HOW TO INCORPORATE AUTOMATED VEHICLES ON ROAD SAFETY AUDITS

Francisco Javier Camacho Torregrosa
Profesor Contratado Doctor, GIIC, Universitat Politècnica de València, España
Alfredo García
Catedrático, Grupo de Investigación en Ingeniería de Carreteras (GIIC), Universitat Politècnica de València, España
David Llopis Castelló
Profesor Ayudante Doctor, GIIC, Universitat Politècnica de València, España

ABSTRACT

Road Safety Audit (RSA) has proved to be one of the best road safety management procedures for design, construction, and maintenance of existing and new road infrastructure. At the beginning, the safety review only focused on motor vehicles and the human driver. Later, as well as nowadays, procedures are also applied to the needs for all vulnerable road users, taking into account that each of the groups (pedestrians, cyclists, motorcyclists) has its own specific requirements.

The new and better capabilities of automated vehicles should be in accordance to road technical features, such as geometry, sight distance, signs, and markings. However, the corresponding standards were developed for human driving, and therefore they must be adapted to the new systems without losing compatibility with lower automation levels. While considerable research effort has been carried out for the digital infrastructure, only some studies have been carried out for the physical one with interesting findings that deserve to be incorporated into RSA procedures, such as: new available and required stopping sight distance; new automated speed as the maximum speed that allows the automated system to maintain the longitudinal and lateral control; readable road markings and road signs to facilitate recognition by both human drivers and connected and automated vehicles; etc. The main objective is to achieve the optimal performance of Advanced Driver Assistance Systems (ADAS).

The main result of this study is a first proposal for a new chapter to be included in the checklists to carry out road safety audits for the different stages and road safety inspections.

1. INTRODUCTION

Road Safety Audit (RSA) has proved to be one of the best road safety assessment procedures for design, construction, and maintenance of existing and new road infrastructure. At the beginning, the safety review only focused on motor vehicles and the human driver.

Later, as well as nowadays, procedures are also applied to the needs for all Vulnerable Road Users (VRUs), considering that each of the groups (pedestrians, cyclists, and motorcyclists) has its own specific requirements.

The Directive 2008/96/EC of the European Parliament and of the Council on road infrastructure safety management (European Parliament, 2008) established the implementation of procedures related to Road Safety Audit (RSA) and Road Safety Inspection (RSI), being mandatory in the trans-European road network at the design stage, under construction or in operation.

A RSA should be carried out for all infrastructure projects, forming an integral part of the design process of the infrastructure project at the stages of: preliminary design; detailed design; pre-opening; and, early operation; following certain criteria for every stage. A certified auditor is appointed to carry out an audit of the design characteristics of an infrastructure project.

A RSI is a formal systematic and periodic road safety assessment of an existing road or road scheme, performed by an independent, qualified inspector or team of inspectors, who report on the existing road accident potential for all kinds of road users (VRUs included), identify traffic hazards related to the road environment characteristics (elements and locations to be improved), and propose measures to mitigate the detected hazards, mainly focused or described as maintenance work.

Both RSA and RSI are considered preventive tools because their application to an itinerary or road section does not require researching on their crash record. There are many checklists available for RSA/RSI. These checklists include several families of elements, such as: Road function; Alignment; Junction; Traffic signing, marking, and lighting; Roadside features; Bridge; Tunnel; Pavement; RS; Public and private service; Traffic operation; Cross-town road; Work zone. However, checklists cannot substitute the experience and expertise of road safety auditors, so the checklists should be used just a reminder of which aspects should be reviewed. There are other limitations, such as that most questions are related to a whole road segment, without any specific spatial and/or temporal focus. Another weakness might be due to the accuracy of answers (Yes/No may be for both Safe/Risk indistinctly).

New Amending EU Directive 2008/96/EC on Road Infrastructure Safety Management (European Parliament, 2019a) extends the scope to motorways and other primary roads beyond the trans-European transport network (TEN-T), including a new network-wide road safety assessment and a more targeted road safety inspection. Moreover, there will be new procedures aiming at ensuring the operational use of road markings and signs, common specifications should be established in order to foster the effective readability and detectability of road signs and marking for human drivers and automated driver assistance systems.

However, the new Directive does not include the automated vehicles as a new point of reference for carrying out the procedures for RSA and RSI.

The Society of Automotive Engineers identifies six levels of automated driving:

- 0 – no automation
- 1 – driver assistance
- 2 – partial automation
- 3 – conditional automation
- 4 – high automation
- 5 – full automation (SAE, 2016).

Every level is defined as the minimum capabilities that the system must fulfill, so a vehicle might present different driving automation levels depending on the environment.

There are vehicles in the current market that reach level 2, and even level 3 under very controlled conditions such as a high-end geometric alignments and road markings. A level 2 driving automation system can negotiate speed and lateral position under controlled circumstances. If the system is unable to process certain information (e.g. sharp horizontal curve or crest vertical curve), it transfers control to the driver – often, with a minimal or inexistent warning – in a disengagement event. Conversely, a level 3 driving automation system is able to negotiate more complex situations, so the system is expected to fail on fewer locations. In this case, the system is even expected to predict this failure in advance, transferring control to the driver in a Take Over Request (TOR) event. While level 3 presents a more complex performance, the time required for the driver to resume control is often beyond driver’s abilities, being reported as unsafe by many experts. In fact, there are many international efforts in reaching level 4 as soon as possible. Level 4 ensures performance without any need of human intervention under certain circumstances involving infrastructure, traffic, and environment. The different combinations of these circumstances are called Operational Design Domains (ODDs).

The new and better capabilities of automated vehicles should be in accordance to road technical features, such as geometry, sight distance, signs, and markings. However, the corresponding standards were developed for human driving, and therefore they must be adapted to the new systems without losing compatibility with lower automation levels.

Current semi-autonomous vehicles are equipped with a variety of sensors, including video cameras for environment identification (road markings, signs, vehicles, pedestrians, etc.) and radar for obstacle detection. Cameras are the basis for Lane Keeping Assist (LKA), and radars are the basis for the Adaptative Cruise Control (ACC) and emergency braking.

These devices aim at substituting human sight, but their location differs from driver's eyes (and also among vehicles), which impacts on how sight distance should be calculated and checked. The new semi-autonomous vehicles should be included for carrying out RSA and RSI as a new point of view for their different sensors (radar, cameras, etc.).

There are other limitations for existing semi-autonomous vehicles. Some studies have recently focused on identifying the limitations of autonomous vehicles regarding line marking and road signs (Austroads, 2019; US TRB, 2018; EuroRAP and EuroNCAP, 2018).

These studies revealed that the quality, position, and consistency of line markings and traffic signs are critical to the performance of automated driving and driver assistance functions. Likewise, it is recommended to use line widths between 100 and 150 mm, a maximum lane width of 4.50 m, and a minimum road marking retroreflection of 150 mcd/lux/m2.

Other studies have explored the limitations of AVs related to road geometry (García, 2017; García et al., 2019; García and Camacho-Torregrosa, 2019; García and Camacho-Torregrosa, 2020). They found that there are still many limitations associated to horizontal and vertical alignment, as well as cross-section and road markings to ensure an adequate performance of semi-autonomous vehicles.

Finally, the coexistence of AVs with non-automated vehicles and other users leads to a complex mixed traffic scenario. The European Parliament resolution of January 15th, 2019 on autonomous driving in European transport (European Parliament, 2019b) highlighted the necessity of incorporating safeguard systems right for this transition phase; stressing the importance of driver assistance systems as a step towards fully automated driving, even now to prevent road crashes by means of active safety systems or reduce the severity of accidents by means of passive safety systems.

2. OBJECTIVES

The main objective of this study is to highlight previous findings on how AVs are constrained by road infrastructure (horizontal and vertical alignment, cross-section, road marking continuity, and pavement condition), by analyzing when AVs might disengage and transfer control to drivers. Based on these findings, new questions will be proposed to be included in Road Safety Audit and Inspection checklists.

However, this paper does not intend to define specific thresholds to be considered in AV-RSA's, but to stablish a framework on which parts of road infrastructure should be compared to the performance of existing and oncoming vehicles.

3. ROAD INFRASTRUCTURE AND LOW-AUTOMATED VEHICLES

Although each car manufacturer equips different sensors and programs its own Active Cruise Control (ACC) and Lane Keeping Assist (LKA), the technical features of their sensors and CPU are similar because they share parts suppliers.

Therefore, the differences in vehicle performance are minimum. Based on this hypothesis, the authors decided to use a BMW 520d from 2017, equipped with the "Driving Assistant Plus" package, which gives it a level 2 of automation, as the car that can properly represent most of semi-autonomous vehicles on our road networks.

The vehicle was driven by a single driver along a total of 3,000 km in the Region of Valencia (Spain). Once both ACC and LKA systems have been activated, which requires the selection of the cruising speed, the car takes control of the accelerator, brakes, and steering wheel, being able to keep the vehicle within the lane as a result of the detection of road markings through two video cameras located in the interior rear-view mirror.

If the system cannot process the gathered information by the cameras, the system transfers control of the vehicle to the driver showing a warning message on the dashboard, without any acoustic signal. The driver is also asked to be in permanent contact with the steering wheel so as to take over control, if needed.

The vehicle performance was recorded through a Garmin Virb Elite HD video camera, which was placed next to the driver's head. The resulting video recordings included road, navigation system, dashboard, and comments of the driver and passengers. To prevent bias, all tests were carried out in daylight conditions, dry pavement surface, and road markings in good condition.

Traffic volume and operation might influence the performance of the assistance systems. However, a Road Safety Audit aims at detecting safety issues regarding road design, so it should be developed to identify the limitations of autonomous vehicles operating under free flow conditions. To allow reaching a reasonable operating speed, the data used in the following studies were collected during non-peak hours.

The horizontal alignment of the road sections was recreated by means of the procedure proposed by Camacho-Torregrosa et al. (2015), whereas the vertical alignment was extracted through Autodesk Civil 3D using LIDAR data provided by the National Plan for Aerial Orthophotography (PNOA, 2016).

3.1 Horizontal curves

This part of the study aimed at analyzing the capacity of the road infrastructure to host semi-autonomous driving systems on isolated horizontal curves (García, 2017). Particularly, the maximum speed at which a semi-autonomous vehicle can travel along this type of road element was identified for each studied horizontal curve.

A total of 132 isolated horizontal curves were considered in the analysis, which were located in motorways, freeways, multilane highways, and two-lane rural roads. Among different geometric features (radius, deflection angle, length, and Curvature Change Rate), the radius resulted in the most influential variable in the studied phenomenon. Specifically, the radii of the observed horizontal curves varied from 172 m to 3,858 m, with an average of 858.8 m.

The automated speed (Va), which was defined as the maximum speed at which the semi-autonomous vehicle was able to perform automatically, was identified for each horizontal curve by traveling along them at different speeds. This way, if the speed is greater than Va, the system is not able to process the gathered information and transfers the lateral control of the vehicle to the driver. It should be noted that Va could not be determined for those horizontal curves presenting a radius lower than 172 m.

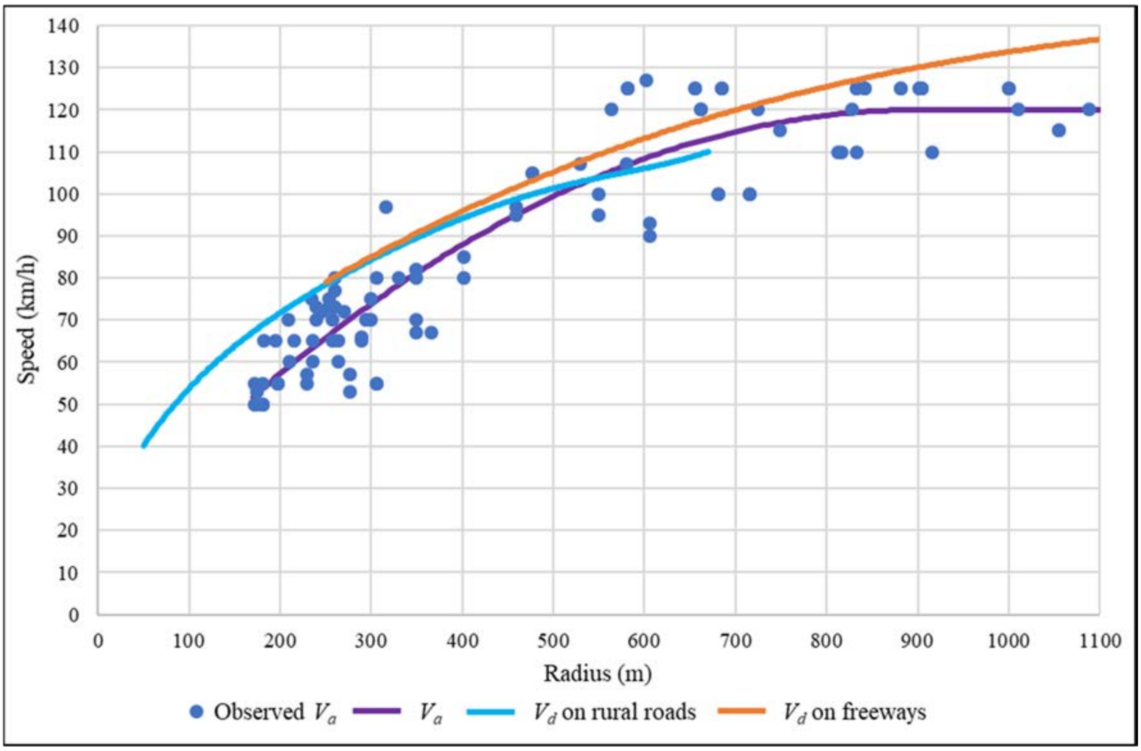

Figure 1: Relationship between the automated speed and the radius of the horizontal curve.

Figure 1 shows the relationship between the radius (R) and the automated (Va) and design (Vd) speeds for each horizontal curve. As expected, the automated speed increases with the radius.

In addition, the automated speed was only greater than the design speed for a few horizontal curves, so an automated driving performance, from the point of view of the road design, is not currently possible mainly along horizontal curves with a radius lower than 500 m.

3.2 Crest vertical curves

Another critical issue related to the automated driving performance of semi-autonomous vehicles is the influence of the vertical alignment. Thus, the objective of this part of the research was to examine the automated driving experience along 42 vertical crest curves overlapped with tangent sections, thus avoiding the influence of the horizontal alignment (García et al., 2019).

It should be noted that the driver tried to go along all studied crest vertical curves at its posted speed limit, but in some cases the operating speed was lower. The K values of these vertical curves ranged between 2.7 m/% and 65.5 m/%, whereas the algebraic difference in grades (A) varied from 0.36% to 11.85%. As a result, 18 of the studied crest vertical curves required the driver to take control of the vehicle. According to the Green Book (AASHTO, 2018), the vertical curve parameter (K) defines its sharpness (Figure 2). It is calculated as the ratio between its length (L) and the algebraic difference in grades (A). Given a parameter K, the stopping sight distance (SSD) can be calculated as follows (Figure 2, top right):

$$SSD = \sqrt{(L/A \cdot 100 \cdot (\sqrt{2 \cdot h_1} + \sqrt{2 \cdot h_2})^2)} \qquad (1)$$

where:

- SSD is the Stopping Sight Distance (m); L is the length of the vertical curve (m)
- A is the algebraic difference in grades (%)
- h1 is the height of eye above roadway (1.08 m)
- h2 is the height of object onto the roadway surface (0.60 m).

This expression is only valid when SSD is lower than L.

This SSD can be tagged as available SSD (i.e. SSD_A), since it represents the road length that can be seen for a certain crest vertical curve design.

In addition, a biunivocal correspondence exists between design speed (Vd) and SSD. For a given design speed, SSD can be determined using Equation 2, which is divided into two terms:

- driver perception-reaction distance (dPRT)
- braking distance (dMT) (Figure 2, top left).

$$SSD = d_{PRT} + d_{MT} = 0.278 \cdot V_d \cdot t + 0.039 \cdot V_d^2/a \tag{2}$$

where Vd is the design speed (km/h); t is the perception-reaction time (2.5 s); and a is the deceleration rate (3.4 m/s2).

This is the required SSD (i.e. SSD_R), since it indicates which is the minimum length needed to stop the vehicle, driving at a certain speed. The Green Book assumes that vehicles are performing at the design speed, so $SSD_R \leq SSD_A$ indicates an adequate design, from this perspective.

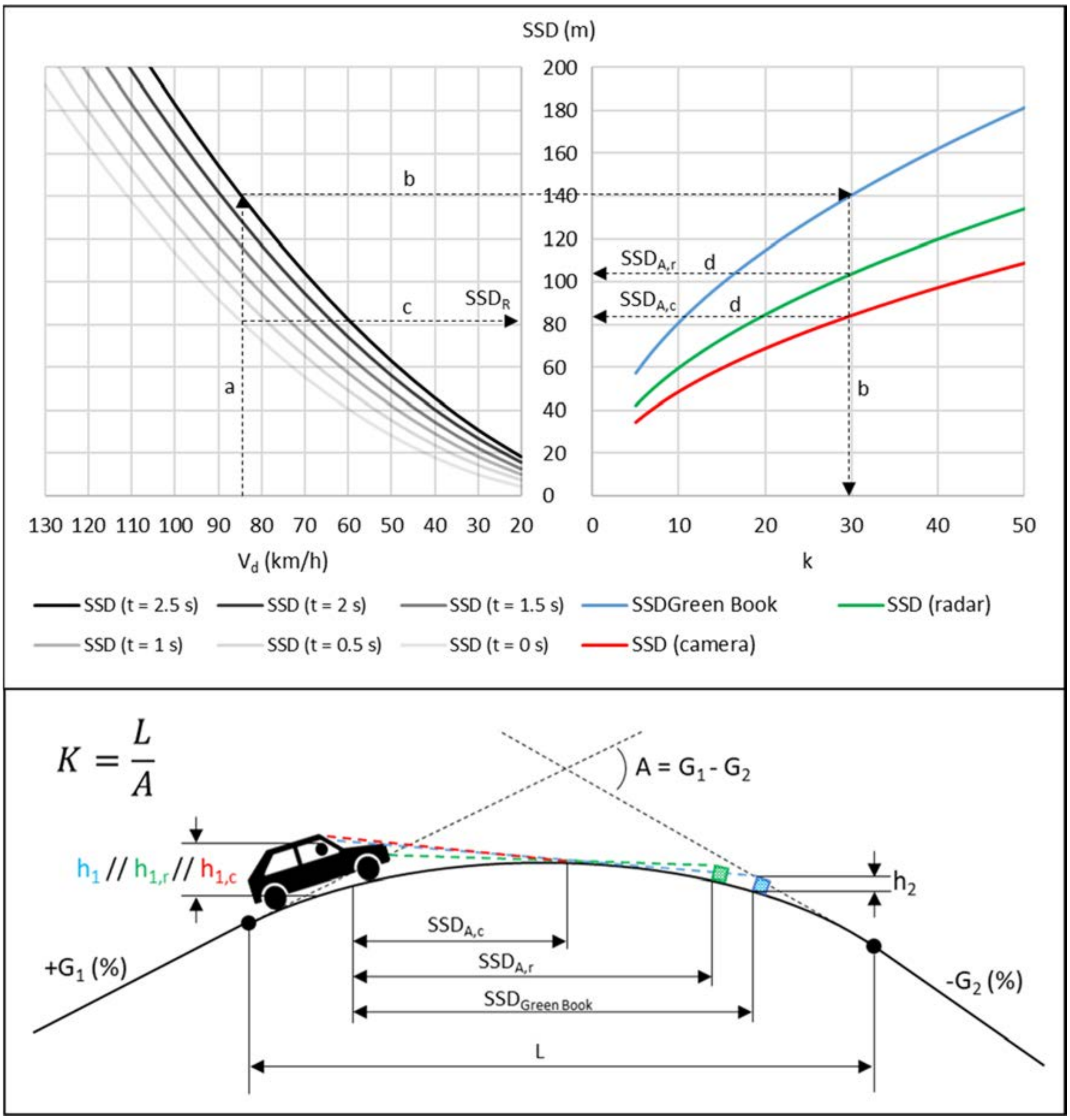

Figure 2: Relationship between SSD, K, and V_d. Left side: relationship between required SSD and design speed (reversed horizontal axis). Right side: relationship between available stopping sight distance and vertical curve parameter K.

The AASHTO Green Book assumes specific values for SSD, but these values must be changed for the devices equipped in the semi-autonomous vehicle: video camera and radar. Therefore, $SSD_{A,r}$ is the available sight distance for the radar, and $SSD_{A,c}$ for the video camera (Figure 2, top right).

The video cameras are usually located in the interior rear-view mirror and are responsible for lane keeping, so h1 can vary from 1 m (passenger cars) to more than 2 m (heavy vehicles), while h2 is 0 m (road markings). On the other hand, the radar is usually placed in the bumper and aims at detecting objects on the carriageway, so h1 ranges from 0.25 to 0.45 m and h2 is 0.60 m according to the Green Book (AASHTO, 2018).

On the other hand, perception and reaction time also changes with these automated systems. This new required distance (SSDR) will be determined considering perception-reaction times ranging from 0 to 2.5 s, since current autonomous vehicle manufactures do not provide the lag that these devices require to process the information and take a decision.

Again, a curve is well designed if the required SSD is lower than the available one for both systems, i.e.: $SSD_R \leq SSD_{A,r}$ and $SSD_R \leq SSD_{A,c}$ (lines c and d in Figure 2). All curves are assumed to be designed according to standards, so $SSD_R \leq SSD_A$ is always true.

As an example, the SSDR for 85 km/h design speed is 140 m (Figure 2: a). According to the Green Book, the minimum parameter K that allows this sight distance is 30 m/% (Figure 2: b). Assuming that the vehicle can perform automatically (i.e., perception-reaction time = 0 s), the SSDR would decrease up to 80 m (Figure 2: c). Likewise, the $SSD_{A,r}$ and $SSD_{A,c}$ would be approximately 105 and 85 m, respectively (Figure 2: d). Therefore, the vertical curve might be travelled in an autonomous way.

However, vehicles need a period of time to gather and process the information, so the success of the system mainly depends on how quick the vehicle system can operate. In the previous example, if the perception-reaction time required by the vehicle is 1.0 s, the driving experience would be manual.

It was hypothesized that the system might shift from automatic to manual in case of having insufficient time to process all information originating from the video camera. Thus, a new parameter called Available Processing Time (APT) was defined as the ratio between the available sight distance for the video cameras (SSDA,c) and the operating speed during the observation.

Figure 3 depicts the relationship between K and APT. First of all, it can be observed that the system tends to transfer the lateral control of the vehicle for K values lower than 20-30 m/%, which is usually associated to a big grade differential.

In addition, those crest vertical curves which required human intervention presented APT values lower than 3 s, whereas the minimum APT associated to an automated driving experience was 2.5 s.

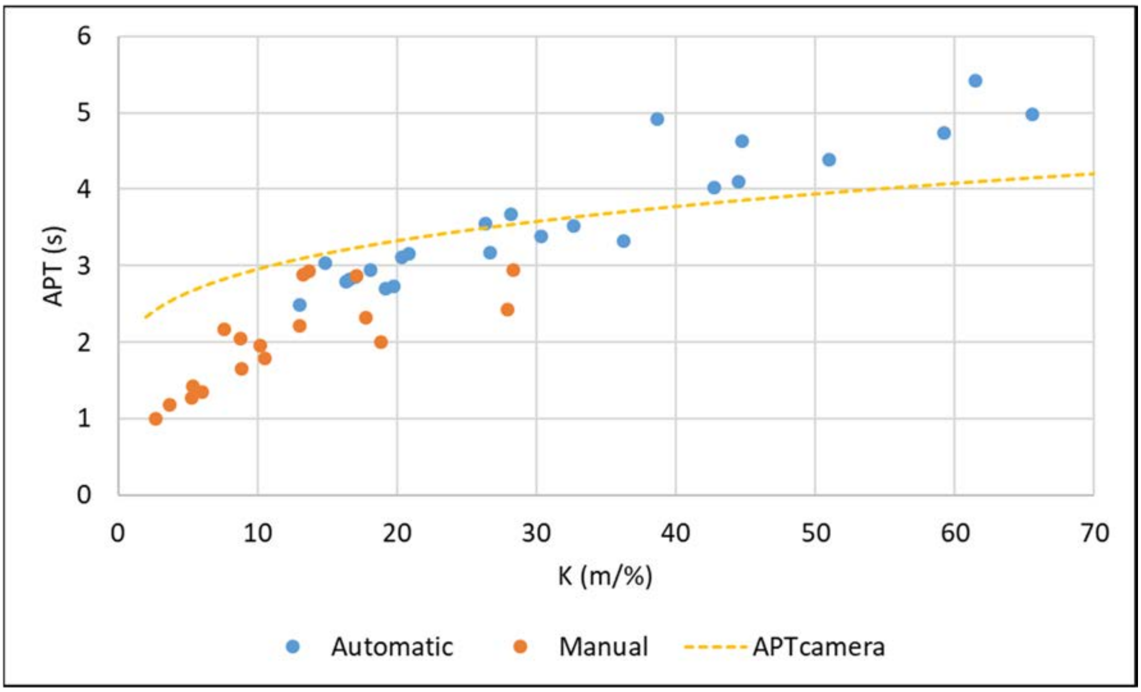

Figure 3: Relationship between *K* and *APT* depending on driving experience.

Therefore, the system needs more than 2.5 s to process the gathered information and take a decision. This processing time includes video recording, algorithms processing, and the time needed to control the vehicle. This *APT* was determined driving at the speed limit (or slightly lower, if posted speed could not be reached).

Figure 3 also shows the theoretical available processing time if the driver travelled at the design speed (dashed yellow line). As can be seen in Figure 4, operating/posted speeds are normally higher than the design speed on sharp crest vertical curves (thus leading to lower APT). Conversely, operating/posted speeds are generally lower than the design speed for smooth crest vertical curves, hence producing higher *APT* than the design-based and enabling more time to process the information and take a decision.

In this case, the automated speed (Va) is estimated as the ratio between the available stopping sight distance for the cameras (SSDA,c) and the minimum available processing time (APTmin). Figure 4 depicts the relationship between the operating speed and the vertical curve parameter (K) for the studied crest vertical curves. Likewise, thresholds for an automated speed considering APTmin equal to 2.5 and 3.0 s (dashed red lines) as well as the curve associated to the design speed (blue line) have been plotted. Additionally, the dashed green lines represent the automated speed for lower APTmin. Therefore, the automatic speed model will be located between both dashed red lines.

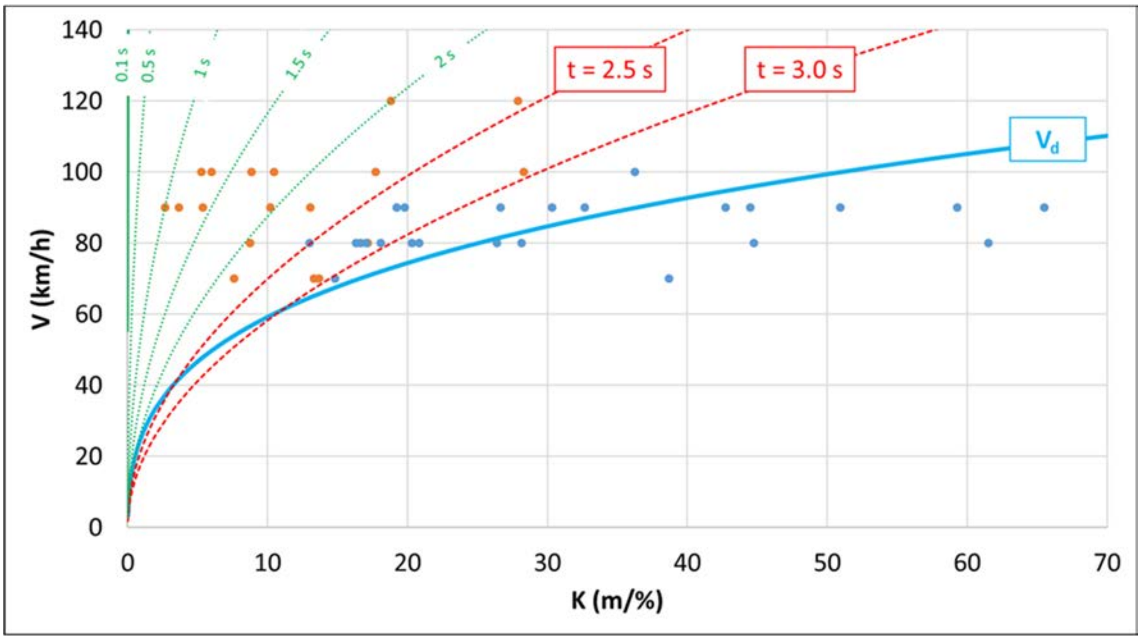

Figure 4: Relationship between the automated speed and the vertical crest curve parameter.

3.3 Lane width

In addition to the horizontal and vertical alignment, the characteristics of the cross-section, mainly lane width, have a great impact on the automated driving performance of semi-autonomous vehicles. To study the influence of this geometric feature on the automatic lane keeping system, an experimental field data collection was performed in an urban environment using the semi-autonomous vehicle described above (García and Camacho-Torregrosa, 2020).

Given that most narrow lane widths are associated with low-speed and urban roads, the data collection was carried out travelling at 50 km/h which is the usual speed limit along these roads. In addition, the use of a constant speed avoided introducing the influence of the speed on the phenomenon.

A total of 12 arterial tangent sections, belonging to a 5.4 km long urban arterial ring road in Valencia (Spain), were selected to be analyzed. This urban road is bi-directional, with several lanes with diverse lane widths, ranging between 2.28 and 3.80 m, with an average value of 2.70 m. The total number of studied lanes was 81 and the minimum number of passes along each lane was 10.

To study the influence of lane width on the automated driving performance, two parameters were defined: the automatic lateral control rate and the manual lateral control rate. The first one was calculated as the ratio between the observed number of passes in an automatic way and the total number of passes, whereas the second one was the number of passes in a manual way divided by the total number of passes.

Figure 5 clusters these rates in 5 cm intervals. As expected, the automatic lateral control rate increases with lane width and, on the contrary, the manual lateral control rate decreases as the lane width is greater. Specifically, the system was always able to perform in an automatic way for lanes wider than 2.75 m, whereas a lane width lower than 2.5 m always led to a manual driving. Additionally, a critical lane width can be estimated as the intersection of both driving performances, determining the same probability for manual and automatic lateral control at a width of 2.72 m.

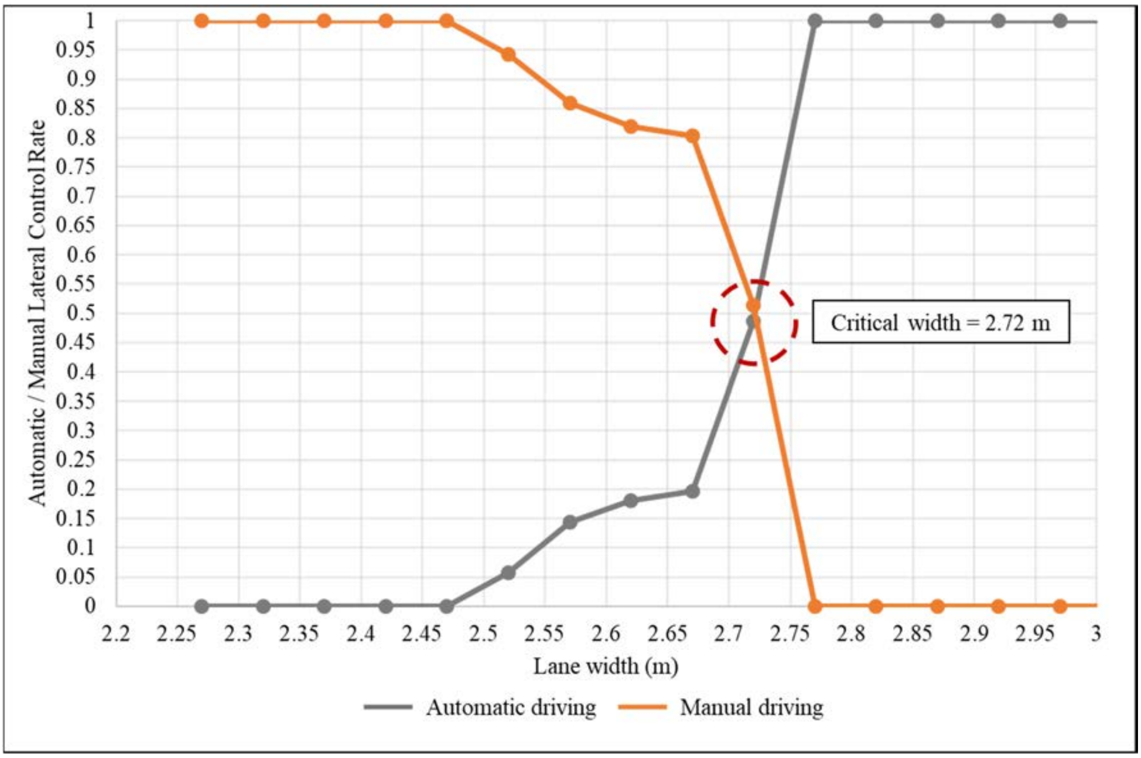

Figure 5: Influence of lane width on driving experience.

Taking into account the observed automatic lane width and the width of the experimental vehicle, the tested vehicle needs a free lateral space of 0.44 m. Since the study only focused on the observed disengagement events and not on the underlying causes, more insight is needed to determine the potential consequences on driving safety and performance. If this limitation arises from the capability of the system to process the visual information, similar limitations for other vehicle types are expected

Conversely, if the remaining lateral space is needed for vehicle maneuvering, it might imply a serious limitation to heavy vehicles, since the minimum width to support automation with current technology is inferred to 3.43-3.48 m. Moreover, these findings clearly define 2.50 m to 2.75 m as an Operational Design Domain threshold, which is not compatible with most low volume roads and some urban environments.

These findings can be complemented with those obtained by Austroads (2019). To this regard, the maximum lane width that allows an automated driving is 4.50 m.

This threshold was established by analyzing autonomous vehicle performance on 25,000 km of different road types in Australia and New Zealand.

3.4 Road marking

When comparing technical capabilities of autonomous vehicles with road infrastructure, a common thought is that signals in good condition establishes an adequate operational domain for semi-autonomous vehicles. Special mention deserves road markings, which are expected to have a good visibility and contrast. However, there might be some cases in which a good infrastructure with good road markings is not enough for semi-autonomous driving (García and Camacho-Torregrosa, 2019).

Thus, this research examines the system capability of the above mentioned semi-autonomous vehicle along different road marking configurations in 25 km of freeway. Particularly, the driving experience was studied on 25 exit ramps and 27 entrance ramps so as to determine the impact of the marking gap, i.e., the absence of the edge road marking at the beginning of the exit ramp and at the end of the entrance ramp. To this regard, Spanish regulations for road markings establish that the broken extension line must begin or finish when the acceleration or deceleration lane becomes 1.5 m wide. This results in a zone with a gap or edge line discontinuity. Its length depends on the cotangent of the corresponding taper. These assumptions are correct as long as the road marking was adequately set up.

At the studied locations, information on the station, ramp type (entrance/exit), existing gap (yes/no), width of the acceleration and deceleration lane (m), horizontal alignment (left curve/right curve/tangent), vertical alignment (upgrade/downgrade/crest curve/sag curve), and driving experience (manual/automatic) was collected. It should be noted that the semi-autonomous vehicle travelled at the speed limit, which was 120 km/h at most locations, and always located on the right lane.

Then, the automatic and manual lateral control rates were calculated for both exit and entrance ramps (Figure 6). As a result, 32% of the exit ramps and 19% of the entrance ramps led to a transference of the lateral control of the vehicle to the driver. In this way, it seems that the analyzed semi-autonomous system is more sensitive to exit ramps, since the lateral control is transferred at a greater frequency.

Similarly, most lane-reductions or additions also caused the system to fail. As said above, this is mainly due to the gap with no channelizing lines that the Spanish guidelines set for these sections. For these configurations, a longer discontinuity of the edge line exists.

Another observed issue was related to road-splits and road merging sections. If the sum of the lanes at the separated sections differ from the merged one, a large zone without any road marking appears, thus impeding any guidance by the semi-autonomous system.

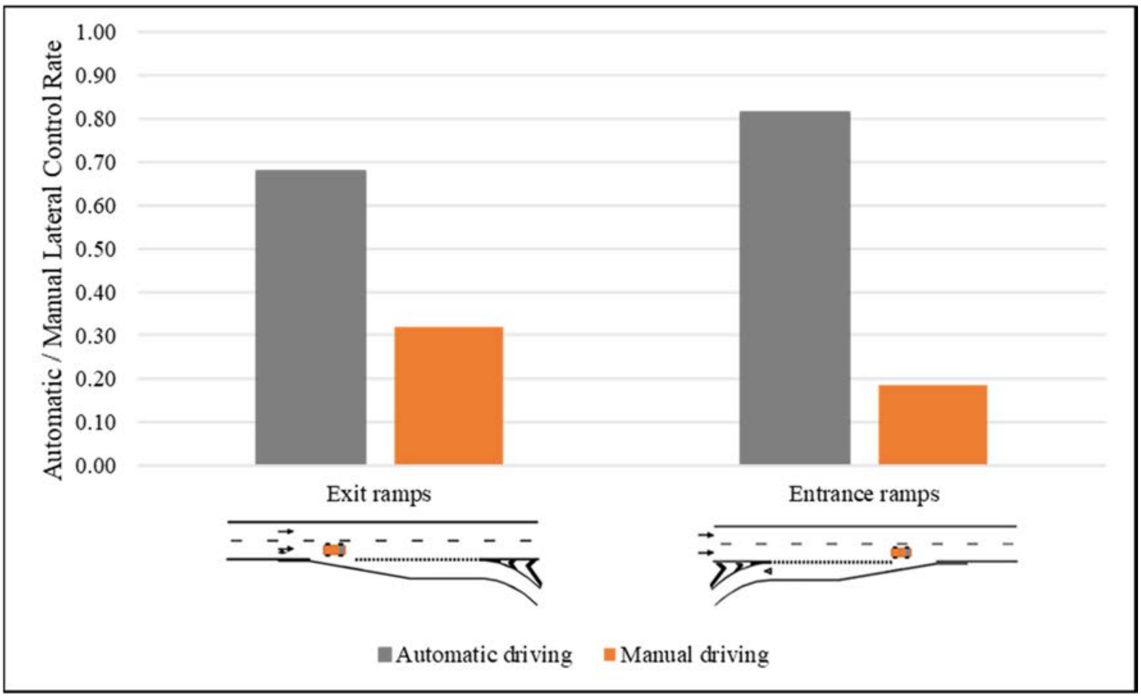

Figure 6: Influence of road markings on driving experience.

3.5 Pavement

In addition to the geometric design and road markings, another important factor affecting the effectiveness of the system of semi-autonomous vehicles is the road surface. As a result of the data collection described in the previous sections, some issues related to the condition of the pavement were also identified.

It was observed that the system often transferred the vehicle control to the driver when the pavement presented longitudinal cracking sealing along East-West sections. Regarding this, the reflection of the sun on this type of surfaces led to confusion to the vehicle system, which could not properly identify the lane markings.

Another feature of the pavement that showed a substantive influence on the performance of semi-autonomous vehicles was the road surface evenness. Particularly, those road segments with sharp unevenness caused a manual driving performance, so road maintenance is becoming more important as the number of automated vehicles increases.

Finally, a special mention should be given to work zones. Although these type of road sections have not been studied yet, they usually present a lack or deficiency of road markings, which will most likely result in the failure of the vehicle system leading to a manual driving performance.

4. NEW CRITERIA FOR ROAD SAFETY AUDITS

In view of these findings, some new criteria have been defined for both Road Safety Audit (RSA) and Road Safety Inspection (RSI), to determine whether a road segment is compatible with existing AVs.

Regarding RSA, the following criteria should be incorporated:

- minimum radius of horizontal curves (Rmin)
- minimum K-value of crest vertical curves (Kmin)
- minimum lane width (wmin)
- continuity of edge road markings.

On the other hand, the following issues should be taken into account in Road Safety Inspection:

- road marking performance, referred to visibility
- cracking sealing
- unevenness
- temporary road marking and pre-marking.

Taking into account that the current automated vehicles reach automation levels 2 or 3, the following thresholds to minimize disengagements are defined:

- Rmin = 500 m.
- Kmin = 30 m/%.
- wmin = 2.75 m.
- wmax = 4.50 m.

According to these geometric thresholds, it is expected that the existing Spanish motorways with a design speed greater than 100 km/h allow an automated driving to the current semi-autonomous vehicles.

Finally, Table 1 shows some questions that should be included in RSA and RSI checklists. These questions are preferred to be included in a new chapter or block of questions, which is proposed to be called “Autonomous driving performance”.

Based on the outcomes of this chapter, the capability of the road to hold autonomous vehicles might be determined. It should be noted that question block 4 only applied to existing roads, i.e., for RSI.

Issue	Yes	No	Comment
1. Horizontal and vertical alignment			
1.1 Does the road alignment have: • horizontal curves with a radius lower than 500 m? • crest vertical curves with a *K* parameter lower than 30 m/%?			
1.2 Is the curvature profile continuous?			
1.2 Is the automated speed lower than the design speed at: • horizontal curves? • crest vertical curves?			
2. Cross-section			
2.1 Is the width of traffic lanes constant?			
2.2 Is the lane width between 2.75 m and 4.50 m?			
3. Road markings			
3.1 Are edge line road markings continuous on: • entrance ramps? • exit ramps? • intersections? • transition sections?			
3.2 Is there any gap on: • entrance ramps (m) • exit ramps (m) • intersections (m) • transition sections (m)			
3.2 Are road markings in good condition?			
4. Pavement condition			
4.1 Does the pavement have cracking sealing?			
4.2 Does the road section consist of an uneven pavement?			
4.3 Are there any temporary road marking or pre-marking along the road?			

Table 1: Questions to be included in RSA and RSI.

Additionally, Table 1 should be complemented with the questions proposed by Austroads (2019) regarding line marking and road signs. Among all these questions, it should be highlighted those presented in Table 2.

Issue	Yes	No	Comment
1. Line marking			
1.1 Are the following lines present? • Left edge • Lane dividing line/s • Right edge • Centerline			
1.2 Are line widths nearing 150 mm, no narrower than 100 mm?			
1.3 Line contrast with surrounding roadway, • As relevant to machine vision during dry daytime conditions? • As relevant to machine vision during wet daytime conditions? • As relevant to machine vision during dry night-time conditions? • As relevant to machine vision during wet night-time conditions?			
2. Road signs			
2.1 Are there: • Static speed limits? • Electronic speed limits?			
2.2 Are road signs of good readability in daytime?			
2.3 Are road signs of good retro-reflectivity in night-time?			
2.4 Are road signs in their expected position?			
2.5 Are road signs obscured?			

Table 2: Questions for RSA and RSI proposed by Austroads (2019).

5. DISCUSSION

Fully automated vehicles (SAE level 5) will ensure an automated experience to their passengers, without the need to take control of the vehicle from any infrastructural condition. This technology is far from being reached, so existing technology is only able to produce partial automated experience. An adequate automated experience should ideally comply with:

- safe, meaning that no disengagements are produced without previous awareness or request to the driver
- reliable, meaning that the driving automation system is able to provide valuable information on how well it is performing (or whether a Take Over Request (TOR) is expected
- comfort, i.e. the frequency of disengagements/TOR should not be so high that drivers preferred to disconnect the system.

Comfortable speed and speed transitions should be met as well. Road infrastructure – combined with vehicle technology – can act on safety and comfort, while reliability can only be addressed with vehicle technology.

Therefore, a RSA/RSI including automated vehicles should explore how safe and comfortable is automation along a road segment, which can be done by analyzing how and how frequent disengagements are produced. A road segment whose geometry ensures performance without any disengagement, combined with adequate environmental conditions, defines an Operational Design Domain (ODD) able to support SAE level 4, which would be extremely safe and comfortable. On the contrary, a road segment with very frequent disengagements is not comfortable, but it would probably be safe from a driving automation perspective. This is because too many disengagements would discourage drivers from connecting the system thus staying in manual driving.

The worst scenario is, in fact, a road segment that causes a low number of disengagements. In this case, drivers might be willing to use the driving automation system, which will probably lead to distractions while the vehicle is performing the driving task (level 3). This increases perception-reaction time, which would be critical in case a disengagement/TOR arrives.

This research, beyond proposing specific thresholds which might be influenced by the vehicle used, aims at identifying the geometric-related aspects that might be the cause of these disengagements. Therefore, its major contribution is the proposal of the new speed concept named automated speed (Va) and the proposed methodologies to address semi-autonomous vehicle disengagements.

RSA should not focus on detecting whether the thresholds defined in the previous section are met or not, but on ensuring that these violations are not isolated, taking place after kilometers of automated driving. Auditors should pursue that high-end road segments meet all requirements for automation and ensure that adequate countermeasures are set in segments where a few disengagements are expected. Some examples of countermeasures might be an adequate signing (e.g. “Warning: Disengagements expected”), texturized pavement, etc. Specific electronic signs could also be proposed, if vehicles are adapted to read them and inform the driver about an oncoming disengagement. These measures would also be valid for transitions from ODDs valid from level 4 to other ODDs not compatible with this automation level. It is important to highlight that these measures must be reliable too, i.e. they should not be too conservative or relaxed. Too frequent signs warning about a possible oncoming disengagement without further becoming true would result in lower trust and, finally, in lower effect when actual disengagements take place.

While these measures would ensure a better performance of automated vehicles, there are two important shortcomings that affect their application:

- a) the diversity of driving automation systems
- b) their technological evolution.

The disparity of driving automation systems – which includes sensors, processing, and Human Machine Interfaces – makes it impossible to define an automated speed threshold that applies to all driving automation systems. In other words, a system might be able to perform autonomously along a horizontal curve of 400 m of radius, but another system might fail. Thus, the thresholds to define clear level 4 ODDs for most driving automation systems should be very conservative, set where the design speed of the road segment is clearly below the automated speeds measured for a wide range of driving automation systems. The main reason of proposing conservative thresholds is to avoid an overconfidence in drivers. As previously mentioned, when the road is prone to cause a lot of disengagements, manual driving might become safer than an automated driving.

In addition, these systems are evolving very fast. Existing limitations might be overcome in months, which hinders defining adequate ODDs, since these might be outdated soon and therefore become ineffective.

Defining the operational thresholds for the driving automation systems therefore becomes necessary. Given the plethora of technologies, harmonized testing protocols focused on determining the limitations of driving automation systems in real world should be developed by Administrations. These tests, combined with adequate thresholds, could be used to certify driving automation systems, ensuring that these will not disengage under some given circumstances. These limitations could also be used as an aim for Vehicle Original Equipment Manufacturers (OEMs) and their suppliers.

The above mentioned limitations would be present while the road infrastructure is only physical, which is barely resilient to changes. A Digital Infrastructure and an adequate communication between road infrastructure and CAVs could provide vehicles information about the ODD, allowing these to adopt and inform the driver about oncoming TORs. This would allow ODDs to change in definition, extension, and incorporate parameters such as traffic and weather conditions. An important effort should be done in advance to define harmonized and standardized vehicle limitations and ODDs. Thanks to it, the automated driving system, combined with HD map, would be able to anticipate the geometric-related disengagements and therefore inform about TOR with sufficient time.

If the digital infrastructure is not present, Variable Message Signs could inform the drivers about road readiness for AVs. Given the variety of vehicle technologies, some pictograms should be developed to show how the road interacts which each of them.

A standardization effort will be required as well to match road infrastructure with vehicle technology, provided that the number of pictograms should be limited since they have to be interpreted by drivers. Moreover, a driver should easily adapt to different vehicles which might obey to different of these pictograms.

In this scenario the role of auditors becomes challenging, since they should check adequacy of the pictograms to the different automation types, which implies readability of the signs, their frequency, and variation in time.

Finally, auditors should also be trained in V2X communications. New possibilities of CAVs, especially vehicle platoons and automated intersections would benefit from these communications but could generate new – and very important – problems if these fail. Degradation of Cooperative Active Cruise Control (dCACC) has been proven to suddenly increase decelerations on the traffic stream, which might not be supported by all autonomous technologies. Hence, auditors should check the strength of these communications and the possibilities of their blackout.

6. CONCLUSIONS

This study identifies some needs for improvement on current RSA/RSI procedures to host semi-autonomous vehicles. These are urgent needs, due to their fast market growth. Limitations regarding road design, road markings, and pavement condition have been identified, and some insight on how these should be incorporated is provided.

A new concept, the Automated Speed (Va), is introduced as the maximum speed at which semi-autonomous vehicles can perform autonomously. The relationship between this parameter and the design speed is of great importance, since a road feature in which the design speed exceeds the automated speed would result in massive disengagements and, therefore, hazards.

Several research of the authors on geometric and cross-section limitations of AVs have been summarized, highlighting how these should be applied by road safety auditors. At first, RSA/RSI should be based on conservative thresholds to ensure that a road feature produces no disengagements to any marketed semi-autonomous vehicle. Vehicle technological development and a better characterization of road-AV interaction will allow to define dynamic ODDs that will be transferred to vehicles via V2X. By doing so, RSA/RSI should adapt to ensure that these dynamic conditions are in line with all vehicles, regardless their automation level.

Existing RSAs already require the intervention of multidisciplinary teams to assess the road quality from different perspectives. Thus, adding autonomous vehicles to the picture might either require specialization of the team or increasing its number with more specialists.

Therefore, efforts must be made to gradually introduce new training on AVs and V2X communications to auditors. They should be able to analyze the potential shortcomings of communication failures, such as degraded CACC. A huge effort should be carried out first by Administrations, OEMs and suppliers to harmonize uniform communication, signage, and HMI protocols that are valid for current and further automation and infrastructure developments.

Further research should concentrate on determining the limitations of the different automation technologies, as well as on defining testing protocols to ensure their harmonization. These will establish a clearer goal for vehicle manufacturers in matching automation with road infrastructure, and a first step to group automation technologies and defining adequate ODDs. These ODDs, combined with the digital infrastructure, will ensure a safe scenario while transitioning from manual to fully-automated driving.

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