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Sport driving skills: A preliminary comparative study from outdoor testing sessions

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ABSTRACT

The optimization of vehicle handling is a multifaceted process that extends beyond the vehicle's design and engineering. This work focuses on the fundamental role that drivers play in shaping the vehicle's overall behavior. While technological advancements have significantly impacted the automotive industry, defining new methodologies and approaches for vehicle controls, there is not yet a uniquely recognized procedure to objectively define the skills and weaknesses of pilots. This paper aims to present the preliminary results of an innovative study, based on an outdoor test campaign with a fully instrumented vehicle, driven on track by several drivers with different levels of experience. Starting from the collected data, a series of objective and generalized metrics have been defined in order to quantify different aspects related to the direct driver interaction with the car and to the trajectory repeatability. By analyzing the results obtained from these metrics, it has been possible to highlight the differences among the participants in the experimental campaign. In order to create a practical visualization of the goodness of the approach, a driver ranking has been defined and it is coherent with both the best lap times obtained by the drivers and their actual experience.

1. Introduction

Drivers are mainly responsible for the behavior of the vehicle on the track and beyond; the driving style, indeed, encompasses a wide array of factors, such as human decision-making, vigilance, and response to unexpected situations, all of which profoundly influence the safety performance of a vehicle. All the technical improvements of the last years made it possible to realize innovative technical solutions and control systems to reduce the risks faced by pilots. Despite this, there are no studies, based on outdoor test sessions, to compare the skills of experienced and amateur pilots and to highlight what are the predominant factors that allow to significantly reduce the lap time on track. Having a robust approach to assess drivers' ability could give a substantial paradigm shift for road safety, leading to customized controls and "tailor-made" driver training. In future autonomous driving scenarios, indeed, there may be the possibility of choosing a certain driving style aimed at optimizing performance, for which it will be strictly necessary to know which parameters and behaviors have to be properly set. Several studies have been conducted on the analysis of pilots' driving style (Constantinescu et al., 2010; Karginova et al., 2012; Wang and Lukic, 2011), although not many focus on the objective characterization of the drivers' skills, such as the identification of professional and amateur drivers, as this work does. Analyzing the methodologies commonly adopted in this research field, the first criticality encountered was the lack of a consistent sample of field data, coming from laps run on track. Instead, the use of a professional racing simulator to compare drivers' behavior is widespread (Han et al., 2019; Dörr et al., 2014; Sun et al., 2018). Among them, particularly interesting is the study proposed in von Schleinitz et al. (2022) in which the authors adopted the approach to identify metrics based on the accelerations and the forces involved, more explanatory than the traditional lap time or average velocity closely related to the track and the vehicle. However, despite the validity of these studies, made possible thanks to advanced driving simulators, they may not take into account a series of phenomena that can occur in real driving conditions. Indeed, the real driving experience is substantially different from the simulated one: the pilot has to choose the right trajectory and adequate speed levels according to the possibility of managing the vehicle without risk and for this reason, he has to face several psychological aspects that could affect his overall performance. In addition, the driver must correctly interpret the vehicle's response, analyzing the feedback it receives from it. Certainly analyzing the driver's sensations through objective metrics allows us to interpret performances in a totally different way, also giving clear indications of risky behaviors and making the driving

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experience on the track safer. One of the most relevant studies is proposed by Segers (2014), in which he analyzed only professional drivers' style from different points of view, like comparisons of the use of steering wheel and pedals, but without a consistent amount of data to support the research from a statistical perspective. Taking inspiration from Segers' work, in Hermansdorfer et al. (2020) the authors identify some metrics, based on acceleration, steering and gear shifting, to classify drivers. Generally, a small number of work deals with identifying differences among professional drivers and not through parameters related to driving style. Research often focuses only on professional drivers or on the comparison between a human driver and an autonomous vehicle/software (Hermansdorfer et al., 2020; Remonda et al., 2021).

Also widespread is the study of the effect that driving style can have on the fuel or energy consumption of vehicles (Ouali et al., 2016; Xia and Kang, 2021). In this context, this work is placed with the aim of finding an innovative driver classification criterion starting from metrics, objective and applicable in every context (regardless of the circuit topology and the vehicle driven), starting only from vehicle data analysis, without any prior knowledge of the drivers. Therefore, although aware of the difficulty of a universal classification since the guide is nondeterministic and influenced by numerous accidental factors, the idea was to look at the vehicle plus man system as an unknown dynamic system whose behaviors are investigated and quantified through objective Key Performance Indicators (KPIs). In addition, modeling the behavior of drivers, acquiring and objectifying their characteristics, can also be useful for exploring the human mind and body to deeply understand how it reacts to sudden stimuli that can arise in various situations, sometimes even critical, on the track. The proposed approach was applied for the analysis of two macro-topics, fundamental for the development of this research:

1. study of trajectories and repeatability
2. metrics definition from acquired data referred to driver direct control actions

For the first point, the study and comparison of trajectories between professional and non-professional drivers involve several issues, such as the identification of the optimal trajectory (Rucco et al., 2015; Alrifaee and Maczijewski, 2018; Antonelli et al., 2019), or the identification of curves in a circuit, for which many approaches have been developed starting from commercial satellite imagery (Li et al., 2012; Gámez Serna et al., 2017). Although effective, these methods require considerable data collection or extensive operator labor. A simpler approach also followed in this activity, is to identify the corner start and end points based on the different phases that follow one another on the track (von Schleinitz et al., 2022). For what concerns the second topic, there are many works in the literature focused on the identification of metrics obtainable from acquired data without invasive processing operations (van Leeuwen et al., 2017; von Schleinitz et al., 2019; Wörle et al., 2019). From them, it emerged that one of the factors that most influence races is the use of throttle and brake, closely linked to the speeds and accelerations the driver is able to reach (Murphey et al., 2009; Feng et al., 2017; Doshi and Trivedi, 2010). Imposing the right acceleration or deceleration is crucial to follow an optimal trajectory. Ideally, the driver should exploit the full potential of the vehicle by operating at the acceleration limits; however, the latter depends on several factors, including the characteristics of the engine, the gear and the tire-road friction coefficient that should also be considered (Bugeja et al., 2017; Villano et al., 2021; Farroni et al., 2020). To resume the proposed strategy, it is important to point out the main novelties of the chosen approach:

- Use of field data acquired on a real sports car and not in a simulator environment, in order to better reflect the conditions that the drivers actually face on track;
- Classify the driving style with metrics that are objective and generalized, applicable to a driver of any experience, to any vehicle and on any circuit;
- Give a practical application of the procedure highlighting the difference between professional and amateur drivers through parameters related to their driving style.

The paper is organized as follows: Section 2 gives an overview of the whole procedure, describing the vehicle and the equipment used, the test sessions and the processing done on the acquired data. Section 3 shows how the objective metrics have been defined, exploiting the available data. In Section 4, all the metrics are used to classify the drivers on the basis of their skills, whereas Section 5 illustrates some applications of the proposed approach with some suggestions for future developments.

2. Methodology: Data acquisition & testing

The presented work is based on the analysis of vehicle data obtained from track tests, which provided an authentic representation of the behaviors exhibited by both professional drivers and amateurs on a circuit for the first time. In this study, real data acquired from track tests demonstrates greater reliability and validity compared to simulated data for several reasons. Firstly, track tests capture the intricate nuances of real-world driving conditions, including variations in surface quality, road irregularities, and other environmental factors that can significantly impact the vehicle's performance (Zarembski and Bonaventura, 2010). Secondly, the inclusion of driver emotions, such as stress, anxiety, and excitement, which are inherently present in real driving scenarios, provides valuable insights into how human factors interact with vehicle behavior (Fairclough et al., 2006; Scott-Parker, 2017; Hancock et al., 2012). Thirdly, the physical limitations and constraints of the actual vehicle, including its mechanical characteristics and limitations, are accurately represented in real data, offering a more faithful depiction of the vehicle's capabilities. Lastly, the dynamic nature of real-time interactions between the driver, the vehicle, and the track cannot be fully replicated in a simulated environment, making real data a more comprehensive and realistic representation of driving behavior. Collectively, these factors highlight the higher reliability of track data for accurately identifying driving styles.

2.1. Vehicle and instrumentation

The term 'data acquisition' refers to the process of measuring physical phenomena and recording them for subsequent analysis. In the context of this research, ensuring correct data acquisition during the testing campaign necessitates the careful selection of appropriate vehicle and sensor systems, essential to capture relevant data accurately and reliably. In this regard, a detailed description of the chosen vehicle and the accompanying sensor systems will be provided, highlighting their capabilities and specifications.

The vehicle used was a Fiat 124 Spider 1.4 MultiAir 140 hp MT, year 2017. It is a two-seater car produced from the year 2016 by FIAT car manufacturer and the model chosen for the tests was the Cabrio one (Fig. 1). It has a turbocharged inline 4-cylinder engine, petrol motor, which produces a maximum power of 140 hp (103 kW) at 5000 rpm and a maximum torque of 240 Nm at 2250 rpm. The power is transmitted to the road by the rear wheel drive (RWD) with a six speed manual gearbox with a central lever.

For what concerns the suspension system, the 124 Spider is equipped at the front with a double wishbone suspension with a stabilizer bar, coaxial spring–damper assembly and attachment on the lower element and at the rear with a five-arm multilink system with a coaxial damper spring group.

As for the braking system, it includes vented discs at the front and discs at the rear, all with a diameter of 280 mm. The tires equipped

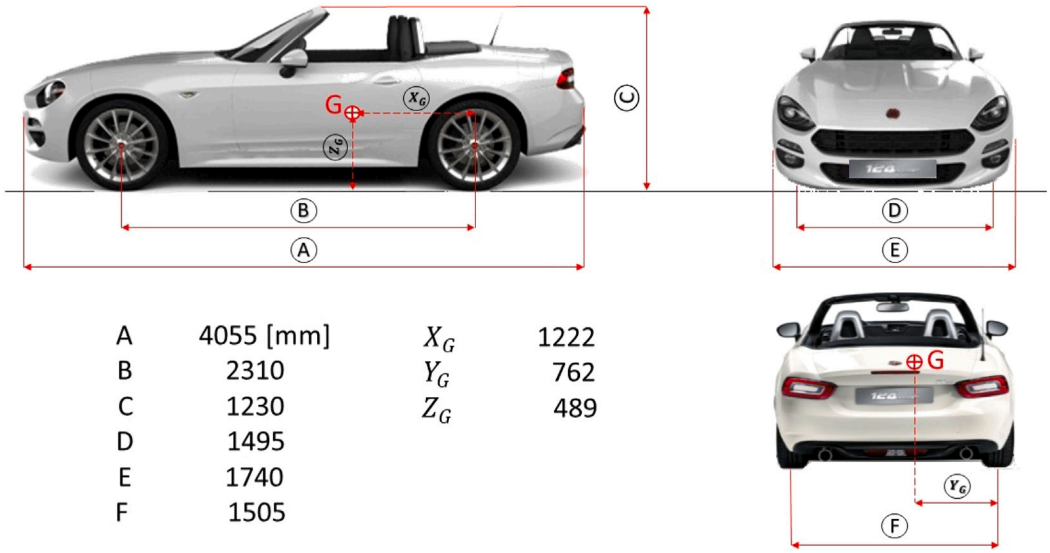


Fig. 1. Vehicle geometric parameters.

were Toyo Proxes R888R 195/50R16, which are summer track tires, homologated for the road and suitable for sports cars, that offer the best performance on dry asphalt, conditions in which the outdoor tests were conducted. To obtain the different parameters characterizing the vehicle and the tires, like the center of gravity position and the suspension kinematics, various methodologies have been adopted (D'Andrea et al., 2021; Genovese et al., 2021).

It should also be noted that, in order to enable drivers to fully exploit the car's capabilities according to their real potential and skills, TSC and ESC controls have been deactivated, leaving only the ABS system active.

Furthermore, four sensor systems were used:

1. Controller Area Network (CAN bus) integrated into the vehicle (HPL, 2002); it provides data relating to the percentage of throttle, brake pressure, gear engaged, steering angle and angular wheels' speed.
2. An inertial platform which, using accelerometers and gyroscopes, allows precise measurements of vehicle accelerations. Furthermore, measurements from high-grade kinematic global navigation satellite system (GNSS) receivers update the position and velocity navigated by the inertial sensors.
3. An optical sensor which allows non-contact measurement of speed and slip angle. This instrument enables direct measurement of lateral and longitudinal components of the velocity vector of the wheels, to also obtain the tire slip indices.
4. A complete data acquisition system capable of receiving various signals such as analog, CAN, counter, encoder and digital. All the channels, passing through the acquisition system, are synchronized with microsecond precision.

2.2. Participants

In addition to selecting appropriate instrumentation, planning the testing session is crucial for the overall success of the research. Therefore, close attention must be given to the choice of circuit and drivers to be compared. This necessitates a study that takes into account the desired outcomes and the specific parameters that will be used to correctly assess them (Lopez and Seaber, 2009; Baldisserri et al., 2014).

The circuit chosen to carry out the tests was the 'Circuito del Sele' in Battipaglia (SA). It is a flat circuit, thus chosen to avoid banking effects and facilitate inexperienced pilots, characterized by a track length of 1700 m, six curves and a 400 m straight, with a maximum speed of around 135 km/h, allowing minimum lap times around 72 s. Thanks to the coordinates of the vehicle's center of gravity, obtained from GPS sensors, and the two track boundaries coordinates, obtained by points from Google Earth, it was possible to reproduce the circuit and drivers' trajectories for each lap in MATLAB environment (Fig. 2).

To correctly conduct the tests, particular attention was paid to the choice of the group of drivers: a total of 13 were selected, including two professionals (indicated by (P) in the following figures). The term 'professional driver' refers to an individual with extensive experience on the track, who pursues track driving as a full-time occupation, whether as a competition pilot or as an instructor. He demonstrates extensive expertise and adaptability in navigating various driving scenarios and dynamic road conditions, with an adequate understanding of car mechanics enabling him to swiftly identify problems and errors, ensuring prompt resolutions, which contributes to his continuous improvement in terms of performance and safety. In particular, the professional driver identified as 3 (P) possesses extensive experience with both the track and the vehicle, whereas the other one identified as 8 (P) is familiar with the track but lacks experience with the analyzed vehicle. The remaining 11 drivers were all amateurs, selected so that six had never had any experience on track while the remaining five had less than three experiences. All the drivers selected were males, for a more rigorous comparison with the professionals, with an age ranging between 22 and 56. The subdivision of the drivers was thus carried out to optimize the resources available and guarantee homogeneous driving conditions between the different drivers in terms of tire and vehicle conditions, as well as visibility, which would have been more complicated to guarantee in the presence of a larger number of pilots.

2.3. Test session

As for the test session, participants were instructed to drive the fastest lap time possible, and, in order to have comparable data, they were put in the same driving conditions: dry track; same setup; same fuel level and track lighting; controls deactivated (TSC and ESC) and tires in the stable performance region, after having been scrubbed from their brand new conditions, still far from the wear performance decay.

For the two professional drivers, six laps have been planned with an intermediate cool down, while for each non-professional driver, 10 laps have been planned, organized as shown in Fig. 3 ('Max Performance' is a lap in which the driver pushes hard to get the best time, while 'Cool Down' is a tire-cooling lap).

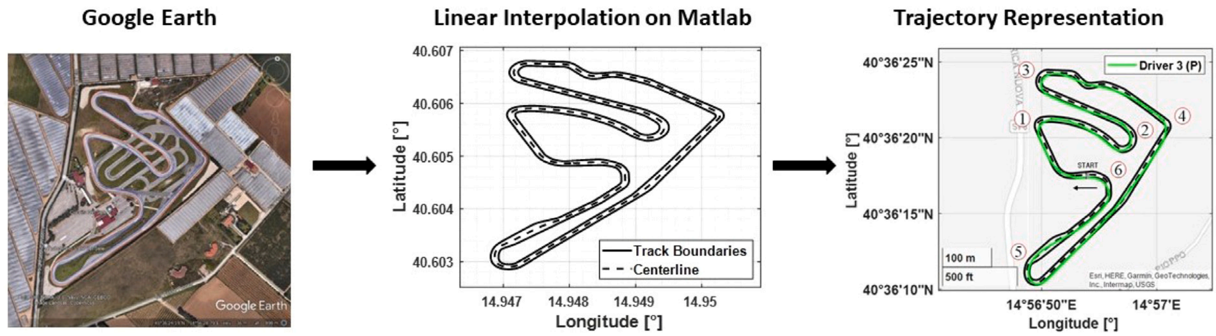


Fig. 2. Sele circuit and MATLAB representation.

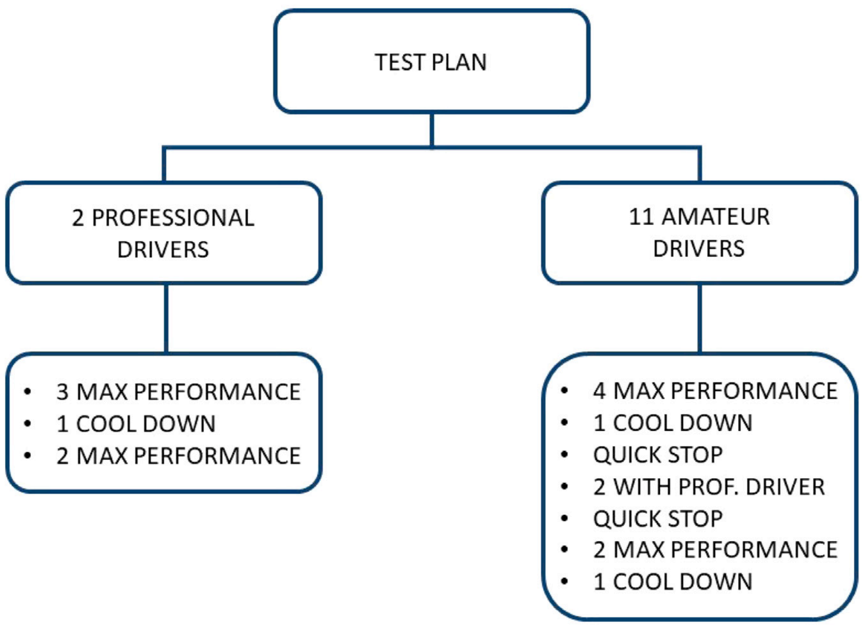


Fig. 3. Test plan.

The difference between the two categories is linked to the decision to introduce, for the amateurs, two intermediate laps in which they were accompanied by a professional driver to receive instructions, to see if just two laps allowed the amateur driver to improve his style. Furthermore, given the greater probability of inexperienced drivers making mistakes, it was decided to plan for them more laps to guarantee a fair number of acceptable laps among all drivers with greater certainty.

It should be noted that no questionnaire was conducted among the drivers before the tests, in order not to be influenced by any subjective opinion of the drivers, in line with the objective of identifying the most objective methodology possible.

2.4. Analysis procedure

The devices described in Section 2.1 were used to provide a large amount of data, which required processing operations, differing from each other in terms of units of measurement and sampling frequency, coming from different instruments. So, they were first organized according to a reference nomenclature verifying the quality of the acquisition. Then some channels had to be resampled to ensure that they all had a reference frequency of 100 Hz and some of them were also modified to make all measurements respect the conventions of the ISO reference system. Once ensured the correct form for all data, they were processed using Matlab code to solve any problems encountered (e.g. phase shift between some signals) and then to appropriately identify relevant indicators for studying drivers' behavior. The data used for the classification of driving styles were predominantly those of a kinematic nature, including steering, speed, acceleration or those referring to elements managed by the driver, such as the gearbox and pedals. In particular, being aware of all the different aspects involved in driving on track, the analysis has been divided into two macro-topics. The first one concerns the study of the trajectories and gear shifting, because it touches on different points that involve the driving style, especially related to corners' strategy, allowing both qualitative and quantitative considerations on the differences among pilots. The second topic concerns the study of the influence of braking and acceleration on performance, involving the interaction of drivers with pedals, comparisons of accelerations and jerk profiles and also identifications of the accelerations' limits reached. The procedure used to conduct these analyses was to first start with a qualitative comparison, usually graphic, to draw general considerations on what could be the most evident differences between the pilots and what quantities could be more useful for the purpose of classifying their style. After that, more quantitative analyses were conducted, with direct comparisons between data and statistical-based identification of objective and generalized KPIs.

3. Results

The results are organized according to the several metrics defined. For each metric it is described how it was obtained, to then show graphical and numerical comparisons between the different drivers. In particular specific considerations are made comparing the metrics between professional and amateur drivers, however, it is important to highlight that this is done just to provide visible and quantitative results, but the metrics are applicable to drivers of any level and represent a general style classification tool.

3.1. Trajectory study: Racing line and curve traveling

The first essential task to conduct this analysis involved gaining a comprehensive understanding of track driving techniques. Consequently, a detailed investigation was carried out, focusing on pivotal aspects such as determining the optimal trajectory to follow and effectively maneuvering through curves. Certain researchers contend that the ideal racing line represents a well-balanced compromise between minimizing the overall distance traveled and attaining the highest velocities (through the selection of a track with minimal curvature). However, it is important to highlight that no absolute best racing line exists, in fact, two drivers can achieve comparable performance outcomes through disparate route choices. Furthermore, the selection of an optimal racing line is intrinsically tied to the specific track layout and the characteristics of the available vehicle (Botta et al., 2012). Moreover, the problem of trajectory optimization is not only of a geometric nature but involves numerous aspects related to vehicle dynamics, including grip, car aerodynamics, power of the car engine and various other influential factors.

Therefore, during the research activity, these studies on track driving have been taken as a reference to get an idea of what the optimal trajectory could be. However, the primary approach adopted in the subsequent analysis focused predominantly on comparing the trajectories employed by different pilots, similar to the methodology employed in Kegelman et al. (2017) where the authors examined the statistical dispersion of professional car drivers' trajectories to quantify the repeatability of their performance.

From a first global comparison of all drivers' trajectories, a distinct pattern of higher standardization became evident among the professional ones, who consistently adhered to a standard racing line. In contrast, the amateur drivers exhibited a greater degree of variability in their trajectories, deviating from the optimal line on multiple occasions and showing inconsistent approaches to curves.

Although the repeatability of the single driver over several laps is not necessarily an indicator of better performance, it allows underlining the greater awareness of expert drivers on how to drive on track, which translates into better management of the vehicle, in terms of steering, pedals and gearbox, thus influencing, even if indirectly, the outcome of the lap. Indeed, in order to identify parameters that would allow to objectively compare the drivers, for each lap of each driver some characteristic distances, function of trajectories, have been identified (Kapania et al., 2016):

- the distances of the centerline and of the racing line from the two track boundaries;
- the distance between centerline and racing line.

In addition, to obtain adequate plots depicting the trend of these distances, a virtual distance channel was computed based on the centerline, in order to make the graphs between the different drivers comparable. All these distances were obtained using the 'Haversine Formula', described in Eq. (1), that allows calculating the shortest distance between two points over the earth's surface (Nordin et al., 2012; Winarno et al., 2017; Hegde et al., 2016).

$$a = \sin^2\left(\frac{\Delta\phi}{2}\right) + \cos\phi_1 \cdot \cos\phi_2 \ \cdot \sin^2\left(\frac{\Delta\lambda}{2}\right) \tag{1a}$$

$$c = 2 \cdot atan2\left(\sqrt{a}, \sqrt{(1-a)}\right) \tag{1b}$$

$$d = R \cdot c \tag{1c}$$

Where ϕ and λ are latitude and longitude in radiant, R is Earth's radius (mean radius 6371000 m) and d is the distance required.

An example is shown in Fig. 4 where the beginning and end of the curves are also indicated.

As expected, the main differences occur in the corners, particularly evident in turns 5 and 6 which proved to be the most difficult; therefore, insights into the individual curves from which to extract general evaluations will be presented below. First of all, it was necessary to identify the starting and ending points of the curves and to do this, reference was made to the different phases that follow one another during a lap on track. In order to identify them, three boolean variables (B_{brake}, $B_{throttle}$, B_{steer}) were used to describe whether the brake pedal, accelerator pedal and steering wheel are active or not. In particular, these assume a unitary value if, respectively, the brake pressure is higher than 10 bar, the throttle percentage is higher than 10% and if the steering angle is higher than 10°, otherwise they assume value 0. To identify the curves, the trajectory of the generic lap has been divided into six sector types (Fig. 5) based on the type of maneuver in progress with the same principle described in von Schleinitz et al. (2022):

- Pure braking: $B_{brake} = 1$, $B_{throttle} = 0$, $B_{steer} = 0$
- Trail braking: $B_{brake} = 1$, $B_{throttle} = 0$, $B_{steer} = 1$
- Pure steering: $B_{brake} = 0$, $B_{throttle} = 0$, $B_{steer} = 1$
- Pure throttle: $B_{brake} = 0$, $B_{throttle} = 1$, $B_{steer} = 0$
- Throttle steer: $B_{brake} = 0$, $B_{throttle} = 1$, $B_{steer} = 1$
- Other: $B_{brake} = 1$, $B_{throttle} = 1$, $B_{steer} = 1$

From this division, the start and end of curves coordinates have been obtained as the start of the pure braking phase and the end of the throttle steer phase, respectively, averaging the data over five laps of the professional driver 3.

At this point, it was possible to deepen the study of the trajectories on the individual curves by making a comparison of the distances of the racing line from the centerline previously evaluated. To show an application in drivers' classification, an example is shown in Fig. 6(a) for curve 5: as usually happens also in the first three corners, the professional driver tends to take the corner wider, then cut more, in order to apply the brake pedal as late as possible and to maximize the acceleration potential of the vehicle coming out of the corners. However, as for the exit, curve 5 is very variable, especially for amateur drivers, probably because it is after a long straight, so it is more difficult to manage the trajectory.

Although these qualitative comparisons are very useful and interesting, the underlying problem was that they are closely linked to the circuit topology, while the research goal was to identify general metrics applicable to any track. This is why the next approach was to quantify the variability of the distances calculated for all the laps of the individual drivers and use it as an index of repeatability of the drivers' trajectory. To evaluate the variability, the absolute standard deviation of the racing line-centerline (RL-CL) distance channels was calculated among all laps of the same drivers, for all the single acquired points in order to create a standard deviation channel for the entire length of the circuit. The reasoning behind this procedure is that a lower standard deviation indicates a greater repeatability of the driver, meaning that he always tends to travel the same trajectory. However, to quantify the difference between the drivers, the average value of the standard deviation channel was evaluated and the comparison results for the different drivers are shown in Fig. 6(b). As can be seen, professional driver 3 has a significantly lower average standard deviation than the other drivers, therefore this original parameter identified proved to be effective in distinguishing experienced drivers from amateur ones.

To further analyze the strategy with which the different drivers approached the curves, three different procedures can be identified depending on the position of the apex point, that is the point where the car is closest to the inside edge of the corner and is determined by the racing line chosen by the driver. The three different possible

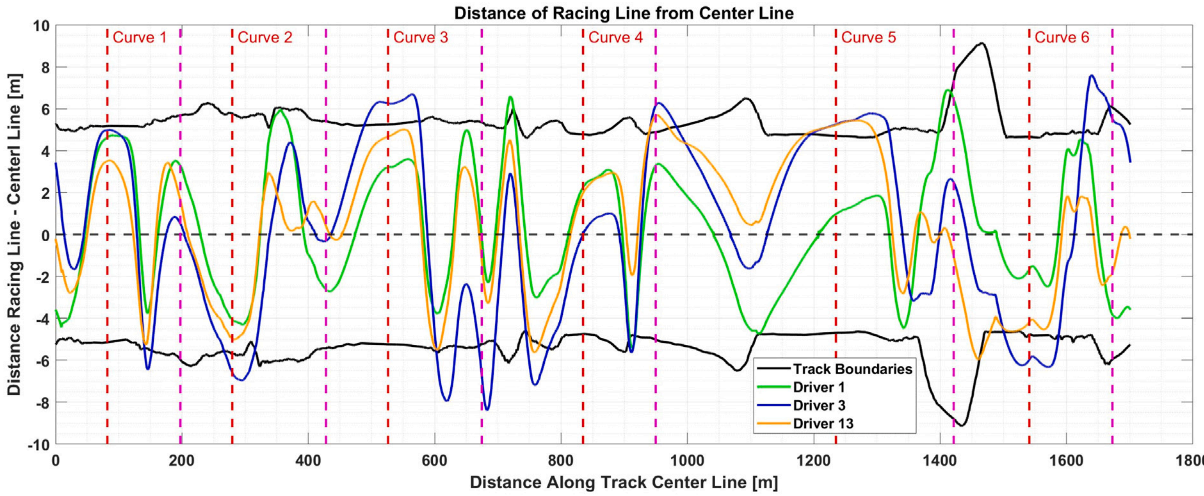


Fig. 4. Comparison of racing line distances from centerline. Observation: the distance of the track boundaries from the centerline is not constant because of the variable track width.

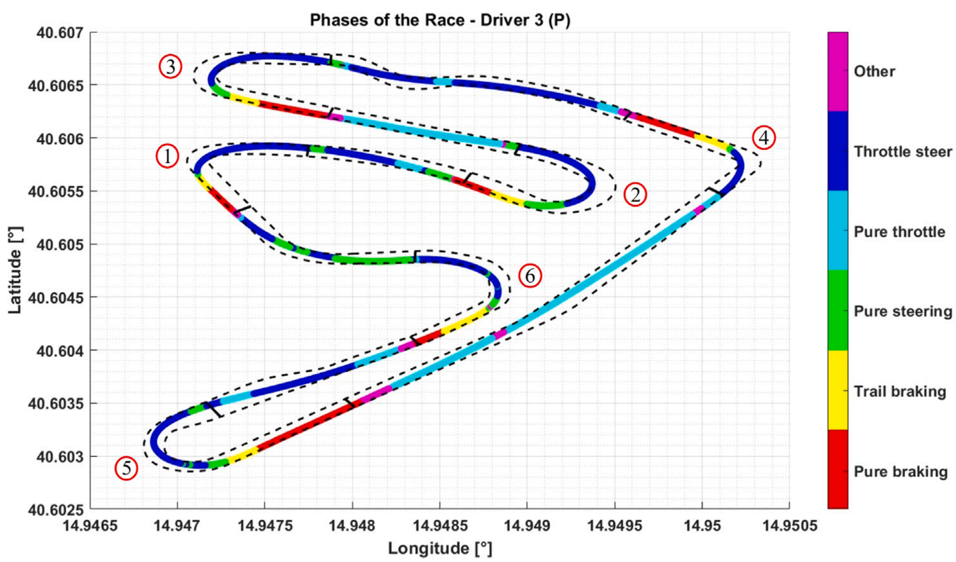


Fig. 5. Different phases of the race.

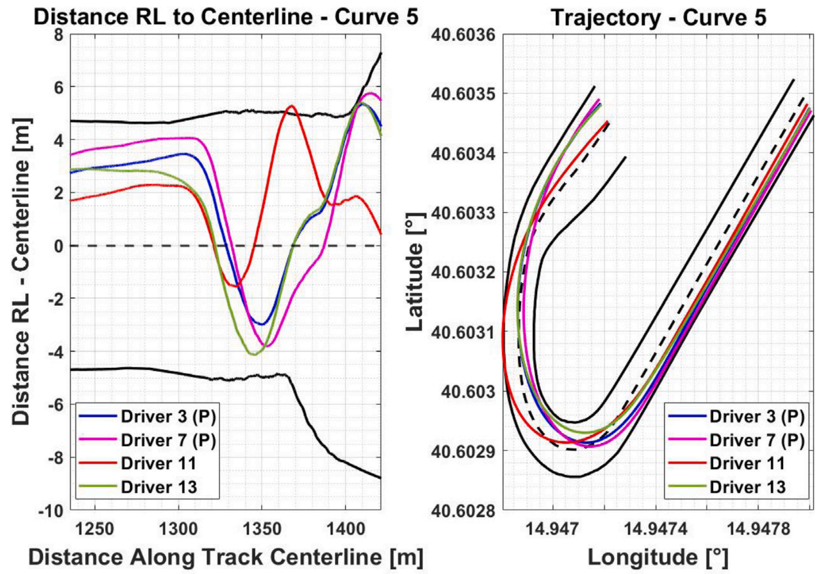
situations are 'Mid-corner Apex', 'Late Apex' and 'Early Apex' (Segers, 2014). Having identified the apex points for each corner as those which minimize the distance of the racing line from the inside track boundary, the laps of the different drivers were then compared to assess the type of strategy used at each curve. Taking curve 6 as an example (Fig. 7), it can be seen that the professional driver uses a 'late-apex strategy' and exits not too wide; this allows him to tighten the trajectory and be in a good position for the next corner. On the other hand, inexperienced driver 11 displayed inconsistent strategy choices, often widening the trajectory excessively. However, an intriguing observation emerged when considering the two laps (8–9) executed following the advice provided by the professional driver. Notably, Driver 11 demonstrated a remarkable adjustment in his trajectory, aligning more closely with the professional driver. This observation indicates that, at least in terms of trajectory choice, the presence of an experienced driver alongside proved to be effective.

In order to quantify and objectify the better repeatability of a professional driver also from the point of view of curve management, the areas of the circumferences containing all the apex points collected in the different laps of the same driver on the individual curves, which are visibly different in Fig. 7, were calculated. A smaller area indicates greater proximity of apex points, thus higher repeatability, and extending the procedure on all six curves and to other drivers, professional pilots showed to always fall into the top 3 as minor area values.

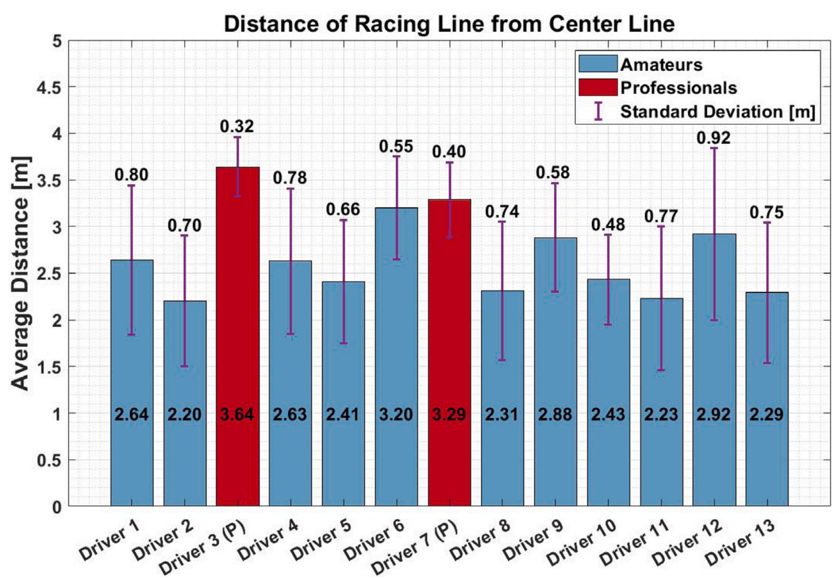
Based on these early results, it can be affirmed that the area enclosing the apex points is also an effective metric for identifying a driver's style, as it is closely associated with repeatability. However, it is worth noting that this metric is not entirely universal, since it is also influenced by the geometry of the curve. Further studies could offer the opportunity to enhance this KPI and make it more universally applicable. In general, the analysis provided quantitative evidence to support the qualitative notion about race car drivers' higher repeatability.

3.2. Gear study

In addition to the difficulty of managing the corners, another problem that emerged from the analysis of drivers' comments was their interaction with the gearbox, thus explored in this paragraph, considering that it was further complicated by the presence of a manual gearbox with a central lever.



(a) Detailed comparison of trajectories - Curve 5.



(b) RL-CL distance - Average and standard deviation.

Fig. 6. RL-CL distance comparison among drivers.

First, professional drivers showed strong consistency in shifting, facing all the corners in second gear and the straights in third, except for the longest one in which they also inserted the fourth. On the other hand, amateurs showed a strong irregularity in the changes and some of them also made frequent errors in the initial phase of the curves where the downshifting of the gear often was not perfect (Fig. 8).

Consequentially, the aspect investigated was the uniformity with which the drivers make the changes. To do this, the speeds in correspondence with the changes were collected for all the laps of the drivers, they were grouped by type of shift (2to3, 3to4) and then the variability of these speeds was evaluated using the standard deviation (Figs. 9(a)–9(b)). In both cases, it is very evident that racing drivers have greater precision and consistency proven by lower standard deviation values. Furthermore, the irregularity of amateur drivers is particularly high in 3to4 gearshifts, probably because often inexperienced drivers make this change in areas of the track where it is not necessary. The problem just mentioned is confirmed by the average shifting speed values, which are more or less in line among all the drivers for the 2to3 shift, but those in the 3to4 gearbox are much more variable and are often very low for amateurs compared to the speed at which the two professional drivers change.

To further explore the differences, the number of engine revolutions before the up-shifts was calculated and compared among drivers. In Fig. 9(c) all the rpm, regardless of the type of gear change, for five laps of drivers 3 (P) and 12 are collected; each dot represents one of the changes of the single driver and, apart from a higher dispersion for the amateur driver, the professional driver shows gear changes at higher rpm, reaching higher shifting speed. Also, it is evident the strong variability that the amateur driver 12 shows, there is no defined rpm range in which he operates. This is further proved by the significantly lower coefficient of variation values for professional drivers (Fig. 9(d)).

In order to generalize this result, the gear charts of the various pilots were also analyzed. The 'Gear Chart' is a purely kinematic diagram based on Eq. (2).

$$n_m = \frac{(V \cdot 60 \cdot \tau_t \cdot \tau_p)}{(2\pi \cdot R_e \cdot 3.6)} \quad (2)$$

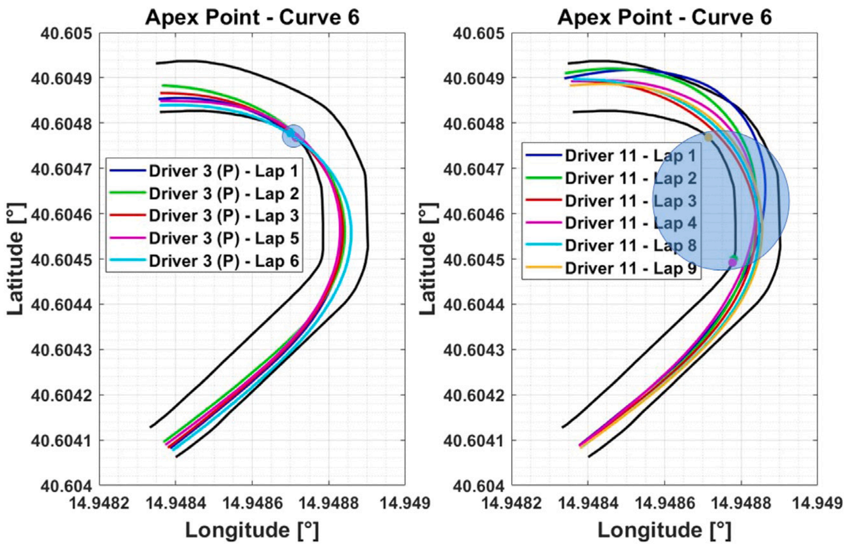


Fig. 7. Comparison of areas enclosing the apex points in curve 6 - Driver 3 (P) vs Driver 12.

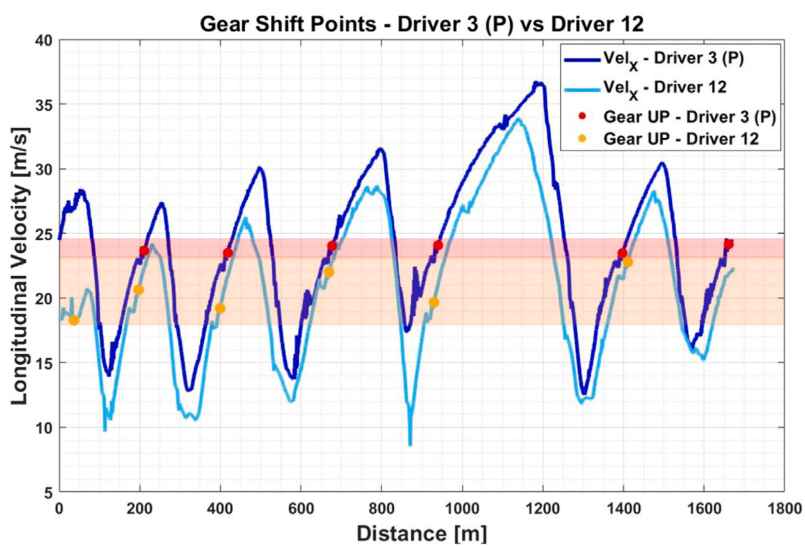


Fig. 8. Comparison of 2to3 gear up-shifting points - Driver 3 (P) vs Driver 12.

Where n_m is the number of engine revolutions, V is the forward speed in Km/h, τ_t and τ_p are, respectively, the transmission ratios to the gearbox and to the bridge and R_e is the effective rolling radius.

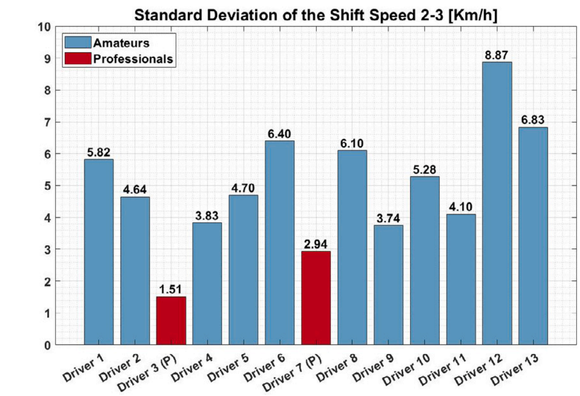
Fig. 10 compares two representative graphs of a single lap of a professional and an amateur driver. The single graph was obtained by plotting the theoretical gear chart (six lines for six gears) and superimposing the actual one on it in black. The theoretical gear chart was obtained from the kinematic Eq. (2), where, as the gears varied, the bridge ratio was kept fixed and the gearbox ratio varied. Then a speed range suitable for the vehicle under examination of 0–200 Km/h was established and the theoretical rpm values were obtained from Eq. (2), delimited in the range 1000 rpm–6500 rpm specific for the Fiat 124.

This graph allows to understand what is the range of rpm and speed covered over the entire lap and thus it was decided to evaluate the area underlying the gear chart for the pilot's working interval and use this as an indicator of exploitation of the car's potential. In fact, by comparing the areas of driver 3 (P) and driver 13 for one of their laps (Figs. 10(a)–10(b)), the inexperienced driver (12) presents an area 20% smaller than the professional because he does not push the car to its maximum capacity, especially in 3rd gear, thus reaching lower values of rpm and speed.

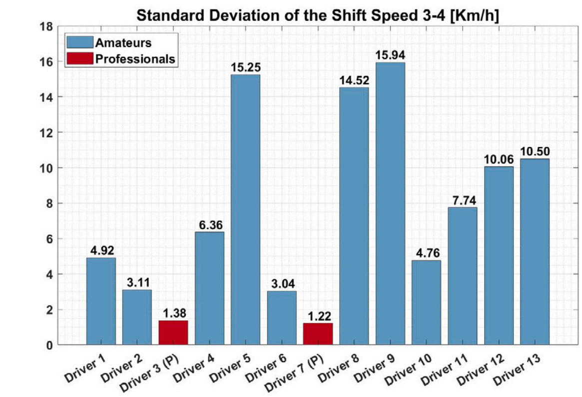
It was then decided to make this comparison of areas between all the drivers, averaging the value over all the laps of the same driver. The results are shown in Fig. 10(c): given the combination of higher area values and lower coefficients of variation, the two professional drivers occupy the top 3 positions, with the amateur driver 6 who also demonstrated notable performance. These results appear promising, suggesting that the area under the gear chart may be a valid novel indicator of a driver's skills. However, further studies will allow a better investigation of its applicability.

3.3. Braking and acceleration strategy indicators

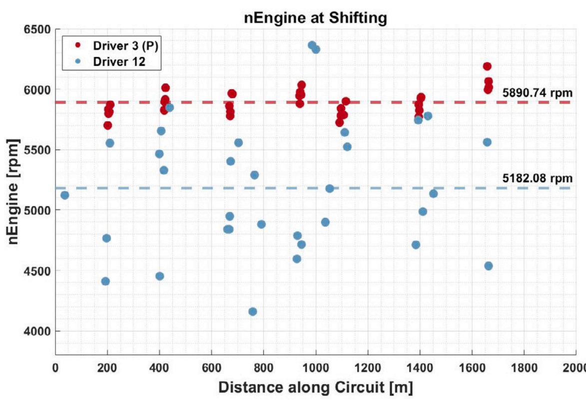
The acceleration and braking phases on track can be difficult to adjust for an amateur driver, as was evident during the test session and further confirmed by the analysis of acquired data. Specifically, the data revealed that inexperienced drivers exhibited higher variations in pedals' activation compared to professionals, who demonstrated a more consistent pattern. Notably, professionals usually achieve the full throttle and the maximum braking pressure a few moments after the pedals' activation.



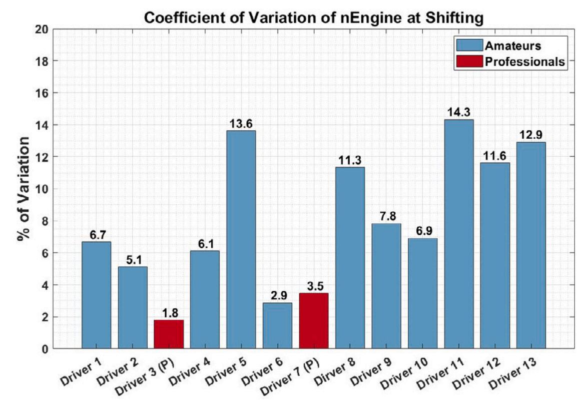
(a) Standard deviation (2to3).



(b) Standard deviation (3to4).



(c) Engine rpm over one lap - Driver 3 (P) vs 12.



(d) Coefficient of variation of engine rpm.

Fig. 9. Gear shifting comparisons among drivers.

Following these qualitative considerations, it was decided to explore the aspects highlighted with the aim of identifying indices that would allow more quantitative comparisons to be made.

The study started evaluating the braking times, which involves the entire duration of each braking phase, and the times taken to reach the peak values of acceleration and braking, starting from the moment of pedal activation. This analysis was conducted for all six curves, and subsequently, the resulting time values were averaged across all laps performed by each individual driver. Notably, professional drivers consistently demonstrated shorter durations in these measures. However, it is important to note that shorter braking times alone do not necessarily indicate superior driving skills. Other factors, such as entering corners at lower speeds, can contribute to reduced braking times. Therefore, a comprehensive analysis considering multiple parameters is crucial to assess a driver's performance and skill level accurately. For instance, considering the combination of both times described above, professional drivers proved to have excellent consistency in reaching the brake pressure peak within the first second maintaining shorter braking times than the other pilots, while reaching high cornering speeds.

Another aspect interesting to investigate was the use of the throttle. From comparison plots, it was noticed the tendency to keep the pedal pressed longer by professional drivers who in fact reached higher speeds at the entrance of the curves.

To better visualize the differences, it was decided to represent the throttle usage indices at fixed percentages by means of bar graphs (Fig. 11(a)), where the fractions of work at a certain percentage of the throttle over the entire lap are represented on the ordinates.

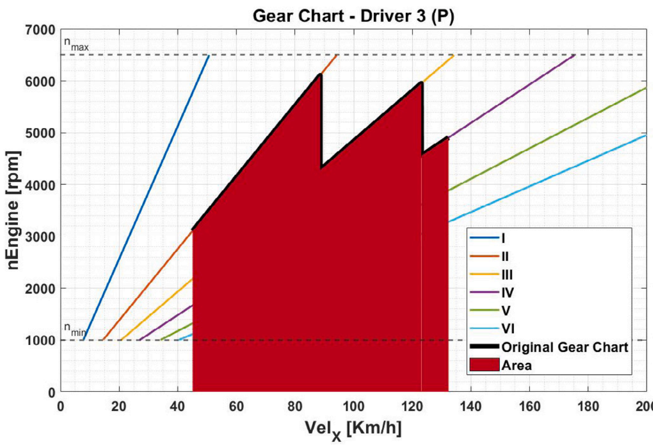
The graph shows the tendency of professional drivers to use more throttle at 100% and less at 0%, which could be an indicator of a greater awareness of how to drive on track. To further quantify and confirm these differences, the average throttle percentage values over the entire lap for the different drivers were calculated, these were then averaged over all the laps of the individual drivers and compared (Fig. 11(b)).

A similar analysis was also conducted on the use of the brake, for which the pressure values reached and the rate of use was compared assuming that at 0 bar the pedal is not pressed and that a pressure higher than 70 bar is considered high. Once again, a first general idea of the pilots' style can be deduced from the histogram in Fig. 11(c). In this case, it is interesting to note the high rates of non-use of the brake (0 bar) for professional drivers, which actually are high also for inexperienced ones, since these, accelerating less, also have to brake less. But above all, what is worth noting is the greater frequency of use of the brake at high pressures by racing drivers, as can be seen from the enlargement. Also in this case the aim was to quantify the differences, evaluating the average frequency of non-use of the brake for the riders and comparing the results also considering the average brake pressure values. Looking at the comparison plot in Fig. 11(d), professional drivers show higher average pressure values, even if with similar pedal engagement time (if not less), this means that they tend to impose more abrupt braking, reaching high-pressure values.

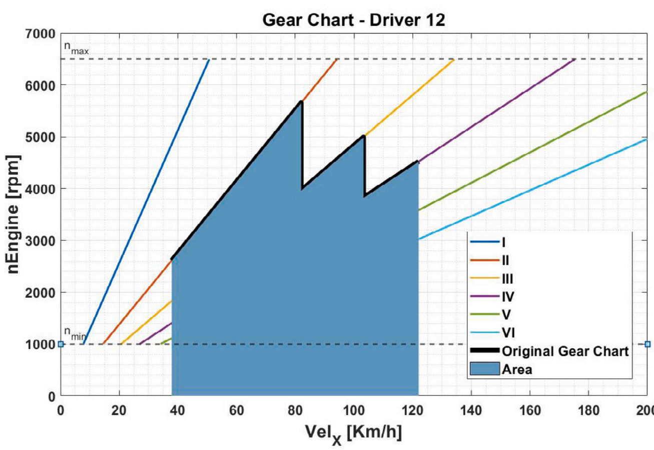
It can be concluded that the identified indicators allow to discern variations, sometimes quite substantially, among the pilots, thus potentially allowing for a more comprehensive classification of their driving styles.

3.4. Jerk study

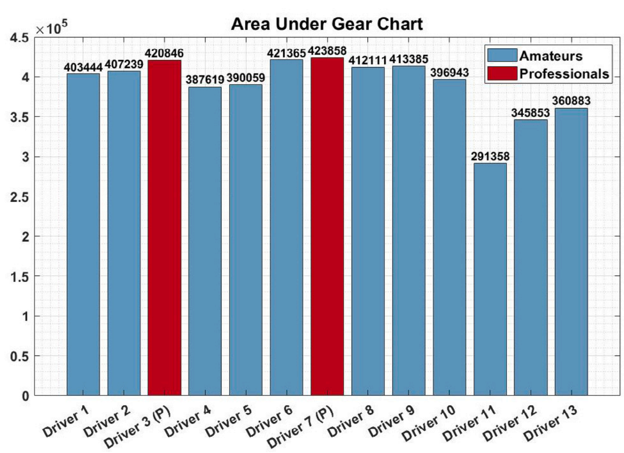
From the studies conducted so far, it emerged a tendency of professional drivers to drive more firmly, imposing more abrupt braking



(a) Area under the gear chart - Driver 3 (P).



(b) Area under the gear chart - Driver 12.



(c) Average areas under the gear chart.

Fig. 10. Comparison of areas under the gear chart.

and acceleration, showing greater responsiveness. The purpose of this paragraph is to propose a method to quantify the aggressiveness of the drivers, understood as the tendency of the pilot to drive at high speeds by imposing heavy acceleration and hard braking, starting from the 'Jerk', defined in physics as the change rate of acceleration or deceleration with respect to time. A jerk profile shows how a driver accelerates and decelerates in a particular direction, resulting in highly valuable in determining the driver's aggressiveness. In particular, it is presumed that more aggressive drivers tend to accelerate faster and thus have higher jerk profiles than non-aggressive drivers (Murphey et al., 2009; Feng et al., 2017; Doshi and Trivedi, 2010).

From an initial graphical comparison, the differences between the drivers emerged more in the longitudinal direction, especially in terms of negative acceleration and jerk peaks, than in the lateral direction, as was predictable since the latter is less involved when driving. The comparison showed a greater acceleration variability imposed by the professional drivers than that of the non-professionals, especially in the braking phases where greater distinctions were noted.

The first global approach, comparing absolute jerk values over the entire lap, was not effective. It was therefore decided to separate the phase with active throttle and the phase with active brake, analyzing separately positive and negative values. Doing so, it emerged the tendency for racing pilots to use a wider jerk in the braking phase, rather than in the acceleration one, which was also confirmed by the average values of longitudinal jerk, substantially higher during braking (Fig. 12). In particular, it can be seen that the drivers showing higher average values are the two professionals and driver 6, who has driving simulator experience.

When considering positive values of longitudinal jerk, it is reasonable to assume that they arise during the acceleration phase or the release phase of the brake pedal. Conversely, negative values of jerk tend to occur during the braking phase or the release phase of the throttle pedal. Given that jerk values are notably higher during the braking phase, it can be deduced that significant positive jerk is primarily generated by releasing the brake pedal, rather than by pressing down on the gas pedal. On the other hand, significant negative jerk is generally generated by pressing down on the brake pedal, rather than by releasing the throttle. Furthermore, the differences among drivers are slightly more marked as regards the negative jerk values during braking, suggesting that the differences are characteristic of the initial braking phase and that the professional driving style involves pressing the brake more 'aggressively', thus decelerating more abruptly. This approach was then detailed on the single curves confirming the same results.

The analysis presented allows to further characterize the drivers' style by also providing information on their readiness and firmness to drive.

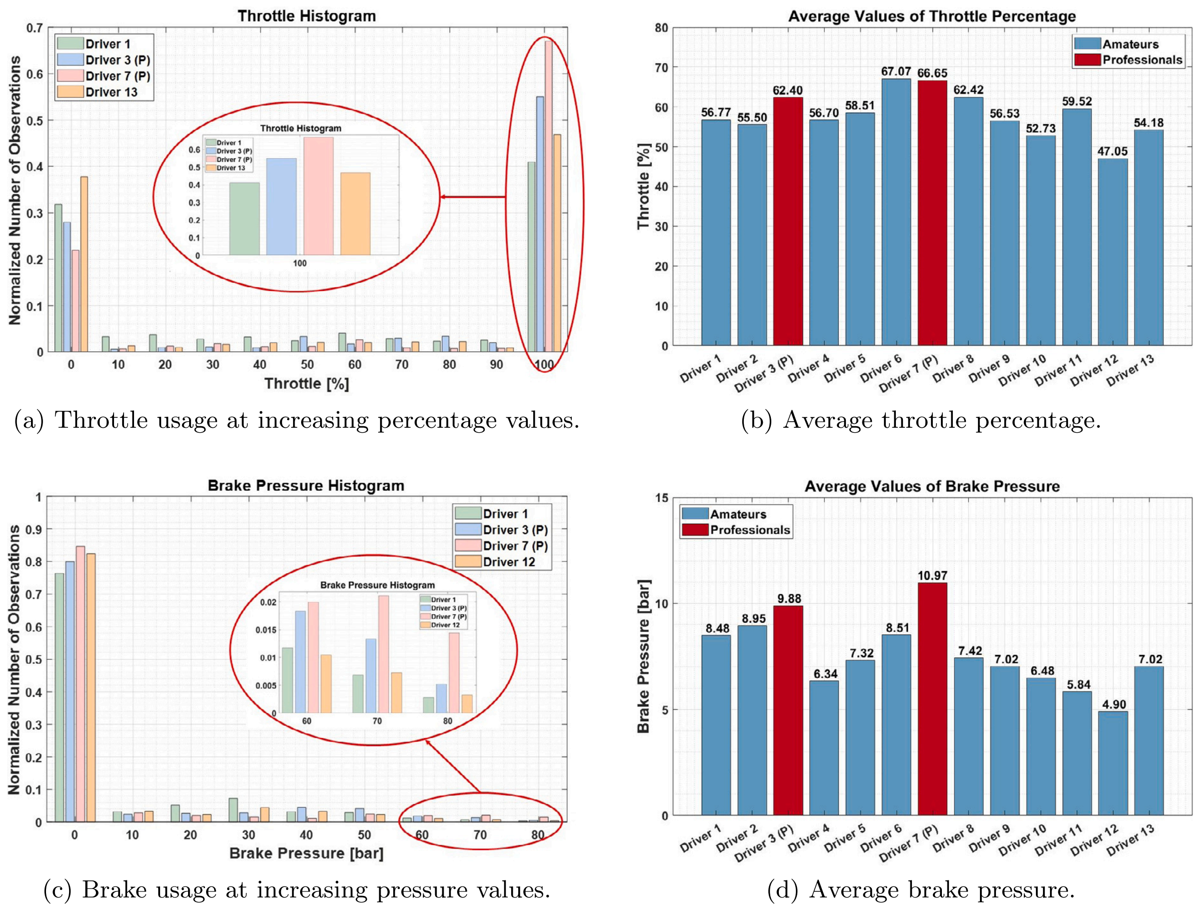
3.5. Accelerations ranges study

There is a final aspect, linked to accelerations, which has a great influence on performance on track, namely how far drivers push the vehicle reaching high accelerations while maintaining control of the vehicle.

To compare drivers' style in terms of acceleration range, the 'G-G Diagram' was used: a graph with the lateral acceleration on the abscissa axis and the longitudinal acceleration on the ordinate axis (Milliken and Milliken, 1995; Goy et al., 2016). In particular, it was decided to make the driver behaviors objectively comparable by identifying the polynomial curves (symmetrical with respect to the y-axis.) that envelope the points represented in the G-G diagram. These curves were obtained by identifying for each quadrant the arcs enclosing the 90th percentile of the experimental points and then combining the two upper and the two lower quadrants by averaging the respective percentiles. It should be specified that these curves identified do not define the global tire grip limits, rather they are indicative of the actual accelerations reached by the drivers.

As noticeable from Fig. 13(a), the main differences between drivers emerged in the longitudinal direction, which is consistent with the high brake pressure and jerk values shown.

In the lateral direction as well, the professional driver exhibits a tendency to employ higher accelerations, albeit only marginally. This is evidenced by a greater concentration of data points at higher acceleration values for the professional driver, indicating their propensity for aggressive maneuvers. In contrast, the amateur driver's data



(a) Throttle usage at increasing percentage values. (b) Average throttle percentage.

(c) Brake usage at increasing pressure values. (d) Average brake pressure.

Fig. 11. Comparison of throttle and brake pressure signals.

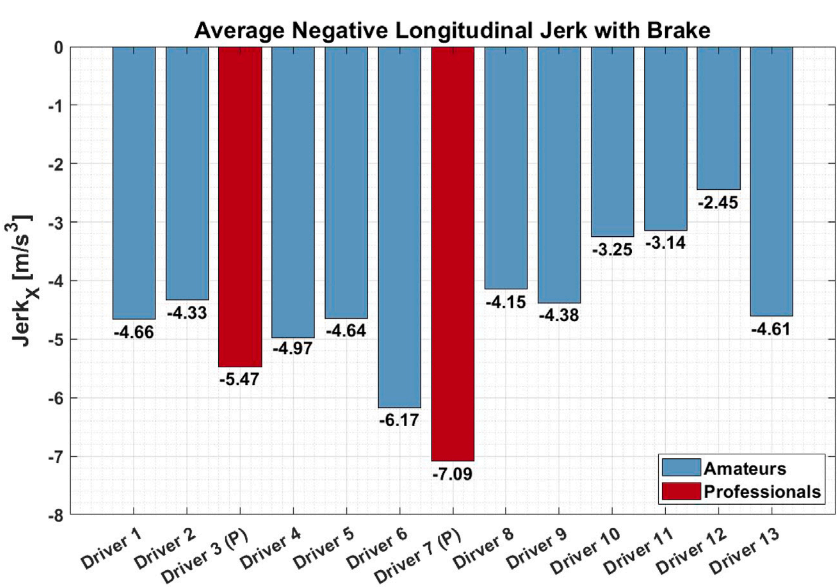
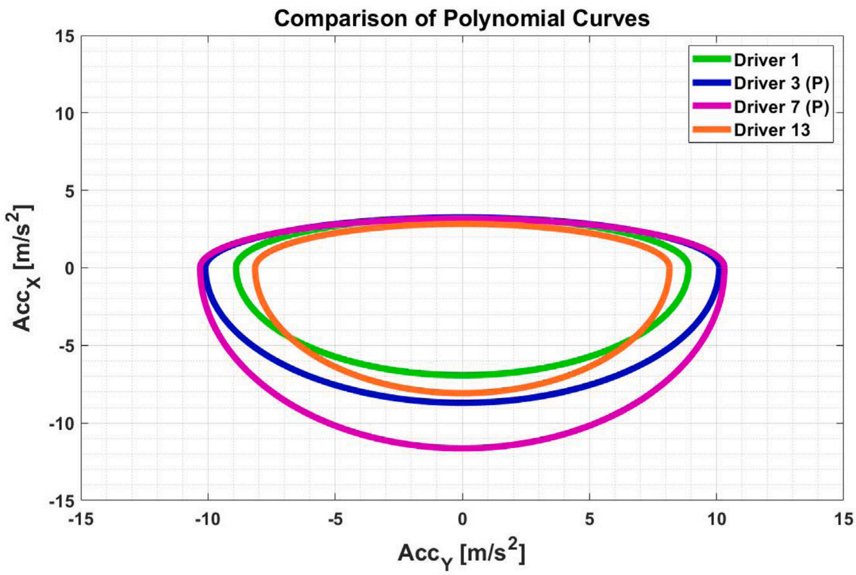


Fig. 12. Average negative jerk - Braking phase.

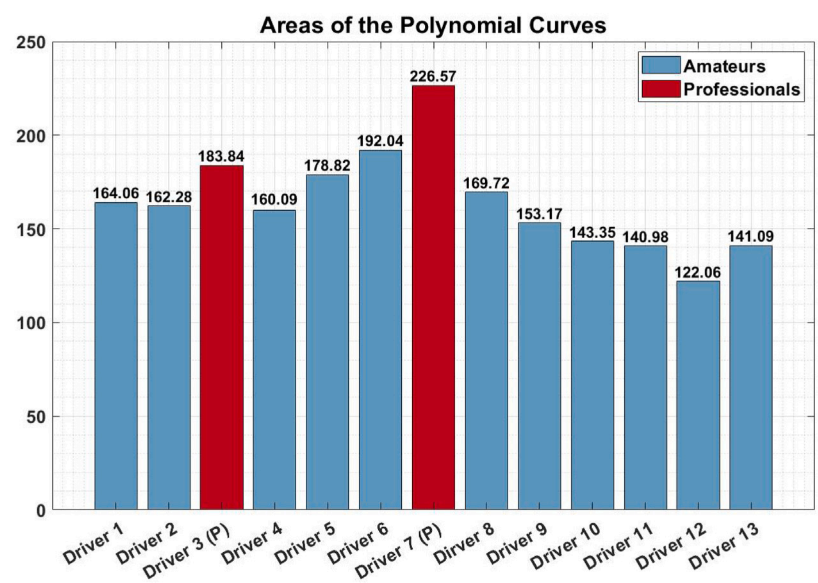
points are more centralized, suggesting a preference for more moderate accelerations.

To numerically compare the results, their areas were calculated for all the laps of all the drivers, and then for each driver an identifying value was calculated as the average of the areas over all his laps (Fig. 13(b)). As expected, the higher average area values correspond to professional drivers and to driver 6, meaning that racing drivers have a greater awareness of the limits of grip and of the vehicle, so they tend to push the car more toward them.

Therefore, these metrics can be integrated into the list of objective criteria that reasonably capture the pilots' style, confirming their potential suitability for this work purpose.



(a) Comparison of polynomial curves among drivers.



(b) Comparison of average areas of polynomial curves among drivers.

Fig. 13. Comparison of polynomial curves enveloping G-G diagrams.

4. Discussion

The final step of this activity was to group all the KPIs identified and establish a level of significance based on their robustness and their influence on the performance on track, in order to classify the drivers through an appropriate synthesis and cataloging. First, three categories have been defined:

1. Metrics strongly related to performance;
2. Metrics less influential on performance;
3. Metrics more related to style and repeatability.

In particular, metrics closely related to the trajectory, such as the standard deviation of the racing line-centerline distances and the area enclosing the apex points, belonging to category 3, were not used to draw up the ranking as they were not considered indicative of the quality of the performance. As metrics belonging to the first category, the average speed per lap, the area under the gear chart, average throttle percentage and brake pressure values and finally the area enclosed in the curves obtained from the G-G diagrams were chosen. All others were included in category 2.

After that, for each metric, membership bands have been established in relation to the values assumed by the metrics for the different drivers and for each increasing band the score assigned to the driver increases by one unit. Finally, for all metrics, the scores obtained by the drivers were multiplied by a scale factor obtained as the ratio between the points assigned to the metric for its importance and the maximum score obtainable for that metric.

$$\text{Scale Factor} = \frac{\text{Importance Points}}{\text{Maximum Score}} \tag{3}$$

Adding up the scores of all the metrics for the drivers, their final results were obtained and a ranking was drawn up according to the descending order of scores. This ranking was compared with that obtained from the average lap time values, to check whether there was consistency with this commonly used performance indicator.

The basic principle is that having assigned the scores according to the influence of the metrics on the performance and having averaged

Table 1
Driver ranking from metrics and from average lap times with classes division.

Drivers ranking from metrics			Drivers ranking from average lap time		
1°	DRIVER 7 (P)	25.52	1°	DRIVER 3 (P)	73.12 s
2°	DRIVER 3 (P)	23.04	2°	DRIVER 7 (P)	75.05 s
3°	DRIVER 6	21.43	3°	DRIVER 6	75.32 s
4°	DRIVER 2	17.49	4°	DRIVER 8	76.18 s
5°	DRIVER 8	17.06	5°	DRIVER 5	76.44 s
6°	DRIVER 1	15.19	6°	DRIVER 1	76.64 s
7°	DRIVER 5	15.13	7°	DRIVER 4	77.26 s
8°	DRIVER 9	15.1	8°	DRIVER 2	77.40 s
9°	DRIVER 4	14.17	9°	DRIVER 10	78.36 s
10°	DRIVER 10	13.5	10°	DRIVER 9	79.27 s
11°	DRIVER 11	9.78	11°	DRIVER 11	80.28 s
12°	DRIVER 13	9.76	12°	DRIVER 13	83.10 s
13°	DRIVER 12	5.96	13°	DRIVER 12	85.87 s

the values of these metrics on all the good laps for each driver, the resulting ranking should be consistent with that obtained from the average lap times.

In the ranking obtained with the metrics, three categories of drivers can be identified (Table 1): professionals (green), intermediates (yellow) and the less practical on track (red). Comparing this ranking with that obtained from the average times, the results and the identified categories seem to be quite consistent. The top three are the same, apart from the two expert drivers who are reversed; for the intermediate class, the positions change but the drivers are the same and the lap times are very close; finally, the last class coincides with the two rankings. Some clarifications need to be made:

1. All the results obtained are average results, so they give a rough indication of what the ranking could be, which is clearly not absolute;
2. The differences among the drivers, especially for those of the same class, are very subtle, so it is normal that the two rankings may be slightly different;
3. The ranking is based on the average lap times, but taking instead the best lap time for each driver, the ranking changes; for example driver 7 has the best time, also lower than that of driver 3, reflecting the positioning obtained by the metrics.

Consequently, based on the synthesis of all the identified metrics, it can be concluded that in this preliminary study, progress has been made towards the objective of establishing generalized parameters for classifying driver styles. In fact, the identified parameters enable the classification of drivers into different categories according to their abilities. The added value of this original approach, when compared to using lap time alone for classification, lies in the fact that the identified metrics offer insights into the specific aspects affecting driver behavior and, consequently, their performance, since they involve various driving factors such as trajectories, gear changes, pedal usage, and more.

It is important to note that the presented ranking was developed with a focus on distinguishing drivers' performance on the track. However, by selecting appropriate metrics (e.g. jerk, acceleration and braking ranges, etc.) and assigning suitable weighting, a similar ranking could be created for other purposes, such as investigating the origin of drivers' aggressiveness to handle issues related to road safety.

In particular, some of the metrics presented in this study, like those related to gear, brake and throttle pedal, were evaluated from information obtained from CAN bus and therefore could be easily evaluated also for vehicles normally used on the road. For the other metrics, it would be possible to install low-cost sensors capable of providing the channels necessary for their evaluation, taking care that the lower quality of the acquired signal does not impact the robustness of the proposed metrics. Thanks to their simplicity, possessing the necessary vehicle parameters, the metric calculation algorithms could be easily implemented on-board on a dedicated control unit, providing real-time information on the driver's style. In this scenario, for example, using the braking data of a specific driver, it would be possible based on his style, to customize the Anti-lock Braking System activation thresholds in order to reduce the unsafety conditions in light of how that specific driver uses the brakes. Analogously, the same approach could be useful to personalize the functioning of the Electronic Traction Control, according to the use of the throttle pedal.

5. Conclusions

In the presented activity, an original approach to the study of driving style identification was described, with the aim of identifying objective and generalized metrics starting from vehicle data acquired on track. With the goal of characterizing and distinguishing the drivers' skills, a test session was planned, involving both experienced and novice drivers, guaranteeing the same driving conditions. In particular, to bring innovation, a methodology involving the use of field data to identify parameters applicable in various contexts has been developed. This approach was used for the analysis of the drivers' trajectories, as well as their way of managing the gearbox and the vehicle at high velocities and accelerations.

From the study of the objective metrics defined, the outcomes are satisfactory, making it possible to distinguish three level "experience bands" that were also consistent with the results obtained in terms of lap times. It can therefore be said that the identified metrics appear effective in classifying driving style and might find applicability in different scenarios in which the appropriate instrumentation and data are available. The illustrated preliminary study could represent a starting point for performing the design of innovative control systems customized to the specific driver behavior, leading to the realization of a more personalized safety strategy. It should be noted that the advice of the professional drivers on track allowed slight improvements for amateurs, although overall they were not found to be decisive.

Among the further developments, one could be to extend the evaluation of the KPIs found to a more extensive and varied group of drivers, in order to understand their robustness and effectiveness. In addition, it could be useful to see what happens using different cars and also on more demanding and long circuits. Finally, some metrics could be improved or new ones implemented, for example, related to the comparison of the steering management or to the identification of the maximum grip value through a Pacejka fitting of the characteristics.

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CRediT authorship contribution statement

Guido Napolitano Dell'Annunziata: Writing – review & editing, Writing – original draft, Methodology, Data curation. **Raffaele Maglione:** Writing – original draft, Software, Methodology, Investigation. **Andrea Genovese:** Visualization, Validation, Investigation. **Aleksandr Sakhnevych:** Writing – review & editing, Validation, Software. **Francesco Timpone:** Supervision, Data curation, Conceptualization. **Flavio Farroni:** Resources, Project administration, Formal analysis, Conceptualization.

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.

Data availability

The data that has been used is confidential.

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