based: it is the only tool for communicating to drivers which is the maximum speed allowed.

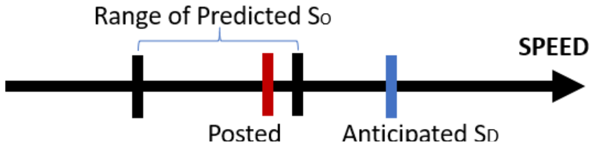

Figure 2: Current ideal relationships between speeds (based on Donnell et al., 2009).

3.5 Road friction

Road friction is crucial for road design and operation. Design friction coefficients (see Lamm et al., 1990b)decreasing with speeds are usually set or recommended in guidelines for settingdesign parameters (sight distance, curve radii and cross slopes, see Eq. 2, 6).

Apart from geometric requirements involving friction, the following inequality should be always guaranteed along the road layout, to avoid skidding (Colonna et al., 2016b):

$$F_P = W_a f_a = W_a\sqrt{{f_L}^2 + {f_C}^2} \geq F_D = \sqrt{L^2 + C^2} = \sqrt{\left(\sum R_L\right)^2 + \left(W_C \pm R_{C,wind} \pm F_c\right)^2} \qquad (7)$$

where: F_P = Friction Potential, provided by roads to vehicles, in given conditions (N);
W_a = Adherent Vehicle Weight (N);
f_a = Friction coefficient (-);
f_L, f_C = namely the longitudinal and cross component of the friction coefficient (-);
F_D = Friction Demand, friction required by vehicles to roads, in given conditions (N);
L, C = namely the longitudinal and cross forces acting on the vehicle (N);
$\sum R_L$ = Longitudinal resistances (air, slope, rolling, intertial, wind) to motion (N);
W_C = Cross component of the weight force (N);
$R_{C,air}$ = Cross action of wind gusts (N);
F_C = Centrifugal force (N).

Clearly, all forces in Eq.7 depend on the boundary road conditions, geometric features, vehicle characteristics, speed. It is rather difficult to consider all those characteristics in the road design, while assessing potential skidding risks. The Friction Diagram Method (Colonna et al., 2016b), based on Lamm et al. (1995, 1999), aims at computing the Friction Demand/Potential ratio (Eq. 7), named Friction Used, section by section, for all the combinations of road geometric elementsand other conditions. If the ratio is ≤ 1, the safety conditions are guaranteed in the design phase (or checked for existing roads).

However, similar complex requirements are usually not mentioned in design standards, which generally only provide reference friction coefficients. These criteria are clearly physics-based, since they relate to the road-vehicle (tire-pavement) physical interaction.

3.6 Cross-sectional elements

The dimensions of cross-sectional elements (mainly lanes and shoulders) are usually defined in standards/guidelines, according to the road type/importance, the traffic volume and its context. The definition of minimum widths is based on the following remarks:

- Lanes should be wide enough for the safe traveling and maneuvering of all vehicles (including heavy vehicles), usually with maximum widths: 2.50-2.60 m;
- Shoulders should be wide enoughto supply additional space for visibility or, in emergencies, forrecovering after lane-departure or maneuveringto avoid crashes.

Lane and shoulder widths of rural two-lane roads lower than, namely, 12 ft (3.66 m) and 6 ft (1.83 m) lead to Crash Modification Factors > 1 (AASHTO, 2010). The effect of lanes wider than base conditions is not considered, while wider shoulders up to 8 ft (2.44 m) lead to positive safety effects. Actually, wider lanes should be not encouraged (even more than 11 ft, according to Noland, 2013). In fact, drivers may increase their speeds due to the greater safety sensation, leading to a counter-productive safety effect.

Hence, the requirements concerning lane and shoulder widths are physics-based for what concerns minimum widths (vehicle dimensions and sight distance).However, lane widths abide by driver-based reasons too: they should be wide enough to "forgive" eventual driving errors (e.g. steering errors in curves)but narrow enough to not incentivize speeding. There is also a slight comfort-based reason for avoiding excessively narrow lanes, which may force drivers to follow extremely fixed trajectories.

3.7 Summary of the classification of road design requirements reviewed

The main traditional road design concepts reviewed are summarized in Table 1, where the classification into driver-, physics- and comfort-based requirements is operated.

Table 1: Summary of the road design concepts/requirements, classified according to the main reasons for their presence in standards/guidelines: driver, physics or comfort-based

Road design concepts/requirements		***Type of requirement***		
Macro-category	*Detailed concept*	*Driver-based*	*Physics-based*	*Comfort-based*
Horizontal alignment	Length of tangents and curves	**X**		**X**[1]
	Radius of circular curves		**X**	x
	Transition curves	**X**	**X**	**X**
	Road design consistency	**X**		x
Vertical alignment	Grades		**X**	**X**[2]
	Radius of vertical curves	**X**[3]	**X**[3]	**X**
	Consistency of horizontal and vertical alignments	**X**		
Sight distance	Sight distance related to stopping, overtaking and other maneuvers	**X**	**X**	
Speed concepts	Design speed	**X**	x	**X**
	Operating speed	**X**		
	Posted speed	**X**		
Road friction	Friction demand/potential		**X**	
Cross-sectional elements	Lane and shoulder widths	**X**	**X**	x[4]

The main categories to which the requirements belong are highlighted in boldface, differently than the other categories to which the requirements belong to a minor extent.
[1]Valid for maximum tangent lengths.
[2]Valid for maximum longitudinal slopes.
[3]Since the determination of the radius of vertical curves depends on sight distance requirements.
[4]Valid for lane widths.

4. Discussion concerning the applicability to AVNRs

The road design requirements were summarized in the previous section and classified into different aspects (human-, comfort-, physics-based). In this section, the considered requirements are discussed in light of their applicability to the case of AVNRs.

4.1 Discussion about requirements for the horizontal alignment applied to AVNRs

Lengths of tangents and curves. Minimum and/or maximum lengths can be set or recommended mainly for driver-based reasons, and to a minor extent for comfort-based reasons (maximum tangent lengths). In case of AVNRs, the length of the main road design elements (tangents and curves) may not influence driving performances (i.e. short curves/tangents and very long tangents may be designed). Since these are requirements aimed at preserving correct drivers' perceptions, they may be not more needed.

The need for preventing fatigue through limiting tangents (comfort-based need) may be not more necessary as well. In fact, humans in AVs may be not interested in tangent lengths, since they may be involved in a series of different activities other than driving.

Radius of circular curves. The requirement concerning the minimum horizontal radius, according to the side friction coefficient, the super-elevation, and the vehicle speed is physics-based. This means that it may be still valid in case of AVNR design. In fact, a relatively high minimum horizontal radius may be required even for very low speeds (e.g. about 25-35 m for different side friction coefficients and cross slopes, for S = 30 km/h). However, it should be considered that vehicles may be able to anticipate the road layout through Infrastructure-to-Vehicle (I2V) communication (see e.g. Meyer and Beiker, 2018). In particular, considering road curves, specific warning roadside units may send messages to vehicles approaching the curve, through I2V technologies, informing about the curve location and geometry, and the safe speed for negotiating the curve, also according to the surface conditions (Olariu and Weigle, 2009). This technology is already applicable (first stages of automation), by alerting drivers through the reported curve-related information. However, in a full automation scenario, these information may be readable by AVs, which can adopt the appropriate speed according to the radius. Hence, Eq.2, which is a fundamental road design relationship, may be still used, but inverted and "solved" by vehicles. In fact, according to the real-time estimated side friction, anticipated radius and cross slope, the AV which is receiving information through I2V technology will autonomously set its speed to a safe curve speed (by using an appropriate margin). In this sense, the designer may lose his/her function of setting design speeds for each road element, since the road itself may suggest a safe speed through its own features and the real-time conditions. This speed may be operated by vehicles in case of free flowing, otherwise it should be adapted to thetraffic conditions (recognizable by AVs too).

Depending on how traffic control will be operated on AVNRs, other scenarios may be considered. In fact, two factors may be fundamental for automated vehicular traffic operations: 1) who owns the vehicles, 2) who controls network operations (Stocker and Shaheen, 2017). Fleet of vehicles may be shared by humans not owning the vehicles. In a full control scenario, fleet of vehicles may be controlled by a central unit which should optimize performances of the road section (e.g. Roncoli et al., 2015, Letter and Elefteriadou, 2017). In this case, the target of the I2V communication is not the single

AV: the information is simultaneously shared with the fleet of specific vehicles and/or all circulatingvehicles. This means that, in the case of curves, the single vehicle safe speed may be replaced by an optimized speed which takes into account traffic conditions.

On the other hand, super-elevation rates may still be needed for comfort reasons. In fact, humans in AVs will still suffer from in-vehicle lateral accelerations. Given this, super-elevations may be applied on AVNRs, even if not for physics reasons. However, super-elevation may still allow higher curve speeds, other conditions being equal (Eq. 2).

*Transition curves.*Transition curves are needed for all the three main aspects of classification (physics, driver and comfort-based). Clearly, the driver-based requirements, currently used for ensuring the correct perception of the transition curve (i.e. some prescriptions for spiral lengths) by the drivers and then, the correct curve navigation, may be not more needed. The same I2V mechanism explained for circular curves is still valid for transition curves: AVs will know in advance the transition characteristics, by setting the appropriate trajectories. Trajectories will likely be governed by the lane-keepingand navigation technologies (e.g. Falcone et al., 2007, Sjöberg, 2016; Kober et al., 2017). This will ensure the navigation in all road elements, especially in those in which optimal trajectories may not be accurately followed: transition/circular curves (e.g. Spacek, 2005).

On the other hand, both comfort and physics-based reasons will still be actual. In fact, transition curves also ensure the gradual transition to the full lateral acceleration in the circular curve. This function, and the design requirements for lengths and geometric parameters based on it, should be preserved for the design of AVNRs too. The same is valid for the physics-based requirements of connecting two different cross sections (from the two-sides slope in tangents to the one-side slope in curves) and of providing the necessary deceleration length from higher speed elements: they will still be needed.

Given the complex nature of requirements to be satisfied in case of spiral transition curves, a simulation was performed in order to identify the magnitude of each category of requirements. This simulation is useful to identify which requirements should still be considered in case of AVNRs, and which requirements could be relaxed instead (i.e. those specifically human-based). The simulation was conducted by:

- Fixing a design speed S_1 (at intervals of 5 km/h, from 60 to 140 km/h) for a hypothetic curved road element placed immediately before another curve;
- Settinga design speed S_2 for the following curve ($S_1 - S_2 = 10$ km/h, for each S_1);
- Associating the minimum radius of curvature to S_1 andS_2 through the Eq. 2;
- Computing the necessary length of road for decelerating from S_1 to S_2 (in the hypothesis of starting the deceleration from the end of the curve with S_1);
- Computing the minimum/maximum spiral lengths based on diverse requirements.

As described in the previous section, prescribed spiral lengths differ according to standards/guidelines. However, most of them agree on the common principles previously described. In this simulation, prescriptions based on MIT (2001) were considered as an example. The results obtained from the simulation performed are described in Fig. 3, where minimum/maximum spiral lengths according to different requirements are plotted against the initial design speed S_1.

Considering to spread results from this simulation to the design of AVNRs for similar cases (limited however to the same reference values used here), some design criteria for spiral transition curves should still be considered. In fact, the human-based requirement for the minimum spiral length (based on the visual perception) seems scarcely limiting (see Fig. 3). On the other hand, the need for constant speeds in curves should still be considered for AVNRs (i.e. to avoid local loss of friction) and then, the need for a fixed minimum deceleration length in case of curve-spiral-curve transition may still be relevant (see Fig. 3). Other constraining requirements for minimum spiral lengths could still be taken into account such as those related to limiting roll speeds (such as in the considered case of curve-spiral-curve transition, Fig. 3, for low speeds) or to limiting lateral accelerations (which could be more demanding in the case of tangent-spiral-curve transition). Whereas, there could be no reasons to set upper boundaries for the spiral lengths, since this requirement could only be related to visual perception of human drivers. Hence, a synthetic requirement for the design of spiral lengths for AVNRs may be represented in this example by the bold shaded line in Fig. 3.

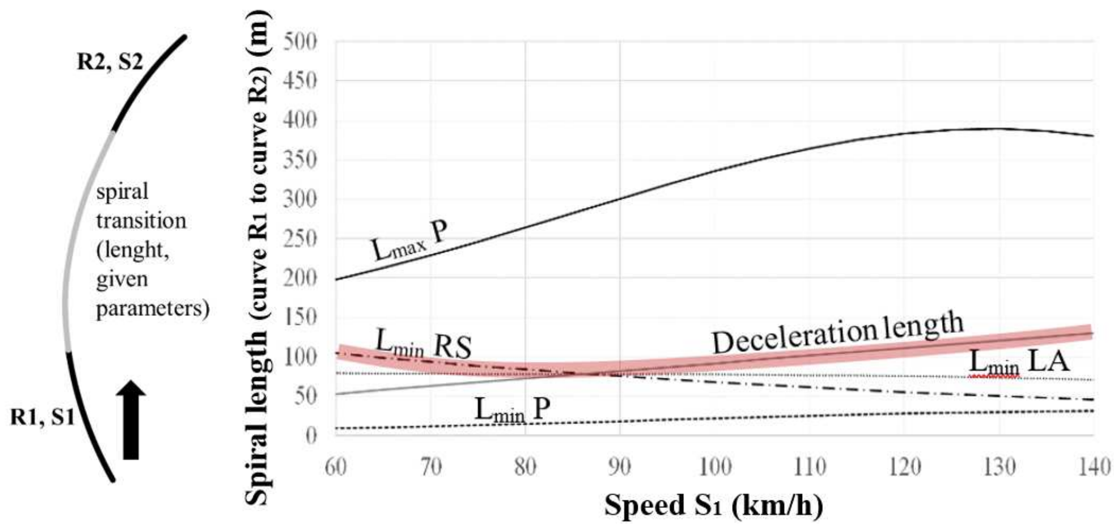

Figure 3: Simulated prescribed spiral lengths in the curve-spiral-curve transition as a function of initial speeds (before decelerating).L_{min} P = min. length for perceptual reasons (human-based), L_{min} LA = min. length for limiting lateral acceleration (comfort-based), L_{min} RS = min. length for limiting roll speeds (comfort and physics-based), L_{max} P = max. length for perceptual reasons (human-based). Global requirement for minimum spiral lengths highlighted through the bold shaded line.

Road design consistency. Requirements concerning road design consistency are essentially driver-based. Hence, strict requirements for setting features of subsequent road elements may be not more needed for AVNRs. Since AVs will communicate with the roadway, there will be no need for matching expectations of vehicle occupants (in AVs).

The comfort-based reason for the road design consistency could still be valid, even if from a different point of view. In fact, the potential presence of an increased elasticity in designing curved elements, may lead to the possible presence of sudden sharp curves after long tangents even in relatively high-speed roads (no need for avoiding surprises to drivers). This may cause discomfort and it should be avoided anyway.

4.2 Discussion about requirements for the vertical alignment applied to AVNRs

Grades.Prescriptions/recommendations for maximum and minimum grades are essentially needed for physics-based reasons (even if physics-based maximum slopesare normally lowered for driver/comfort-based concepts).Pavement drainage should still be needed for AVNRs, then keeping prescriptions for minimum longitudinal slopes.

The need for maximum grades (lower than the highest possible for physics-based reasons) may still be valid as well. In fact, even if driverless, heavy vehicles should still encounter physics-based resistances in travelling at high speeds on steep uphill grades. This means that the speed of following vehicles may be limited, causing discomfort, in case of impeded overtaking maneuver. For this reason, maximum uphill slopes should be still recommended for AVNRs. Also in downhill slopes, the maximum slope may be still limited for not fostering the overheating of brakes. The comfort-based reason for limited downhill slope (possible dangerous braking) could be not more valid instead. In fact, the ending point of the longitudinal slope could be easily anticipated by the AVs, which may dose the braking force along the slope, avoiding safety issues and additional discomfort.

*Radius of vertical curves.*The radius of vertical curves should be mainly set according to sight distance and other physics-based reasons (minimum radius of vertical curves). Sight distance requirements are discussed in next sub-section (see also Khoury and Amine, 2019; Wang and Yu, 2019), while the other reasons are treated here. The need for a minimum radius of vertical curves should be still valid for AVNRs. The contact of vehicle parts with the pavement different than tires should be always avoided indeed.

The comfort-based reason for setting minimum vertical radii (Eq. 4) can be applied to AVNRstoo. In fact, very high vertical accelerations may still cause discomfort to vehicle occupants, even if not drivers (such as for lateral accelerations in curves).

*Consistency of vertical and horizontal alignments.*The recommendations for ensuring consistency between vertical and horizontal alignments are solely driver-based. In fact, they are based on the drivers' visual perception, by preventing distortions of the real road scenes. For this reason, the horizontal/vertical alignment coordination may be not more needed for AVNRs. The driver's eye will be replaced by the on-board sensors, based on lane-keeping, steering and positioning recognition algorithms for ensuring correct trajectories, even in case of misleading road scenes (e.g. horizontal curves upon sags).

This occurrence could significantly alter the prescriptions for the design of vertical radii in case of AVNR design. To explain this, a simulation was carried out by:

- Fixing a horizontal radius (at intervals of 50 m, from 50 to 1500 m);
- Considering a crest vertical curve in correspondence with the horizontal curve;
- Computing the minimum vertical radius required for sight distance reasons;
- Computing the minimum vertical radius required for comfort-based reasons (limiting vertical accelerations) and coordination with the horizontal alignment;
- Repeating the above described operations for diverse gradient changes $\Delta i = |i_1-i_2|$.

International prescriptions based on sight distance for crest curves are very similar. Comfort-based requirements are also often present. In this simulation, prescriptions based on MIT (2001) were considered as an example. It was assumed that AVs would still need to visually scan the road ahead and then to maintain sight distance requirements for crest curves. Whereas, as a coordination requirement, it was assumed that the vertical radius should be at least 5 times the corresponding horizontal radius (stricter requirements can also be set, see e.g. Intini et al., 2019). Results of the simulation are shown in Fig. 4, where the minimum vertical radius is plotted against the corresponding horizontal radius.

Figure 4 clearly shows how the coordination requirement could lead to higher minimum vertical radii than the comfort and sight-distance based requirements, especially for very low and very high horizontal radii (e.g. in the highlighted example case of Δi = 1 %). Hence, ignoring this human-based requirement could result in reducing the volume of excavations needed, then potentially reducing the environmental impact of AVNRs.

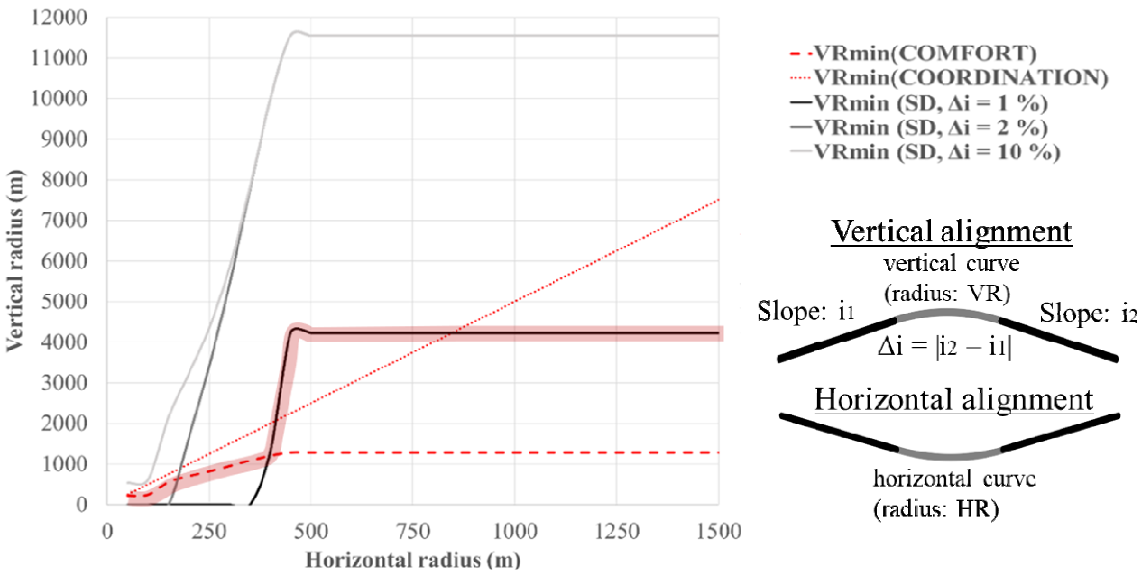

Figure 4: Simulated prescribed minimum vertical radii as a function of horizontal radii, according to different criteria (sight distance, comfort and coordination of the alignments, for different slope changes $\Delta i = |i_2 - i_1|$. Global requirement for minimum vertical radii highlighted through the bold shaded line (for the example case of Δi = 1 %).

4.3 Discussion about requirements for the sight distance applied to AVNRs

Requirements concerning sight distance are both physics- and driver-based. In this case, the possibility of modifying existing road design standards/guidelines for AVNRs is evident from Fig. 1, where the difference between the solely physics-based SSD (PRT = 0) and the SSD including driver-based factors (PRT > 0) is highlighted.

The main difference between traditional road design and road design for AVNRs consists in the different subject who is scanning the road scene. In fact, in the first case, the design is based on the drivers' eyes (i.e. considering the height of the driver's eye from the ground) and perceptual capabilities (i.e. considering perception and reaction times). Some design assumptions are needed, since perceptual capabilities may vary among drivers and this can be not reflected in detail in standards (Campbell et al., 2012). In the second case, the AV will continuously scan the road in all directions (see Fig. 5) with both short-range (especially for lateral obstacles, see Shieh et al., 2017) and long-range sensors (such as LIDAR, up to 200 m, see Hecht, 2018). The current available on-board sensors are based on both cameras and radars which may be able to detect all types of obstacles (vehicles, other objects), other than lane edges and centerlines. Hence, their function should be not limited to ensure the correct positioning of the vehicles inside the lanes (e g. Cao et al., 2017) but also to induce emergency braking if obstacles are noticed.

Clearly, the potential for reducing sight distance requirements for the AVNRs design depends on the actual and/or other future available technologies. In fact, the distance which may be covered by long-range radars will represent the available sight distance for driverless vehicles. If a maximum scanned distance of 200 m (a potential maximum distance of 300 m for object detection is indicated by Hecht, 2018), and the PRT = 0 curve (Fig. 1)are taken into account (identification of obstacles can be almost instantaneous), then this available sight distance could allow the safe vehicle stopping at high speeds (e.g. 130 km/h) in good friction conditions (e.g. $f_L = 0.5$), in level tangent sections. In case of wet pavement (e.g. $f_L = 0.2$), speed may be reduced to 100 km/h for ensuring the same safety level. Considering the current traditional design, and a similar available amount of sight distance (200 m), on wet pavements (e.g. $f_L = 0.2$), the speed corresponding to an appropriate stopping sight distance is 80 km/h, far less than the speed which may be adopted for the AVNR design. Hence, the following two considerations emerge:

- on one hand, appropriate speeds may be automatically selected by AVs, once data about friction and road geometry are obtained through I2V technologies, and the available sight distance defined by the on-board technologies is known.
- The AVNR design may potentially be less constrained by sight distance requirements, with a higher level of flexibility according to boundary conditions.

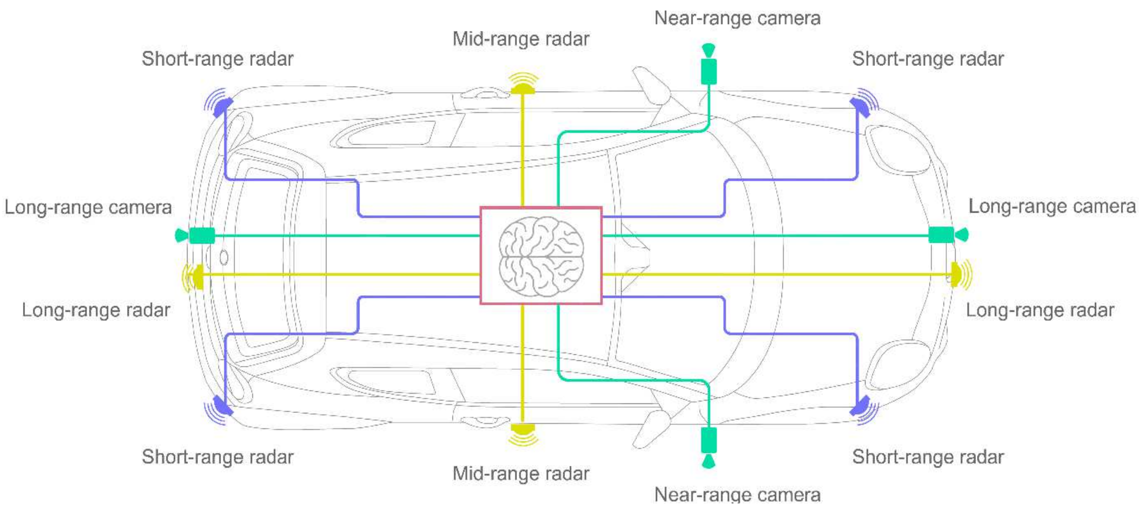

Figure 5: Currently available on-board sensors for AV operations, based on Hecht (2018)

The discussed possible modifications in the sight distance requirements for the AVNR design can also lead to practical important changes for the widening of shoulders due to visibility reasons (in presence of lateral obstacles). In fact, if a PRT reduction is taken into account, then the required stopping sight distance (SSD) in curve may be reduced as well. Hence, the comparison with the same available sight distance ASD (prudentially considering a line of sight of AVs sensors comparable with human sight) may lead to a reduction in shoulder widenings. To account for this, a simulation was conducted by:

- Fixing a curve radius R_C (at intervals of 15 m, from 45 m to 510 m);
- Computing the corresponding design speed S_C through the Eq. 2;
- Computing the available distance SD, considering the presence of an obstacle at the edge of the shoulder in the curve section;
- Finding the speed S_L corresponding to the point of view where the tangentstarts;
- Finding the minimum shoulder widening to get the limit condition: SSD = ASD;
- Repeat the described operations for flat (i = 0%) and downhill slopes (i = -5 %);
- Repeat the described operations for standard PRTs and PRT decreased to 1 s.

In the simulation, the hypothesis: SSD ≥ Lc(curve length) was considered and Lc was fixed to the minimum prescribed length. The presence of spiral transition curves was also omitted for the sake of simplicity. Prescriptions by MIT (2001) were followed as an example (which include also applying lane widenings for sharp radii, starting from an example baseline of 3.75 m). Results from the simulation are reported in Fig. 6.

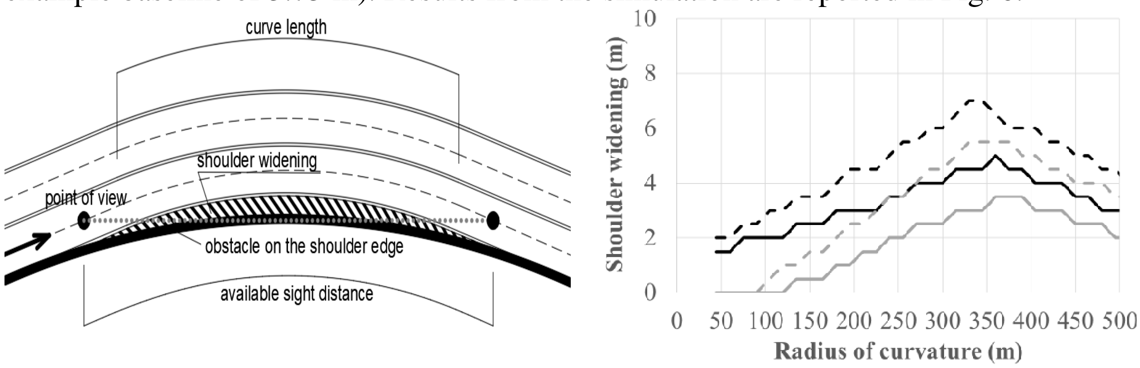

Figure 6: Simulated minimum widening of shoulders as a function of the curve radius. Black lines represent downhill slopes (i = -5 %), while grey lines are for flat slopes. Dotted lines are for standard PRTs, while bold lines represent the case of PRT = 1 s.

From the analysis of Fig. 6, it is evident that the reduction of PRTs (in this simulation down to 1 s) could lead to a significant reduction in the widening needed on shoulders for visibility reasons. Clearly, this example is based on theoretical remarks, since very high shoulder widenings should be avoided and they may imply a severe revision of the alignment design. In any case, the simulated reduction of widening simulated could result in limiting road widths, then potentially reducing the environmental impact of AVNRs.

The discussion conducted was specifically focused on stopping sight distances, but it can be easily extended to the other sight distance checks (i.e. passing and other maneuvers such as lane changing), which are based on similar principles.

It should be underlined that the discussion made above is based on the assumption of an individual vehicle operating in the traffic flow. However, Vehicle-to-Vehicle (V2V) communications will eventually make possible to share several information between vehicles (see e.g. Vinel et al., 2015). Among these information, the presence of obstacles on the road may be shared between all the vehicles operating on the same road section, potentially further reducing sight distance requirements, or adapting speeds accordingly far in anticipation. Another possible scenario may be the traffic operation managed by a central control unit, which should be aware of all the obstacles present on the road and automatically provide communications to all vehicles present in the network. Note that, in these latter cases, the effect of decreasing widening of shoulders could even be augmented (up to no need for widen shoulders), while in the simulation performed the AV line of sight was prudentially considered as comparable with the human sight.

4.4 Discussion about requirements for speeds applied to AVNRs

*Design speeds.*Setting design speeds for various elements in diverse contexts is crucial for the traditional road design. This is needed for both driver and comfort-based aspects.

The driver-based needs are taken into account in setting maximum design speeds for both high and low-speed roads (and minimum design speeds for low-speed roads). For AVNR design, there will be no need for setting maximum design speeds, since the AVs will likely govern the safety of their occupants, by autonomously setting speeds based on external inputs from the road and the other vehicles (I2V and V2V technologies).

Comfort-based concepts are considered in setting minimum design speeds for both high and low-speed roads. These concepts may still be considered as valid for AVNRs too. In fact, the presence of road elements which may excessively limit speed on the roads through their features (e.g. sharp curves) may cause discomfort. In particular, the traffic on main high-speed roads may be slowed down by sharp curves, eventually made possible in case of no restrictions on minimum design speeds. Hence, the presence of design speeds requirements could still be important while defining the minimum road standards that a given link should have, which are in turn based on speeds (e.g. minimum radius).

Operating speeds. The recommendations for limiting the difference between design and operating speeds will probably lose their function for AVNRs, since they are essentially driver-based. The concept of "operating speed" itself may be entirely modified: the travel speeds of different AVs in a road section may not follow a distribution characterized by a high variance. Conversely, speeds followed by different AVs in the same road section (under the same boundary conditions) may be very similar, since the same information about road geometry and other conditions may be available for all vehicles in the section.

Considering the design speed in a traditional way, one may say that in this case the operating speeds of AVs could be similar to the design speeds. However, as stated in the previous section, the interpretation of the design speed itself may change. Except from minimum design speeds, there may be no need for setting design speeds for different road elements. This is another reason for considering recommendations for limiting the difference between design and operating speeds as overcame for AVNR design.

Posted speeds. For the previously explained reasons, there will be no reasons for setting speed limits through traditional road signs on AVNRs. In fact, the safe speed may be autonomously selected by the AVs, and not by drivers as currently it is. However, the I2V technologies providing information to vehicles also concerning the safe speed to be followed, may be regarded as an evolution of the concept of posted speed sign, a sort of "digital posted speed". The fundamental difference is that there will be no reason for AVs to travel at speeds lower than the safe speeds automatically selected thanks to the information received, that is all AVs in a road section will likely travel at the same safe speeds. This will likely cause an increase in road capacity (see also Litman, 2018), which is strongly related to the average travel speeds and speed variance. In fact, driverless vehicles in the AVNR design may be considered as all road familiar drivers in the traditional road design (all AVs will be connected to the infrastructures and between them, sharing all the necessary information). This means that there will be no need to reduce design capacity values (TRB, 2010) for considering the presence of unfamiliar drivers and their interactions with the other vehicles (see e.g. Trubia et al., 2017).

On the other hand, the safe speed may vary on the same section according to the actual road conditions (not fixed as most of current speed limits). Hence, the concept itself of "speed limit" may be replaced by a dynamic "safe speed" followed by all AVs in a given section, not only depending on geometry and sight distance, but also on actual conditions.

4.5 Discussion about requirements for road friction applied to AVNRs

While in the traditional road design it is rather difficult to take into account all the possible interactions between road friction and all other road/vehicle characteristics, this could be easier for AVNR design. In fact, some technologies are able to estimate the road friction coefficient in real-time, by using torque measurements and/or simple GPS-based and accelerometers measurements (Hahn and Rajamani, 2002; Li et al., 2006; Grip et al., 2008; Rajamani et al., 2012; Choi et al., 2013; Li et al., 2015). Real-time tire-road friction estimation can be used for controlling the vehicle dynamics (e.g. Anti-lock Braking System), easier for electric ground vehicles (Chen and Wang, 2011; Wang et al., 2015).

This opportunity may be used for setting safe speeds also based on friction measurements (Colonna et al., 2018). In fact, safe speeds should be mainly determined for AVNRs according to sight distances and road friction, depending on a wide set of boundary conditions. An example of how safe speeds may be governed and set on AVNRs is represented in Fig. 7, related to a rural curve section:

- A central unit may store basic default information on traffic and road geometry;
- Sensors on the road infrastructure connected to the central unit will add information concerning current conditions (e.g. weather, water depth, etc.);
- A safe speed is determined by the central unit according to both default and actual conditions and shared with vehicles entering the section, through I2V connection;
- The vehicle entering the section will provide actual friction measurements on the road through its sensors, and communicate (V2I) these data to the central unit;
- The safe speed may be updated considering the actual friction measurements and shared with the following vehicles (I2V communication);
- The system will act as an iterative loop, considering also the potential redundancy provided by the V2V communication, having data shared between vehicles.

This simple example assumes independency between road sections, and that communications will be included within a limited area. However, vehicular and infrastructure data may be continuously shared among the network. The quantity and the distance of data sharing will depend on the technology advancement and the capacity to handle data, by simultaneously avoiding security issues.

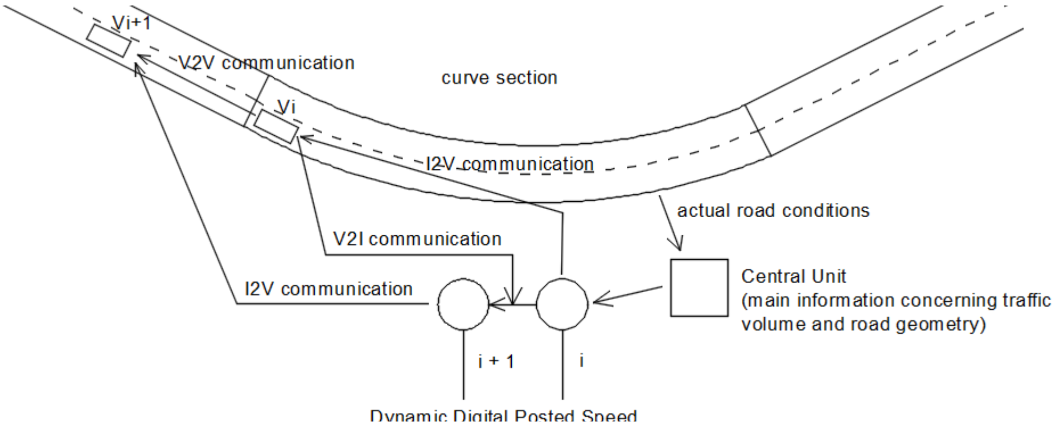

Figure 7: Infrastructure-vehicle communications for determining dynamic safe speeds

4.6 Discussion about requirements for cross-sectional elements applied to AVNRs

Cross-sectional elements will anyway depend on vehicle widths. A prevision concerning the dimensions of AVs in the future is hard to be made. If their widths are assumed similar to nowadays (e.g. up to 2.60 m), lanes should still have a minimum width of around 3 m. However, as the guidance system will be driverless, this requirement should be mainly dedicated to ensure the sufficient space for the safe transit of AVs. On the other hand, there will be no more reasons to consider driver-based concepts (i.e. lane width ≥ 11-12 feet, or 3.3-3.6 m, for safety reasons). At least one lane among the total lanes in the cross section could have a larger size than the minimum of 3 m, to host public transport or any large vehicle. In the early stages of automation, it is likely that, especially in urban environments, automated transport (e.g. public transport) could travel together with traditional vehicles. In these cases, travel lanes can be physically separated (e.g. for automated transit, see e.g. the CityMobil EU project: http://www.citymobil-project.eu/).

Shoulders may still be needed for emergency recovery purposes also for AVNRs, even if for cases different than lane departure due to errors or distraction. However, for this latter reason, it is likely that shoulder width (in standard cross-sections) could be reduced, so that the AV which encounter a failure could stop in emergency stopping bays, located with given spacing along the routes (such as in the current scenario). Moreover, the current needs and prescriptions for road barriers should be updated in case of AVNRs, due to the discussed changes in the role of speeds, skidding risk, and human-based risks.

Given the discussion reported above (for reducing lanes and shoulders), the total road width could be likely reduced for AVNRs (in case of same total lanes) than in case of traditional roads. This isgenerally positive, among the other reasons, for saving land.

5 Concluding remarks

In this article, the main International road design requirements were reviewed and classified, according to their main reasons: human, physics, comfort-based (see Table 1).

The applicability of those requirements for a future scenario of AVNR design was discussed. In particular, it is evident that human-based requirements could drastically change in case of roads traveled by AVs, while other requirements could still be valid. The main conclusions from this study, based on the discussion, are drawn as follows.

AVNR design may require more relaxed prescriptionsfor the design of alignments, the speeds and the sight distance than the current practice. The most evident human-based requirements which may be not more necessary in case of AVNR design concern:

- Road design consistency (between horizontal and vertical alignments);
- Check of differences between design, operating and posted speeds (posted speeds could even be not more needed as they are in the current form).

Significant changes to the current prescriptions were highlighted through the results of the simulations run in case of 1) not considering coordination requirements between horizontal and vertical curves, 2) considering the effect of reduced perception/reaction times on the widening of shoulders for visibility reasons. These less severe prescriptionsmay have a positive impact on environmental issues especially for low-speed roads, in which roads may fit closer the terrain than nowadays, e.g. by avoiding excessive excavations and/or embankments.Moreover, other specific aspects which may significantly change are related to the tangent and curve lengths, which are mainly set according to human-based remarks. Some minor changes were discussed for cross-sectional elements (e.g. reducing lane widths), and the conception of design speeds.

On the other hand, the essentially physics-based design elements, such as the design of curves (minimum radii and super-elevation), grades, the role of road friction, the sight distance requirements based on road geometry, the need for transition curves and emergency spaces (shoulders/bays), should still be considered for the AVNR design.

The comfort-based requirements are instead still valid in case of AVNR design, as humans will suffer anyway from phenomena such as excessive accelerations (vertical and lateral), excessively low speeds, sharp curves on high-speed roads, high uphill slopes. Hence, those aspects should still be considered.

However, it should be noted that this study was limited to the aspects of rural design, which is a still largely unexplored field in the research about vehicle automation. It could be surely useful to enlarge the present study to the urban environment, by reviewing issues and differences potentially arising in the shift of roads towards automation, which represents an (immediate) future challenge for all the stakeholders involved.

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