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# Road design influence on driving behaviors: The influence of curve design, a case study

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## ABSTRACT

Road geometry has always been a key feature for road safety concerns. It will become more crucial in the context of future transportation, especially with the advent of Connected and Autonomous Vehicles (CAVs). In fact, recognizable and intuitive road alignments would simplify the driving tasks for both humans and CAVs (independently from the rate of automation). Thus, not only building consistent and self-explaining roads is fundamental for new and old vehicles, but also adjusting the existent ones, operation that seems even harder. Since most of the existing roads would need massive interventions, policy makers and road designers might choose between making adjustments being compliant with the current regulations in toto or adopting countermeasures supported by specific safety assessments to make existing roads safer, also in the perspective of future changes. In this optic, the present study tries to investigate a typical geometric design issue of existing roads, i.e., the presence of a long segment followed by a sharp curve without transition curves on undivided two-way two-lane rural roads. This alignment does not reflect the current recommendations for road alignment, so it was investigated the effect of such a design on users and safety for a specific testbed. The users' behavior was investigated recording the kinematic parameters of the traveling vehicles. This data collection was run using radar traffic counters, placed on the roadside throughout the entire layout of the investigated segment-curve, to get speed and acceleration. The data were elaborated to investigate driving behavior in free-flow conditions. A K-means cluster analysis was run to characterize the users' behaviors in terms of speed and acceleration. Hard braking was found to be strongly related to high speed, as well as ongoing deceleration on curve was detected for all the vehicles with high speeds on the segment. Results about users' behaviors were compared to the available crash dataset to understand the possible implications of human factors on occurred crashes and to simulate the decision process of safety-related adjustments of existing roads.

## 1. Introduction

Designing roads has always been a complex task, since it accounts for several aspects of transportation engineering, encompassing traffic forecasts, capacity, geometric alignment and safety. All these features must be consistent to provide a safe environment. The road design task will be more challenging in the upcoming future considering the transition in progress: new vehicles and Connected and Autonomous Vehicles (CAVs) are being and will be deployed with ever more technological features that will help humans in driving. However, the technological features need intelligible roads to work efficiently and support humans [80,83].

In this optic, road design must combine the safety features for human drivers and self-driven/driving assisted vehicles, especially about road signals and geometric characteristics. The latter seems to be a huge issue for most of the existing roads that were designed to comply with old standard prescriptions. Thus, currently, most of the time roads are already obsolete for the travelling vehicle fleet and even more so for the upcoming ones. Ambiguous road geometry uncompliant with current standards can induce misperception badly affecting the driving behavior: drivers are more prone to be involved in risky situations due to excessive speed, and hard deceleration or acceleration [62,76]. These behaviors are extremely dangerous if in contrast with the prescriptions on roads (like posted speed limits or signals) and with the regulatory checks of the alignment (speed greater than the ones for having adequate stopping sight distance; speed exceeding the maximum design

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speed associated to the geometric elements of the layout; inadequate acceleration/deceleration spaces).

All these mentioned aspects become particularly relevant while talking about rural roads, since rural roads have been found to be the most dangerous ones in terms of fatality [47]. This riskiness of rural roads seems to be a constant through the time [25] and the reasons are multiple, starting from the human behaviors: drivers are more prone to drive under the influence, not wearing seatbelts [67]. Moreover, when talking about two-way two-lane rural roads, other factors emerge, such as the dimensions of lane width and shoulder width, more often insufficient to ensure safe travels [58]. Crashes on two-way two-lane roads are also correlated with the presence and features of curves [29,32,46], speed, and accesses [3]. Conversely, the degree of curvature is inversely related to crashes, in fact sharper curves are travelled at lower speeds [33]. Moreover, on this road typology, the absence of a physical barrier between the two traffic flow directions creates black spots for crashes in case of inadequate driving trajectories. This is exacerbated by the fact that head-on crashes can have severe consequences [1,28]. All these highlighted aspects of the two-way two-lane rural roads underline the fact that, on this type of roads, the geometric features generally compel drivers to more restricted behaviors than on divided freeways and highways [8,10,20,64]. Given this evidence, ensuring an appropriate road geometric design consistency is crucial. For example, the effect on safety (in terms of crashes) of the transition between straight sections to curves depends on several aspects, such as (see e.g., [26,44]): the tangent length, the presence of the transition curve, the radius of curvature and its relationship with the previous curve on the road layout.

### 1.1. Objective of the study

Considering the existing roads belonging to this road type, many of them were designed complying with old prescriptions, therefore there are obsolete geometric design as the lack of transition curves between segments and circular curves. This aspect needs to be assessed with regard to the perceived safety and consequent driving behavior, especially thinking of the importance of such elements in the case of automation. Will the human driver be ready to safely take over the vehicle in case of disengagement by the automation, in the transition from segments to sharp curves? Will be the CAV ready to perceive and behave adequately to sharp curves, providing comfort and safety to users, going from a segment to a curve?

The answer about the correlation between ambiguous geometric design and driving behaviors can be a milestone in the procedure for prioritizing road adjustments, also considering future innovations. This analysis can affect also the choice between using ad-hoc countermeasures or re-designing the geometric layout for safety purposes. Moreover, the driving behaviors, also in accordance with the vehicle fleet composition (new and dated vehicles) can provide some clues about the geometric design suggestions for future standards, in agreement with the requirements of new vehicles.

Hence, given this context, the aim of the study is to understand the impact of an ambiguous geometric layout on kinematic parameters and on driving behaviors, investigating speeds, braking and accelerations. These results can highlight some important clues about road management under unsafe or ambiguous conditions. For this instance, a correlation with historical crash data was provided, trying to link the driving behaviors with the geometry and safety risks. This assessment takes its ground by an analysis of the human-driven vehicles behavior in the transition from segments to curves on two-way two-lane rural roads. This aspect is also crucial pointing to the upcoming presence of ADAS and CAVs on roads to provide intuitive geometric design that prevents risky situations due to high speed or braking. In fact, the horizontal alignment must be easy to be understood by disengaged human drivers, making them comfortable in taking over and suddenly driving on curves.

## 2. Literature review

In this section, a literature review encompassing the main topics covered in this study is conducted. It is divided according to three fundamental aspects: the relationships between road geometric design and the driving behavior, which guided the road design practice and regulations in the last decades; the new challenges introduced by the road/vehicle automation regarding the interactions with the road layout and, finally, the research approaches previously used to practically investigate these aspects. Given the context of this research, the literature review is particularly focused on two-way two-lane rural roads.

### 2.1. Road geometry and driver behavior

The main aim while designing roads or intervening on existing ones must be to provide self-explaining roads [74]. These roads should be interpreted by the drivers such as they can drive according to the road layout, without any misbehavior. For driver behaviors on roads, it is intended the driving attitude of the subject in terms of complying the rules, being safe, speeding and accelerating according to the driving environment. The geometric alignment must guide itself the drivers to be compliant with the geometric features and with the road prescriptions, as signals. According to these premises, the investigation of driver behaviors on two-way two-lane rural roads is crucial to be aware of the most useful design interventions to make the road safer for the current travelling fleet and for the future ones. With this regard, several studies have been conducted on the influence of the road geometric design on driving behavior, such as reported in the following.

As far as the different elements of the road layout are concerned, horizontal curves are more related to driving speed variations, than on the lateral position [11]. In fact, their sharpness induces drivers to slow down [33,87]. Another aspect that influences the drivers' speed is the available sight of distance, reducing it forces drivers to be more cautious in driving [87]. On the other hand, free-flow long tangents are correlated with harsh events more than other geometric elements [63]. Lane width and shoulder width are strongly correlated with driver displacement from the center of the lane. When the shoulder is at least 0.50 m, the driver starts being comfortable in driving at the center, otherwise it will adjust its position to feel the adequate space for maneuvers, also invading the opposite lane [54]. In this optic, both narrow shoulder and lane width are associated with reduced safety [58].

From motorways to other rural roads, the impact of road geometry and road pavements on crash rate is greater [49]. Complex road geometry features are associated with a greater rate of attention by the drivers, both on horizontal and vertical alignment [36]. The effects are visible on speed and lateral positions, providing more dangerous driving conditions, if not adequate. Moreover, the roadside elements do not seem as well influential on driving behavior [8].

### 2.2. Road geometry and connected and autonomous vehicles (CAVs)

What has been stated until now is valid for human-driven vehicles, but in the optic of CAVs, different scenarios could be outlined. Since sensors and automation need clear input to work efficiently, it is immediate that roads should show intelligible geometric features. For instance, SAE level 2 vehicles (nowadays massively deployed on roads, [85]) cannot autonomously execute sharp curves, requiring the intervention of human drivers [50]. Human drivers can be already misguided by the presence of the sharp curve, if the geometric layout is ambiguous. Moreover, the need to take over the assistant system can increase the risk of executing a curve. Thus, the horizontal alignment must be in line with the expectations and readiness of a disengaged human driver, who should comfortably take over and suddenly drive on curves. The hypothesis of designing curves with wider radii, of course can help the Advanced Driving Assistant Systems (ADAS) in executing them smoothly but can lead to greater speeds [33,36] and greater environmental and construction costs of undivided two-way two-lane rural roads. In fact, ADAS can help in braking before curves to manage them better, reducing the run-off risk [19], but also new developed trajectory models can simplify, at different speeds, driving the small radii curves [7]. However, thinking about the future CAVs, programmed to efficiently work for all the dynamic driving task (DDT) and through limited or unlimited operative domain design (ODD), the outcomes are completely different. In fact, the switch from human-driven vehicles to fully autonomous ones will lead to reduced perception and reaction times and reduced stopping sight distance. In this optic, the radii of horizontal and vertical curves will be reduced as well [35,77,82]. Thus, the right geometric design approach to deal with both the ADAS-equipped vehicles and autonomous vehicles must be found. In fact, unclear curve perception, due to variable design criteria and road structure, induces 63.3 % of vehicle disengagement from the driving tasks, requiring immediate takeover by the human driver. Together with the mentioned problems, small radii and great speeds before the curves strongly impact the disengagement occurrence [15].

Thus, considering safety concerns for all the possible vehicle types involved in the immediate future (human-driven vehicles, ADAS-equipped vehicles, and CAVs), horizontal curves along two-way two-lane rural roads seem one of the most dangerous spots on roads, as previously highlighted by literature [2,14,30,33,46,60].

Starting from the investigation of what happens at curves can pave the way for new road geometric design standards, trying to prevent the failure occurrence due to intrinsic road features [37]. In fact, curve length, deflection angle, and chord length combined with traffic volume, all had statistically significant effects on crash frequency [69]. Another chance is to work on some valuable countermeasures for curve safety improvement, like relying on optical circles and herringbone patterns, to influence driver behavior while entering a curve [6] or improving models for curve management by ADAS [19]. These mentioned aspects related to geometric standards and countermeasures represent a chance to improve the functionalities of the existent automated systems and ADAS, but also to update the international road design standards founded on outdated studies for old vehicular fleets. In fact, prescriptions should be thought of for promiscuous scenarios, simultaneously accounting for the needs of different vehicles.

### *2.3. Tests to investigate human behavior during driving tasks*

Matching the need of investigating the influence of road geometric design on human drivers with the intent of looking also to the future of transportation systems, an analysis about previous similar research frameworks was done.

Several studies have been conducted on driving simulators [6,9,14] to collect a great amount of data with a low-risk approach, some others have been based on naturalistic data [16,31,79]. These two approaches are used to investigate the overall behavior of drivers throughout the entire test path. In fact, naturalistic data provide an overall view of different users in real driving conditions in different contexts and conditions. Driving simulators, on the other hand, provide a safe environment, where all the boundary conditions can be set to investigate some specific conditions and aspects during travels. Naturalistic data, due to their completeness can be used to validate risky behaviors in driving simulator studies [38]. When the analysis should be focused on more specific conditions, for example an intersection, or a curve, other approaches different from the driving simulator (outperforming the research needs and, in some cases, creating a fictious driving scenario) can be also used, in the absence of naturalistic data. The video-based approach [18] was one of them. It was used in an on-site study, to collect naturalistic driving data (including road traffic trajectory data) using static video cameras installed near the road facility [72]. Video-based approaches can be used for detecting the typology of aberrant behaviors and sometimes the cinematic parameters beneath the misbehavior. Other methods of analysis can be based on traffic counters [21,86]. All these methodologies aimed at detecting not only the traffic but also all the possible misbehaviors like hard acceleration, curve cutting and hard braking [18,65,68,70]. From the analysis of human behavior, it is possible to get if the drivers are cautious, i.e., drivers that keep safe behaviors, with normal braking, low speeds, compliant to the rules, or aggressive when the driver does not respect road rules, performs speeding and hard braking [23].

Thus, being aware of drivers' aberrant behaviors can be a first step towards adequate countermeasures. In this study, countermeasures are intended to tackle the road geometry issues and the human failures together [61,78,81].

## 3. Methodology

To address the research questions stated in the previous sections, an experimental study was conducted. The methodological flowchart used to answer the research goal is here synthesized to provide an overall framework of the conducted analyses.

The research goals have been pursued by field data collection to carve out the main outcomes. In this optic, the need to rely on a case study was assessed. The selected case study area has been the Metropolitan City of Bari, Italy.

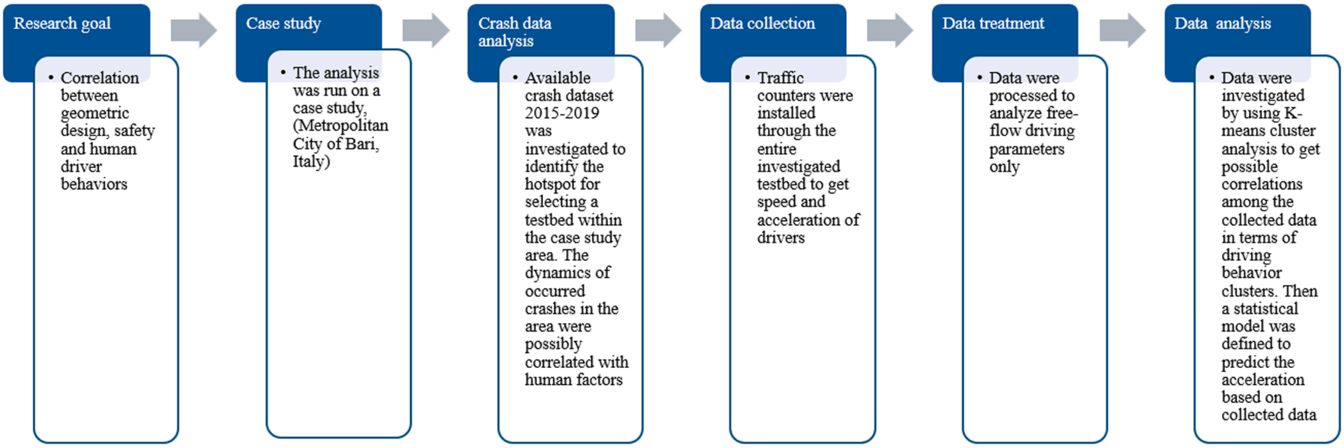
Each of the steps detailed in Fig. 1 are described in the following subsections, reporting about the selection of roads, the collection of data, how they were treated and then the analysis of the filtered data, according to the stated procedure.

### *3.1. Road site selection*

As previously anticipated, the selection of the road site was conducted within the two-way two-lane rural road network belonging to the Metropolitan City of Bari, Italy. In particular, the choice was based on the history of crashes. The crash dataset used for this specific assessment was the one provided by ISTAT-ASSET for the Metropolitan City of Bari for the years 2015–2019 related to Fatal and Injury crashes (F+I crashes). This dataset was filtered to get only the crashes occurred on the targeted road typology (undivided two-way two-lane rural roads). Considering the dataset, the crashes occurred on curves were the majority. Therefore, considering the sample of Italian roads belonging to this specific typology [42], the average percentage of curves on two-way two-lane segments was calculated (14 %). In this way, starting from the overall number of crashes occurred on curves on the inquired network in the investigated period (5.78 crashes/year), the average crash frequency at two-way two-lane curves in the investigated area was calculated: 0.17 crashes/(curve*year). Then, this average value was compared to the curve crash frequency of each of the 206 roads in the network and it was found that the Province Road n.120 (SP120) Polignano a Mare – Castellana Grotte had the greatest discrepancy from the average, $\Delta = 1.27$, showing a value of 1.44 crashes/curve*year.

One specific section belonging to the SP120 was chosen according to the most significant geometric characteristics inquired by the research: assessing the compliance and the competence of vehicles [73] with respect to the default curve behaviors considered by road standards. Thus, the road section should include a long segment, where drivers could potentially speed up to values greater than the posted speed limit (50 Km/h), followed by a sharp flat curve. The importance of neglecting implications of vertical alignment is to make an assessment that just considers the influence of the horizontal alignment on drivers. Analyzing the SP120 curves, all the succession segments-curves lack the interposition of transition curves. The chosen curve is the one in Fig. 2 and all its geometric features are highlighted in Table 1, as well as the design speed associated with the horizontal elements according to Italian standards. In summary, this curve was chosen as it was deemed to be representative for our research purposes.

All traffic crashes that occurred in this period on the road section were then analyzed in detail (location, type, dynamics), to investigate


Research goal
- Correlation between geometric design, safety and human driver behaviors

Case study
- The analysis was run on a case study, (Metropolitan City of Bari, Italy)

Crash data analysis
- Available crash dataset 2015-2019 was investigated to identify the hotspot for selecting a testbed within the case study area. The dynamics of occurred crashes in the area were possibly correlated with human factors

Data collection
- Traffic counters were installed through the entire investigated testbed to get speed and acceleration of drivers

Data treatment
- Data were processed to analyze free-flow driving parameters only

Data analysis
- Data were investigated by using K-means cluster analysis to get possible correlations among the collected data in terms of driving behavior clusters. Then a statistical model was defined to predict the acceleration based on collected data

**Fig. 1.** Flowchart of the procedure applied for the proposed research.

**Fig. 2.** Area of investigation in Italy, within the borders of the Metropolitan City of Bari. The selected section of the SP120 (in red) is highlighted in the picture, together with the related vertical alignment (colored figure). Image source: Google Earth.

whether the road geometric design itself or the driver behaviors were the main contributory factors and to find possible relationships with other on-site data collected in this study, explained in the following.

### *3.2. Data collection*

The traffic behavior on the transition from segment to curve and over the entire layout of the curve (length equal to 120 m) must be assessed through the collection of speed and acceleration for each vehicle. This was achieved using traffic counters based on radar detection (Sierzega SR4). This equipment was considered the most suitable way to continuously record data about vehicles during their trips. The traffic counters detect the day, the time (with a precision of 1 s), the speed of vehicles and their dimensions, as well as the travelling direction and the time gap between two consecutive detections. The behavior of vehicles from the entrance in the curve to the end of the curve was the aim of the

**Table 1**
Summary of road features and related design speeds for the chosen section of the SP120, within the area of the Metropolitan City of Bari.

| **SP120** | | | |
|---|---|---|---|
| **Regular Asphalt pavement** | Yes | | |
| **Road category according to Italian Road Geometry Regulations** [56] | Local rural roads | | |
| **Total paved road width** | 6.40 | m | |
| **Lane width** | 3 | m | |
| **Safety barriers** | Yes | | |
| **Average daily traffic** | 4094 | vehicles/day | |
| **Posted Speed Limit** | 50 | Km/h | |
| **Average Radius** | 120 | m | |
| | | **Dimensions (m)** | **Design Speed, Vp (Km/h)** |
| **Entering Segment** | **Length** | 846.31 | 100.00 |
| **Curve** | **Radius** | 105.00 | 57.21 |

detection, thus, the traffic counters were mounted adjacent to the lane of interest. All the data about the other lane, where vehicles exit the curve, were neglected. Another issue to be bridged was to find a way to process uniformly data. In fact, one possible way to get the acceleration from the recorded speed was relying on the time lag between two following recordings. However, the precision of this procedure could have been affected by the extreme variability of time between two consecutive recordings, according to the speed, that could have also led to wrong reconstructions of the speed profile and propagation of errors. One way to pursue this goal is to fix a space interval and consider just the speeds as variable (addressing implicitly the time). Under this umbrella, the counters should have been mounted at fixed space intervals. They were mounted according to [21], on road light poles spaced 30 m each, as highlighted in Fig. 3. The position of poles was ideal for the installation, since they were on road curbs, protected by the guardrails, not visible by users (so their behaviors can be undisturbed). Six traffic counters were mounted. Their installation was considered after their validation by the Sierzega SRA Software. It was verified that the six counters read instantaneously the vehicle speed, and it was possible to recreate the speed profile of each vehicle travelling in proximity of the counters. One counter was placed 30 m from the starting point of the curve. The second counter at the beginning of the curve. Then all the other 3 counters were mounted on the curve interspaced by 30 m distance. The last counter was placed 30 m from the exit point of the curve.

The counters were left on road for 3 consecutive workdays at the end of May 2024 to have a statistically significant sample of data. All the recorded data were extracted and processed.

### 3.3. Data treatment

The undisturbed behavior of drivers towards road characteristics is realistic when not influenced by the traffic, in free flow conditions. Hence, the only investigated data should belong to isolated vehicles. There is still a gap in literature about exact timing thresholds to consider a vehicle as isolated. In this case, a 20 -seconds-threshold between two consecutive records at the same counter was set as the limit to consider a vehicle as isolated. In fact, this time is approximately twice the time that a vehicle compliant to the posted speed limits takes to travel through all the 6 counters. The filtered database includes 3822 data of isolated vehicles out of 11866 total recordings.

For the sake of understanding if different time periods may impact speed and acceleration behavior of drivers, the day was divided into four time slots:

1. Morning from 7 am to 1 pm
2. Afternoon from 1 pm to 8 pm
3. Evening from 8 pm to 0 am
4. Night from 0 am to 7 am

Each time slot was categorized by a categorical variable from 1 to 4 (as in the list).

Moreover, the dimensions of vehicles were categorized according to a binary variable: 0 if light (length from 0 m to 6 m), 1 if heavy vehicles.

All the kinematic parameters of the vehicle were obtained in correspondence of each traffic counter. In particular, the following variables

**Fig. 3.** Location of the 6 traffic counters (numbered from #1 to #6) on the selected section of the SP120. The spatial gap between two consecutive counters is equal to 30 m (colored figure). Image source: Google Satellite.

were extracted:

- Speed data $V_i$ corresponding to each of the six traffic counters.
- Acceleration/deceleration data $A_i$ calculated as the acceleration/deceleration between the Vi and the following $V_{i+1}$ measurement.
- Acceleration/deceleration value A2–4 calculated as the acceleration/deceleration between the V2 (speed at curve entrance: traffic counter #2) and the V4 (curve exit: traffic counter #4), that is the average acceleration value recorded through the entire curve section.

### 3.4. Data analysis

The obtained variables were used to study the behavior of drivers at curves. First, a descriptive analysis of speed and acceleration/deceleration data was conducted. The analysis of the different speed and acceleration means, standard deviations and frequency distributions is useful to characterize the driving behavior. These values can be also compared to design standards to check if design assumptions are met in case of existing road conditions. Design standards, in fact, were defined with the old vehicle fleet, and due to the new travelling fleet, their prescriptions might be obsolete.

After, a deeper investigation of the collected data was required. Since the main aim of the data collection was to get possible correlations between the road geometric design and the driver behaviors, different driving behavioral types were characterized by clustering speed and acceleration data by using an unsupervised learning method: the K-means algorithm, see e.g., [4,24,40,43]. This step should inquire how drivers face the same geometric layout, by investigating if they follow the prescriptions induced by signals and geometry or they disregard such indications relying on their own perception. Three variables used for the cluster analysis: V1, speed on the segment; A1, the acceleration at the transition from segment to curve; A2–4, the average acceleration value recorded through the entire curve. The Euclidean distance measure was used to compute the distance between each data and the centroids. The optimal number of clusters was defined by using the elbow method. In this way, it is possible to identify groups of drivers characterized by different curve speed and acceleration behaviors. The K-means algorithm was run in the R environment.

Moreover, a relationship was searched between average curve acceleration (A2–4) as dependent variable and initial speed (V1) and segment-curve deceleration (A1) as independent variables. In fact, it is expected that the curve acceleration behavior depends on speed and acceleration on the previous segment and on the transition to the curve. The other collected variables were used to predict A2–4: vehicle type (binary variable: light or heavy) and time slot (categorical variable: morning, afternoon, evening, night).

## 4. Results and discussion

In this section, the main outcomes of the analysis are presented and discussed. The first analysis presented is the one related to the crash dataset investigation. In fact, crash data are useful to identify the crash-leading factors and later correlate them with driving behavior. Hence, after having disclosed the crashes, the second part of the results is about the outcomes from the data collection in terms of speed and acceleration driving the segment-curve testbed. After that, the next step is to get the correlation between the road design and the mentioned variables to understand how drivers are prone to be compliant with imposed prescriptions by geometry and signals. To get this aspect, the cluster analysis was run identifying behavioral clusters starting from the speed and acceleration. Starting from speed and acceleration, a correlation was found and then, all the variables collected during the data collection were used to define a statistical model to predict the acceleration starting from the other driving conditions. All these results are propaedeutic to define the current driving behaviors in response to ambiguous geometric design, given the aims of this study.

### 4.1. Crash data analysis

Overall, the selected road (SP120) was affected by 33 crashes over the period 2015–2019 (equal to 0.62 crash/year/km average annual crash frequency over the entire length of the road). The curve ratio over segments for the SP120 is 0.43, significantly higher than the average Italian value (three times greater [42]). The crashes occurred on curves are 17, 51.1 %. Crash types are the following: 6 sideswipe, 8 run-off-road, 2 head-on and 1 fixed-object crashes. From this analysis, the presence of sharp curves (average radius equal to 120 m) on the entire SP120 road and steep vertical alignment seem to create issues to driver while facing curves. By the way, 5 run-off crashes happened with wet pavement conditions, increasing the challenges encountered by the drivers. Looking at the location of those crashes, it is evident how subsequent curves overlapping with high vertical alignment variations create unsafe conditions, such as unreadiness of drivers to adjust trajectories at their travelling speeds.

Among all the recorded crashes, just 3 occurred on the selected curve. 1 head-on, 1 sideswipe and 1 run-off. The run-off involved one bicycle, and it is possibly explained by the absence of wide shoulders where bicycles can find shelter and the narrow lane width.

The other two crashes happened due to the presence of a minor intersection on the curve. The absence of run-off crashes on this curve could implicitly indicate that on isolated curves with no vertical alignment issues, even though the curve radius is sharp, the absence of transition curves could not be necessarily detrimental for safety, based on crash records only.

The highlighted safety issues could be mitigated by reducing speeds: especially head-on and run-off can be extremely affected by high-speed regime, both in terms of occurrence and severity. Head-on and sideswipe are clearly correlated also with the lane width issue, present on two-way two-lane rural roads. In fact, it emerged from previous studies that inadequate lane and shoulder widths are the most common causes of crashes on this type of road [58]. The reduced dimensions of the cross-section of roads are as dangerous as the presence of sharp curves (radius minor than 250 m) on the head-on crashes. Acting on these aspects together with a well-paved road can improve the safety of the site [13]. Reduced curve radius, and curve length can increase the crash frequency [51]. Goyani et al. [34] found that crashes (cars and HCVs) decrease as the curve radius, deflection angle, and length increase. Similarly, as the tangent length increases, the difference between operating and design speeds increases, making inconsistent highway alignment, resulting in increased likelihood of crashes. These results are in line with what was found on the selected road section in terms of safety. About driving behavior, these findings can help in identifying some risk patterns from drivers and identifying some approach to mitigate these ambiguities.

All the assumptions made analyzing crashes should be coupled with results in terms of speed and acceleration data, presented in the next sections. through which it is possible to state if drivers are aggressive, cautious or compliant [22]. These results can be important because they might highlight how some safety issues can be improved by acting contemporary on human driving habits and geometric countermeasures.

### 4.2. Speed and acceleration values: results and discussion

Some descriptive statistics of the results in terms of speed and acceleration are reported in the next table (Table 2).

Results show that the average speeds are greater than the posted speed limit for all the counters, but they are in line with the design speed associated with the radius of the curve (57.2 Km/h). However, through the curve, more than 20 % of vehicles go faster than the design speed of the curve. This means that the intrinsic risks associated with the curve increase. This risk factor is going to be added to the presence of a long

**Table 2**

Descriptive statistics of speeds (V1 means the speed recorded at the first counter, and so forth until the sixth counter), percentages of vehicles travelling within given speed ranges, accelerations (the average acceleration in curve A2-4 was calculated too) and percentages of vehicles falling in given acceleration ranges.

| | | V1 (km/h) | V2 (km/h) | V3 (km/h) | V4 (km/h) | V5 (km/h) | V6 (km/h) |
|---|---|---|---|---|---|---|---|
| **Speed analysis** | **V85** | 81.00 | 71.00 | 65.00 | 63.00 | 67.00 | 65.00 |
| | **Vmean** | 69.56 | 61.43 | 56.45 | 54.76 | 59.05 | 57.16 |
| | **Vmax** | 115.00 | 99.00 | 85.00 | 85.00 | 91.00 | 86.00 |
| | **Vmin** | 21.00 | 20.00 | 20.00 | 19.00 | 20.00 | 18.00 |
| | **St. Dev.** | 11.48 | 9.72 | 8.55 | 8.13 | 8.20 | 8.20 |
| | **Coeff. of variation (c.v.)** | 0.17 | 0.16 | 0.15 | 0.15 | 0.14 | 0.14 |
| | | % | % | % | % | % | % |
| **Percentage % of vehicles driving at the speed ranges (Km/h)** | **20–40** | 0.94 | 1.85 | 3.13 | 3.61 | 1.60 | 2.69 |
| | **40–60** | 19.46 | 44.79 | 65.18 | 72.53 | 55.74 | 63.72 |
| | **60–80** | 64.27 | 50.54 | 31.27 | 23.75 | 42.22 | 33.17 |
| | **80–100** | 14.70 | 2.79 | 0.42 | 0.10 | 0.44 | 0.42 |
| | **100–120** | 0.63 | 0.03 | 0.00 | 0.00 | 0.00 | 0.00 |
| | | A1 (m/s$^2$) | A2 (m/s$^2$) | A3 (m/s$^2$) | A4 (m/s$^2$) | A5 (m/s$^2$) | A2-A4 (m/s$^2$) |
| **Acceleration analysis** | **A85** | −0.80 | −0.30 | 0.00 | 0.88 | 0.29 | −0.15 |
| | **Amean** | −1.43 | −0.78 | −0.25 | 0.63 | −0.28 | −0.52 |
| | **Amax** | −0.08 | 0.74 | 1.52 | 5.96 | 6.37 | 0.88 |
| | **Amin** | −6.35 | −3.21 | −3.21 | 0.49 | −5.48 | −2.59 |
| | **A Std. Dev.** | 0.67 | 0.51 | 0.35 | 0.30 | 0.94 | 0.67 |
| | | % | % | % | % | % | % |
| **Percentage % of vehicles accelerating with acceleration within the ranges (m/s$^2$)** | **1 < −1** | 26.52 | 72.45 | 95.7 | 92.06 | 82.74 | 2.17 |
| | **−1 < −2** | 57.49 | 24.64 | 4.20 | 7.59 | 10.86 | 87.71 |
| | **−2 < −3** | 14.01 | 2.59 | 0.00 | 0.21 | 3.72 | 9.76 |
| | **−3 < −4** | 1.45 | 0.32 | 0.04 | 0.11 | 1.98 | 0.37 |
| | **−4 < −5** | 0.42 | 0.00 | 0.00 | 0.00 | 0.62 | 0.00 |
| | **−5 < −6** | 0.11 | 0.00 | 0.00 | 0.03 | 0.08 | 0.00 |

tangent before the curve and the absence of spiral curves, which are clearly correlated to crash occurrence increase [27]. There are very few vehicles travelling below 60 Km/h in the segment (20.40 %). Those drivers, who can be identified as “cautious” with respect to other drivers, can also drive heavy and agricultural vehicles, which are not rare on this road segment. Drivers exhibit lower speeds in curve (V2-V6) than on the segment (V1). In fact, on the segment, a more “aggressive” behavior in terms of speed (i.e., speeds higher than the posted speed limit) is the most frequent. The same consideration can be made looking at the acceleration values.

Speed behavior is in line with what demonstrated in previous studies [48,55,57] about the well-known dependency between speed and curve radius and about the misperception or misbehavior of drivers while entering a sharp curve. The great speed detected on the segment before the curve is in line with what highlighted by a previous analysis about the inconsistency of tangents with driver behaviors [34]. Moreover, high speeds are of course associated with a greater crash likelihood, however, two-way two-lane rural roads are travelled at high speeds only when the road geometry is extremely linear [66]. In this case, the presence of a long tangent before the curve can be associated with a “linear” geometry, that contributes to the increase in speeds. As soon as the curve starts, speeds become averagely lower [33,36,87].

Acceleration on two-way two-lane rural roads is highly variable due to the presence of traffic also in the opposite directions. Thus, traffic volume undoubtedly influences the variability of acceleration, but also driver and vehicle characteristics impact on it, especially in peak traffic conditions [5]. In the proposed study, the acceleration seems to be highly affected by the geometric characteristics of the road, as previous studies highlighted also in terms of operating speed [34,75]. The detected acceleration on tangent before entering the curve (-1.43 m/s$^2$ on average) is close to the one used in driving simulators (-1.2 m/s$^2$), to represent the driving behavior on two-way two-lane rural roads, deriving from Bokare’s model [12]. However, given the case study area (Italy), it is also useful to make a comparison with the prescriptions of the Italian standards for road geometric design. In these standards, which are mandatory for newly designed roads, the design deceleration value is set to −0.8 m/s$^2$ in the transition from segment to curve. It is important to note that the average deceleration value is almost twice the deceleration prescribed by standards. However, it must be underlined that the regulation prescriptions consider the presence of a transition curve between segment and curve. The absence of this element, which may lead to harsh decelerations, can justify the high deceleration values found.

Even though it is evident that along the curve the driver’s behavior is not homogeneous, not all drivers brake as well as not all drivers speed up (Fig. 4). This uncertainty can be justified especially by the great variability of human driving behavior, but also by the absence of the transition curve that induces drivers to keep going with their braking in curve too, and to start speeding up as soon as passed the middle point of the curve. However, the driving behavior variability is at maximum before the curve. In fact, going into the curve section, the behavior tends to be more uniform (see the coefficients of variation in the previous table).

Acceleration was related in previous research to safety risks, especially hard braking maneuvers [41,59]. The presence of various braking behaviors, with few cases of really hard braking or acceleration on the curve (with maximum values around ± 6 m/s$^2$, representing the 6 % of the entire recorded braking/acceleration maneuvers), seems to demonstrate an adequate perception of the speed behavior imposed by the presence of the sharp curve, also if compared with recorded crashes. This aspect can be related to the absence of motorized vehicles run-off detected on the investigated curve through the crash dataset period. However, the greatest acceleration/deceleration behaviors are correlated with the chance of running-off the road due to a misperception of the road alignment by the drivers. Therefore, the detected hard maneuvers could possibly lead, in the future, to run-off. To prevent this phenomenon, looking closely at the speed and acceleration (cinematic driving behavior), can provide valuable pieces of information also about countermeasures for road safety. In these terms, these results highlight how thinking about some countermeasures to reduce the variability of driving behaviors can be extremely important for more homogenous safety conditions. Under this umbrella, this issue should probably be

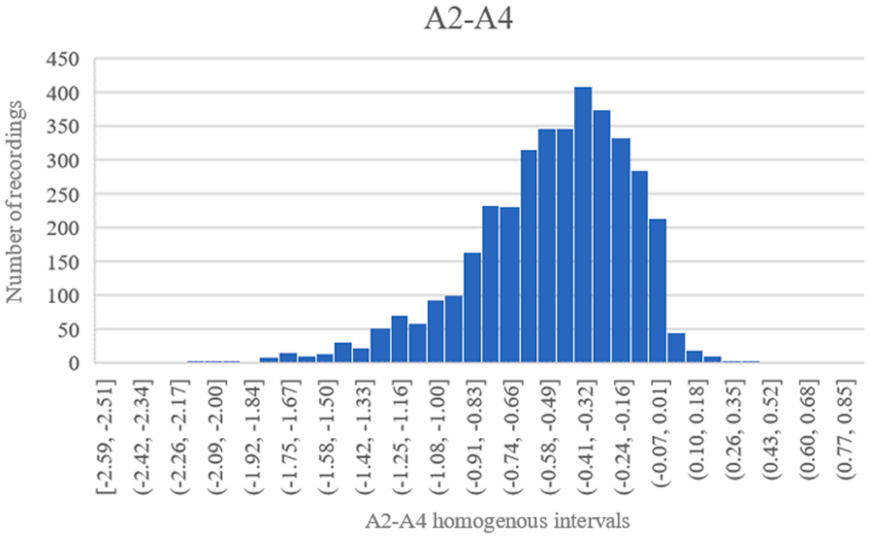


**Fig. 4.** Distribution of acceleration for the drivers (3844 data) along the investigated curve on the SP120.

mitigated by the introduction of transition curves, where drivers can start adjusting their unsafe driving conditions. Nonetheless, for the sake of safety, redesigning road alignment is not always possible, it is important to define priorities between adjusting an existing road through minor countermeasures and major interventions, like introducing a transition curve [45]. Moreover, the detected sideswipe and head-on could also be prevented with homogenous behaviors and speeds.

### 4.3. *Cluster analysis of driving behavior*

After the K-means algorithm was run, the application of the elbow method revealed that the optimal number of clusters is three (Fig. 5). The K-mean algorithm was applied to the sample composed of 3822 isolated vehicles. This sample was deemed adequate for the scope of this research. Note in fact that previous studies have applied the same algorithm on smaller samples for the analysis of driving behavior [17,53].

Moreover, most of the variance in driving behavior was found to be explained by V1 (about 82 %) and A1 (about 13 %). These two variables can explain about 95 % of the variability in driving behavior (Fig. 6). The less variance explained by A1 is since the vehicles are considered in free-flow conditions, while the acceleration/deceleration behavior is particularly useful to characterize drivers [5], when the traffic is high and when overtaking maneuvers occur [12] Fig. 6 shows the clustering of data into three groups in a standardized V1-A1 space, while absolute mean values for each cluster are presented in Table 3.

Since most of the variability in driving behavior is explained by the initial speed V1, three clusters of driving behaviors can be roughly assigned to three classes according to the speed. The behaviors were identified with reference to the average speed value recorded by the first counter, i.e., significantly lower, significantly higher or similar to it. Since the first counter, V1, is placed almost at the end of the tangent, the speed is related to the approach that each driver is showing in the transition from a linear layout to the curve. So, this approach was categorized in three different categories: the cautious drivers, i.e., those showing the lower speeds (blue color), the average drivers, i.e., those showing speeds similar to the average (red color), the aggressive drivers, i.e., those showing the higher speeds (green color). This classification into a “cautious” category is dependent on the fact that these drivers tend to approach the curve in a safer way, adjusting their speeds to drive comfortably, to lower values than other drivers. The opposite (i.e., the “aggressive” category) pertains to drivers showing speeds greater than the average, so the ones who drive according to their desired speed which does not align neither with the posted speed limit and nor with

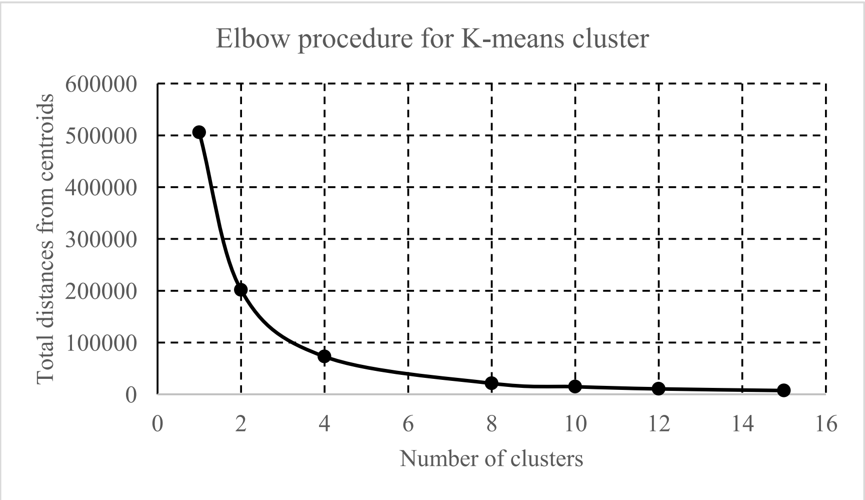


**Fig. 5.** K-means cluster’s elbow method to determine the optimal number of clusters.

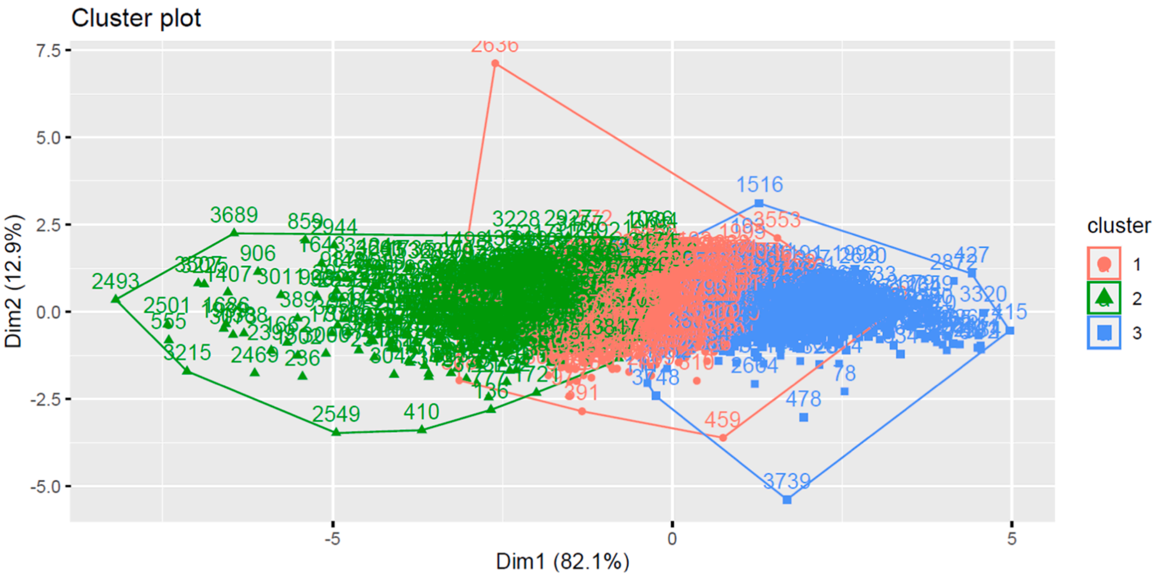


**Fig. 6.** Results from the K-means cluster analysis highlighting the three clusters of driving behavior in the space: V1–(Dim1) - A1 (Dim 2). On the x-axis and y-axis, there are the values of Euclidean distance between all points to the centroid for V1 and A1, on the respective axis. Cluster 1 is for average drivers; Cluster 2 for aggressive drivers; Cluster 3 for compliant drivers (colored figure).

**Table 3**
Cluster analysis for the three variables, before being normalized for K-means cluster.

| | | Dim 1 -V1 (Km/h) | Dim 2 - A1 (m/s$^2$) | Dim 3 A2-4 (m/s$^2$) |
|---|---|---|---|---|
| **Cluster 1 (49.8 % of data)** | **Mean** | 70.06 | −1.39 | −0.48 |
| | **Std. Dev.** | 4.03 | 0.39 | 0.26 |
| **Cluster 2 (22.9 % of data)** | **Mean** | 84.66 | −2.21 | −0.92 |
| | **Std. Dev.** | 6.30 | 0.63 | 0.38 |
| **Cluster 3 (27.3 % of data)** | **Mean** | 55.99 | −0.81 | −0.24 |
| | **Std. Dev.** | 6.60 | 0.35 | 0.21 |

the road alignment. For this reason, they are labeled as aggressive drivers, because this behavior is always associated with increased risks. The "average" drivers are in between these two extreme categories. However, it should be clarified that part of the variability is also explained by the acceleration behavior.

One half of the observations were classified into a cluster of drivers showing an average behavior. The other half is roughly split into a cluster of prudent drivers and a cluster of aggressive drivers. Thinking of SAE level 2 and 3 CAVs, different matters arise. Increasing the automation level, driver distraction and aberrant behaviors can increase. On one hand, vehicles equipped with ACC may be equated to prudent drivers, which however may need to take-over if the vehicle is not able to drive the curve [15,19]. However, they still can use a low deceleration value, which is compatible with the default value of Italian standards, even if transition curves are absent, thanks to the capability of ACC of reducing speed before curves [19]. Nevertheless, in the case of ADAS misperception of curves, drivers should react in time to perform such safe deceleration, otherwise they may perform hard braking or not manage properly the curve.

On the other hand, 72.7 % of drivers drove with deceleration values greater than 0.80 m/s$^2$. This is an important aspect of the analysis, which states how curves can be managed even in absence of the transition curve. The absence of transition curve is generally considered an issue for road safety [27,84]. Introducing transition curves can have positive effects on CAVs because they increase the perception of the curve and reduce the motion-sickness experienced by passengers [71]. The absence of spiral curves can be quantified by CMFs, arriving up to 2.09 times the crash frequency of a tangent. This is because intrinsically the curve presents several safety concerns, that can be mitigated by the presence of a transition curve [30]. Moreover, as emerged from Table 3, aggressive drivers need to adjust their behavior throughout the curve due to the absence of the transition curve; thus, they show great decelerations A1 and A2–4 to slow down to an acceptable speed in curve. Therefore, redesigning the alignment to be compliant with the current regulations (especially introducing the transition curve between the tangent and the curve) can be an optimal solution to reduce crashes and to improve the readability of the curve from human-driven vehicles and CAVs [39].

By looking at the relationship between A1 and V1 in a non-normalized space (Fig. 7), it seems that these two variables are linked. Several attempts were made to find the best fitting curve between these two variables, having in mind the impact on driving behavior (an aspect with several degrees of variability). Among the different attempts, the two most powerful correlations were the linear and the quadratic one. The correlation by a quadratic function could explain the 73 % of the variance based on the R$^2$ value (more than the linear one). The explanation of this correlation resides in the two investigated variables, meaning that only a quarter of the variability of acceleration is not dependent on speed, but on non-cinematic parameters. This can be justified by the fact that cinematics can explain a part of the complexity of the overall human driving behavior. The result was expected since the hard braking maneuvers are made by drivers at high speeds and the less intense braking is done by low-speed vehicles. The explanation of the fitted curve is that travelling at 24.5 Km/h does not require any braking to enter the curve. All the speeds greater than this one should require the driver's actions. The absence of the constant term of the quadratic equation of the V1-A1 relationship is explained by the fact that if V1 is null (x), A1 is null (y) too. On the other hand, if A1 is null, a speed, V1 different than 0 can exist. This justifies the presence of the linear V1 term in the equation. The V1-A1 correlation can infer that, in such cases, the presence of a transition curve can have a negligible impact on driver behaviors approaching the curve, because people brake mostly according to their previous speed, not according to other geometric factors.

The variability of the speed is strictly related to the variability of acceleration approaching the curve. Nevertheless, the speed on

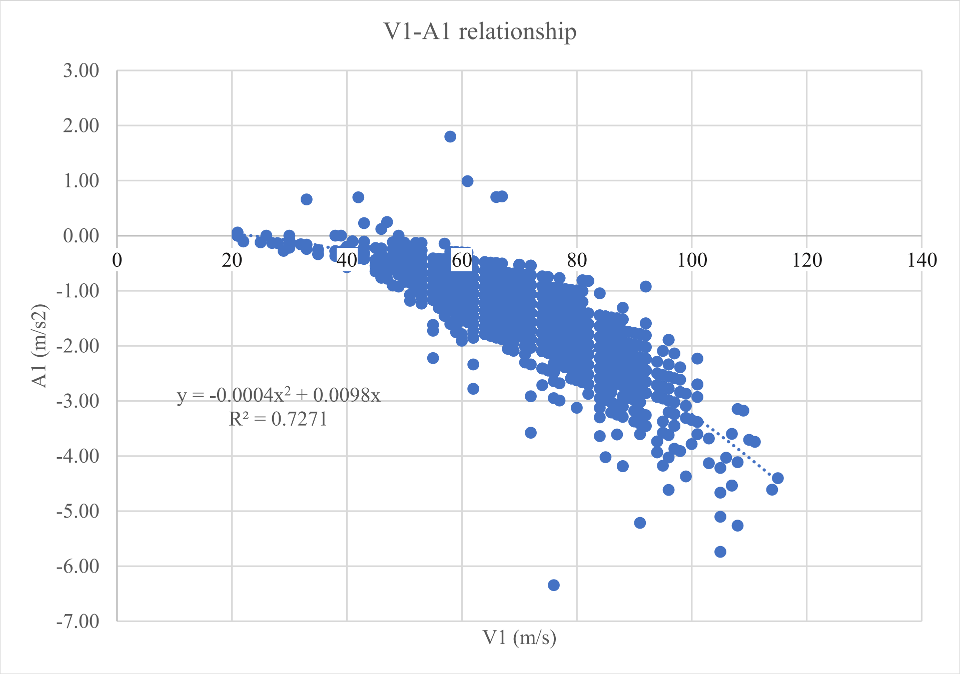


**Fig. 7.** Relationship between A1 and V1 explained by a parabolic relationship. V1 (km/h) is on the x-axis, A1 (m/s2) on the Y-axis.

segments has also implications on the driver behavior on curve. While the speeds are high, the deceleration on curves continues and it is greater when the speed is great [52]. The standard deviation also suggests that A2–4 variations are low and equally distributed over the three clusters. This result highlights the importance of speed when entering the curve on the overall driving behavior throughout the entire curve.

### *4.4. Modeling: results and discussion*

The data modelling was aimed at finding a correlation between the V1, A1, A2–4 and other possible factors, like the vehicular type and the time slot.

Looking at the modeling step, results are reported in the next table. Two attempts were made, the first one relating to just A1 and V1. A1 was calculated as a function of V1, but also of Vehicle type and Time slots. The second attempt was calculating A2–4 as a function of both A1 and V1 and the same factors: Vehicle type and Time slots. In the next table, the results of linear modelling are summarized (Table 4).

The afternoon period can potentially lead to higher A1 values than the morning period, while the heavy vehicles show a negative correlation with A1, as well as V1. Even if in previous studies, heavy vehicles were the one with the greatest speed and acceleration variation from theoretical conditions [75]. However, the influence of vehicle type (first model) and time slot (second model) seems negligible for the purpose of predicting acceleration behavior.

The time slot of the day was used in modelling speed data also to validate the 20-seconds-threshold for isolated vehicles. In fact, according to different time periods traffic may vary, and speed can vary accordingly. It was found that speed was not significantly related to any of these slots, especially at night (slot 4), when vehicles should be isolated. This result showed that the set threshold was accurate for representing the behavior of isolated drivers.

**Table 4**
Results from the linear model (statistically significant coefficients at the 5 % significance level are highlighted in bold type).

| **A1 = f(V1; Vehicle type; Time slots)** | | | | | |
|---|---|---|---|---|---|
| | *Estimate* | *Std. Error* | *t value* | *Pr (>\|t\|)* | |
| **Intercept** | 1.969 | 0.038 | 51.834 | $<2x10^{-16}$ | $R^2$=0.703 |
| **V1** | **−0.048** | $5.00 \times 10^{-4}$ | −92.842 | $<2 \times 10^{-16}$ | |
| **Heavy Vehicle** | −0.055 | 0.029 | −1.867 | 0.062 | |
| **Time Slot 2** | **0.041** | 0.013 | 3.006 | 0.002 | |
| **Time Slot 3** | −0.025 | 0.018 | −1.436 | 0.151 | |
| **Time Slot 4** | 0.011 | 0.019 | 0.591 | 0.554 | |
| **A2–4 = f(V1; A1; Vehicle type; Time slots)** | | | | | |
| **Intercept** | *1.216* | *0.043* | *28.054* | $<2 \times 10^{-16}$ | $R^2$=0.317 |
| **V1** | **−0.019** | $8.00 \times 10^{-4}$ | −23.738 | $<2 \times 10^{-16}$ | |
| **A1** | **0.028** | 0.014 | 2.026 | 0.042 | |
| **Heavy Vehicle** | **−0.103** | 0.025 | −3.997 | $6.54 \times 10^{-5}$ | |
| **Time Slot 2** | −0.002 | 0.012 | −0.206 | 0.837 | |
| **Time Slot 3** | −0.300 | 0.015 | −1.905 | 0.057 | |
| **Time Slot 4** | 0.023 | 0.016 | 1.396 | 0.163 | |

## 5. Conclusions and limitations

This study tried to investigate the influence of sharp curves on driver behaviors, quantified as speed and acceleration output. Moreover, the driving behavior was correlated with the crash occurrence and crash typology. The results could also pave the road for road countermeasures in case of promiscuous traffic with CAVs, knowing how human drivers behave and the performance of sensors, identifying the best option for the optimum coexistence of different types of vehicles. The analysis was run over a section of an undivided two-way, two-lane rural road belonging to the Metropolitan City of Bari area, SP120, where a sharp curve was anticipated by a long segment. The data collection was made thanks to radar traffic counters, equally interspaced on the road. The investigated curve was one of the safest along the road layout, which showed instead a great average crash frequency at curves, almost three times the average value for the same area. In this optic, the absence of the transition curve, together with the human behavior variability was studied to understand the adequateness of national standard prescriptions for curves in presence of existing vehicles and the future ones. The transition curve was not found to largely affect the crash occurrence, but its absence can anyway be related to risky conditions. In fact, drivers tended to adjust their behavior during the curve itself, increasing the variability of their motion. This aspect can lead to run-off crashes or head-on, in case of invading the opposite lane for difficulties in managing the curve trajectory. Also considering SAE level 2 and 3 vehicles, that can help in braking maneuvers and in keeping trajectories, being aware of the human behavior is necessary. In fact, more aggressive behaviors can lead to hard takeover or to completely disengage driving assistance. On the other side, remarks about how to improve the geometric aspects of existing roads were done: adjustments should consider the human driver needs of adequately perceiving and acting to the road environment; and the self-driving vehicle chance of executing driving tasks with reduced radii dimensions and reduced stopping sight distances. Therefore, this study can pave the road for similar analyses and assessments. This is one of the main aspects related to the practical applicability of this research together with the outcomes about speed and acceleration that can help in redesigning existing roads and, alternatively, finding low-cost but effective countermeasures (speed enforcements, lane width increase, shoulder width increase).

In fact, from the results, it seems that long segments induce aggressive behaviors, that need to be hardly managed on sharp curves. When the speeds are low (up to 24.50 Km/h), the acceleration/deceleration is almost null. Running the k-means cluster analysis emerged that approaching the curve, on tangent, around 50 % of drivers were with an average behavior (greater than the posted speed limits −70 Km/h > 50 Km /h-). The remaining 50 % was split almost equally between aggressive drivers, with speeds of 84.66 Km/h and very cautious drivers with speeds close to the speed limit (55.99 Km/h). However, on average, drivers' speeds in curve tend to the curve design speed, even if more than 20 % of drivers speed up (speeds greater than 60 Km/h).

In conclusion, two different models were proposed to calculate the acceleration from the detected variables. The first linear model, the one for A1 prediction was the most valuable. The significant variables for A1 were speed V1, vehicle type (heavy vehicles) and time slot (afternoon from 1 p.m. to 8 p.m.). This result can be used for practical applications, i.e., knowing the percentage of heavy vehicles and speeds before the curve, the acceleration can be calculated, and the road can be adjusted accordingly to ensure safer and comfortable travels.

One of the main limitations of this study is related to the sample size used for the analysis. In the case of the sample for the K-means cluster, it was relatively small, but sufficient for the analysis and to obtain meaningful results, as also stated by previous studies. As for the number of investigated curves, the size of the sample is limited to one curve only. This is due to two main aspects; the first one is related to the purpose of the study. It is a preliminary investigation of the effect of the curve on driving behavior, with connections with road safety and future transportation development. Thus, this study does not aim to be universal but to track a path for future investigations in the same field. The second aspect is that the two-way two-lane rural roads of the investigated area showed similar geometric characteristics and similar driving behaviors, as emerged from spotted traffic analysis. Therefore, the preliminary analysis was run on the most dangerous transition from tangent to curve among the investigated ones. Of course, further studies and analysis will apply the same approach to other curves within the same area, with different radii and the presence of transition curves, to understand the possible variability of driving behaviors under slightly different conditions. Despite the mentioned limitations of the study, the generalizability of the results can be applied to sites with very similar conditions (as for rural roads within the investigated area). Eventually, it is due to assess that this research is the first part of a bigger research framework aimed at understanding the influence of geometric design on driving behavior on roads where the crash occurrence is relatively high, as the two-way, two-lane rural roads, in light of the future implementation of CAVs and consequent road standard reviews and updates.

## CRediT authorship contribution statement

**Ranieri Vittorio:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Funding acquisition, Formal analysis, Conceptualization. **Coropulis Stefano:** Writing – review & editing, Writing – original draft, Visualization, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Berloco Nicola:** Writing – review & editing, Visualization, Resources, Investigation, Formal analysis. **Intini Paolo:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation, Formal analysis, Data curation.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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The authors declare that the contents of this article have not been published previously. All the authors have contributed to the work described, read and approved the contents for publication in this journal. All the authors have no conflict of interest with the collaborating entity and any organization mentioned in this article in the past three years that may have influenced the conduct of this research and the findings.

## Data availability

Data will be made available on request.

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