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Mine4Race: A user-friendly toolset for enhancing racing telemetry analysis and visualization

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ABSTRACT

In motorsports, from amateur racers to professional teams, optimizing performance is essential, whether it is by reducing lap times or maximizing power efficiency. Identifying potential driving improvements and understanding vehicle limitations are key factors in this pursuit. Even the smallest details can make a difference, making on-track data analysis critical. Engineers must rapidly interpret and communicate insights to drivers and teams, often under intense pressure. In collaboration with a motorcycle racing team, we identified key priorities and challenges in track-side data analysis to develop Mine4Race, a visual analytics system designed to help engineers in exploring telemetry data with riders. The system offers specialized charts and performance comparisons across laps, allowing users to highlight critical aspects of driving behavior and vehicle dynamics. In addition, Mine4Race features a simulation module based on configurable motorbike parameters and integrates external data sources, such as maps and weather conditions, to provide a comprehensive analytical framework. With its web-based design, it ensures optimal accessibility and usability, even in the fast-paced environment of the racetrack. We assessed the system's effectiveness through a case study conducted during a real-world racing competition, where domain experts actively utilized it for in-depth performance analysis.

1. Introduction

The world of competitive racing, such as Formula 1, MotoGP, or other motorsports, is characterized by intense moments, split-second decisions, and a continuous pursuit of performance excellence. This leads to a meticulous workflow driven by attempts, upgrades, and strategy decisions to find the right balance between settings and results. Developing a competitive prototype is an intensive engineering challenge in combination with the driver's feelings and characteristics.

Information visualization has gathered success in competitive sports in general, encouraging researchers to explore domain-specific methods for performance assessment [1]. Motorsports require advanced spatio-temporal analysis instead of statistics-based evaluations [1,2]. This is driven by the presence of vehicle telemetry data collected during races and practices, supporting model-based analysis and estimations [3,4]. Engine performance metrics, tire condition, GPS-based racing line, throttle and brake characteristics are a few examples of valuable information that engineers usually analyze [5]. Each experience on track brings important insights: during each session, teams define accurate strategies for testing new improvements. In-depth investigation of the information collected for each single lap and the comparison among different laps provide a crucial performance overview, highlighting the positive or negative outcome of the team decisions. The significant volume and complexity of the telemetry data pose a substantial challenge. Transforming this data into actionable insights requires advanced analytical methods combined with intuitive and well-designed visualization tools to make the information easily accessible and usable.

Commercial platforms already provide mature environments for telemetry inspection and lap comparison. In professional teams, however, these tools are often complemented by custom routines for simulation and exploratory analysis (e.g., MATLAB). Such scripts typically remain local to individual engineers, rely on specific hardware configurations, and are difficult to reuse or reproduce by others. As a result, analytical workflows often become fragmented, with telemetry visualization, simulation models, and custom code distributed across separate tools. Despite the maturity of commercial software, this fragmentation exposes a broader methodological gap: the lack of accessible and reproducible systems that can unify data visualization, custom analytical routines, simulation and contextual information within a shared framework. Most available solutions are closed and desktop-based, providing limited mechanisms to integrate team-developed code or to standardize simulation workflows, restricting reproducibility and knowledge shar-

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ing, which are increasingly recognized as key factors in scientific and engineering research [6–8].

In close collaboration with the experts of a motorcycle racing team, we developed *Mine4Race*, a web-based system that unifies telemetry visualization, spatio-temporal comparison, and simulation within a single, coherent environment. The platform provides a consistent analytical workflow that bridges data inspection and computational modeling, enabling engineers to perform advanced analyses through an intuitive browser-based interface. By centralizing these capabilities in a server-side environment, Mine4Race reduces hardware and software dependencies and promotes continuity across different stages of performance evaluation. This architecture shifts the workflow from device-specific, individual tools to a centralized environment accessible from any browser, allowing team members to use advanced analysis and custom simulations without programming expertise or hardware constraints. The simulation algorithms can be updated or extended with new routines, reflecting the modular nature of the system. Mine4Race therefore acts both as a practical tool for on-track evaluation and as an adaptable framework for prototyping and research, evolving as new analytical routines are developed within the team. Our main contributions are summarized as follows:

- **A unified visual analytics environment** combining multi-channel telemetry data, contextual information and simulation results within a single platform.
- **Tailored visualizations and comparative charts** supporting spatio-temporal reasoning, lap comparison and performance interpretation.
- **Integrated simulation support** through a server-side computation engine that manages MATLAB-based analytical routines accessible via the browser.
- **A real-world case study** conducted with domain experts during a race weekend, illustrating how the system supports typical analytical and simulation-driven tasks.

2. Related works

This section reviews existing methodologies and tools used in sports analysis and data visualization. By examining previous studies, we provide a comprehensive background to contextualize recent advancements and identify key challenges in motorcycle racing data analysis.

2.1. Sport data analysis

Data analysis plays an important role in sports to support athletes and teams in evaluating and improving their performance. This is reinforced by the growing amount of data collections and big data [9,10] due to sensors and tracking systems now available to gather information about multiple sport aspects [11]. Several solutions have been proposed to improve the representation of sports data and statistics to extract actionable knowledge [12–14]. In this regard, *visualization* is essential to detect insights and improve the analytics workflow, assisting the strategy and decision-making process of teams and workers [1,15]. Researchers have thus worked in collaboration with domain experts to develop tools that can offer targeted and in-depth data visualization to illustrate the relevant information in different sports [16–21].

Competitive sports data also contain multiple dimensions such as space and time [22], which makes *the spatio-temporal analysis* a key aspect for a proper performance evaluation [2,23–26]. For example, in motorsports, race engineers use visualization of spatio-temporal data from telemetry data to study the complex nature of moving object data and the approach of different drivers in the trajectory [27].

2.2. Motorsport and telemetry data

Motorsports involve numerous technical aspects, requiring teams to work both on optimizing the driver's racing strategy and fine-tuning the vehicle's setup. The expert analysis of even the smallest details is crucial to enhancing performance, as races are often decided by mere thousandths of a second [3]. Many research studies have been conducted to model the main dynamic characteristics of a motorcycle to improve the racing performance [4,28], including tires considerations [29,30] and ideal lap definition [31,32]. In [27], the authors explored the enhancement of cornering performance analysis by leveraging immersive visualization techniques to provide a more intuitive understanding of the dynamics involved.

Table 1
Feature comparison among different software.

Feature	RaceTime	RaceStudio	OptimumLap	Mine4Race
Data Analytics	✓	✓		✓
Simulation			✓	✓
For Beginners	✓		✓	✓
Mobile Support	✓			✓

However, there is still a significant gap in the literature on the analysis of telemetry collected on the track [33] with respect to the visualization of data related to statistics and general motorsport information [34]. To our knowledge, mainly commercial solutions [35–37] (advanced software for professionals) are currently designed for in-depth telemetry analysis. Table 1 reports the comparison in terms of general software objectives. RaceStudio [36] is widely regarded as the standard for data visualization in motorsport telemetry analysis. It supports advanced techniques and extensive customization options, making it highly versatile but requiring a steeper learning curve to master. RaceTime [35], on the other hand, is a great option for consumers looking for quick and easy access to telemetry data because it prioritizes usability and simplicity and is especially designed for mobile platforms. OptimumLap [37] focuses mostly on supporting simulations and offers an intuitive interface that can accommodate even novice users. While these tools offer a wide range of functionalities and are tailored for professional use, they can often be overwhelming due to their complexity and limitations in terms of hardware and operating system requirements.

3. Background

In this section, we describe the general terms and background context used during our work.

3.1. Terms and race structure

Motorcycle racing represents a complex and multifaceted system, in which teams work on their bike prototype to compete. The race engineers operate on track to optimize the performance in cooperation with the rider and several other profiles, from mechanics to data analysts. Besides specific tests tailored to the type of the event, the racing competitions are usually divided in distinct main *sessions*, in each of which a driver runs multiple *laps* of the track. Common sessions are:

- *Practices*, in which the riders are familiarized with the circuit layout and the bike settings. Teams have the possibility to test different solutions before the race, adjusting settings for optimal performances and identifying possible limitations to overcome.
- *Qualifying rounds*, forming the starting grid of the race. Riders compete independently to obtain the best possible lap, the order of which establishes the starting position.
- *Race*, representing the core of all competitions. Riders compete head-to-head to complete a pre-defined number of laps. It involves special challenges and skills, like overtaking the opponents and tire management.

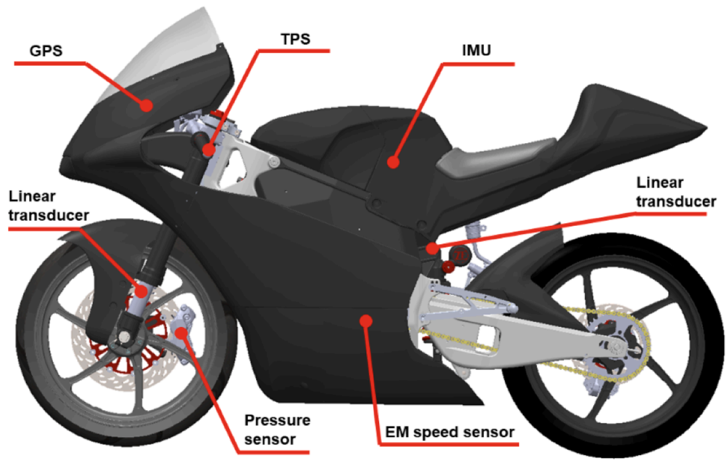

Fig. 1. Possible sensors layout for the motorcycle.

3.2. Motorcycle data

Information regarding a rider's performance primarily comes from *lap times* (including times for each sector of the track), and *telemetry data* collected from the bike.

In particular, telemetry data represent a cornerstone technology in modern racing. Based on different sensors embedded within the bike and a data logger, engineers have access to comprehensive data about several aspects of the bike. The sensor network supports the understanding of the rider driving, potential issues and weak points to be fixed for maximizing the performance on track. After each session, engineers download data from the bike to begin the analysis with the rider.

Fig. 1 shows a possible layout of sensors available on the bike. They are described in more detail in the following.

- The *GPS* sensor tracks the *trajectory* during the whole lap (position and speed) highlighting if the rider correctly follows the ideal line (i.e., the optimal trajectory to fully exploit the potential of the bike, especially at turns [31]).
- The *IMU* (Inertial Measurement Unit) sensor captures the *acceleration* and the *roll rate* of the motorcycle, allowing to evaluate the ability of the rider in exploiting the bike potentialities.
- The *Pressure sensor* monitors the *braking* while entering the turn, indicating if the braking behavior is optimal.
- The *Engine speed sensor* measures the *engine rotational speed (RPM)*, is used to analyze gear shifting.
- The *TPS* (Throttle Position Sensor) is used to read in which way the riders act on the *accelerator*.
- The *Linear transducer* (both on front and rear suspension) helps the engineer to merge the *suspension stroke* and the *suspension speed* travel with the sensations of the rider and optimize the motorcycle dynamic behavior. The suspensions are the link between the asphalt and the sprung masses and consequently characterize the behavior of the motorcycle as well as the rider's confidence. Proper setup configuration is required to face the circuit layout and guarantee optimal feeling.

4. Scope and requirements

In developing our interactive toolset for visual analytics, we first conducted a target study with domain experts to understand the challenge and the several aspects involved. In this section, we describe the motivations leading to our application (Section 4.1) and the corresponding requirements agreed with the experts (Section 4.2).

4.1. Design study with domain experts

The development of Mine4Race was characterized by a one year iterative process in collaboration with the team 2WheelsPoliTO[1], born in 2009 at Politecnico di Torino (Italy), one of the top worldwide engineering universities.[2] The team was a valuable and expert point of view, involving distinct divisions to work with people having different background and knowledge.

Based on their experience, we defined the mandatory design requirements to provide a suitable application. They revealed interest in a system capable of lightening the workflow for data analysis while overcoming the limitations of common commercial software, such as hardware requirements and integration. We summarize the main requirements for a racing team as follows:

R1 - Rider performance evaluation. Evaluate the rider performance and bike behavior at each session by comparing different laps, highlighting potential weaknesses, particularly in corners and trajectory. By inspecting data such as speed, acceleration, and braking, engineers can fine-tune various parameters to enhance overall performance on the track. Likewise, riders must assess their weaknesses by reviewing their results after each session.

R2 - Easy tool access. Provide easy access to proper tools (i.e., visualizations, computations and simulation scripts) for studying the effects of new bike setups, strategy and track conditions with a hierarchical layout, thus offering an intuitive overview complemented by options for in-depth analysis.

R3 - Integrated functionalities. Integrate all functionalities into a unified system that allows visualization, data collection, and simulation, while offering seamless extensibility to add new features.

4.2. Design goals definition

On top of the requirements defined in Section 4.1 in collaboration with 2WheelsPoliTo team, we established the main design goals to provide a valuable system for spatio-temporal analysis, simplifying the access to relevant insights.

G1 - Trajectory analysis with geo-localizazion on map. When analyzing a rider performance, one of the major aspects is the investigation of the trajectory on each sector of the track. This exploration can lead to effectively detect errors or weak points to improve. It is also essential to compare the trajectories of different laps and thus observe how the

[1] https://www.2wheelspolito.com.

[2] https://www.polito.it/en/polito/communication-and-press-office/poliflash/politecnico-is-confirmed-among-the-best-technical.

performances are affected, with special focus on turns. This analysis requires the support of geographical maps to better visualize the behavior of the rider and its evolution during the different sessions. In this way, engineers are not limited to pure raw data, but they can figure out if the track is being properly exploited and study the relevant areas of interest (e.g., ideal line, breaking points, speed).

G2 - Compare indicators among different laps. The work of a racing team usually relies on two main moments: (1) practice sessions and (2) race. The former is crucial for race preparation, since engineers and riders have the opportunity to test different solutions, find the optimal bike setup, increase the rider confidence with the bike and the track. After each session, it is important for the engineers to analyze with the rider the telemetry data collected by the bike. Similarly, at the end of the race, they investigate data to understand the key aspects and potential issues occurred. To evaluate the effects of the tested strategies and solutions, the system is expected to provide access to comparisons between laps, considering the collected parameters as performance indicators (e.g., speed, pressure on brakes, RPM). This improves the whole decision-making process and offer a valuable tool to validate changes of both the bike setup and the driving style.

G3 - Flexible dashboard to create customized comparisons. Since racing teams usually need to design specific working strategies, the experts showed interest in having a flexible system open to customization. In fact, engineers should easily focus on specific areas of interest according to their working plan. Instead of being rigid, the analytics system should offer a customizable dashboard when choosing which charts and information to show (e.g., measures, frequency), and provide an in-depth overview tailored to the specific team's needs.

G4 - Integrate analysis with supplementary information. The telemetry analysis requires the integration of additional information and advanced charts to complete the overview of the specific session. This is also important for future investigations and post-event comparisons: each performance is affected by not strictly bike-related parameters, including weather and track conditions. To have consistent analysis is important to integrate weather information concerning the specific time and location of the studied lap. Moreover, the team suggested the need of adding textual comments to track specific considerations and descriptions about the given lap. This ensures a complete platform to share information with the team and to retrieve important annotations at a later stage.

G5 - Compatibility and easy-to-use. The time window for decisions may be short during sessions and teams may require an easy-to-use toolset, accessible from different devices, including tablet and smartphones. The solution targets professionals, semi-professionals, and amateurs, whose resources are limited but still needing a versatile system without advanced skills or special hardware resources. The optimal choice is a flexible system compatible with multiple devices, meeting the different needs of users and race situations.

G6 - Usability. The application must be highly user-friendly to streamline the work of experienced engineers and facilitate the training of new team members. The implementation simplifies analysis tasks by prioritizing expert needs in the interface layout, enabling dynamic integration of external simulations

5. Mine4Race

We propose *Mine4Race*, a web application that provides an in-depth analysis of the data collected by motorcycles during races and practices. Based on the telemetry uploaded, users can have access to customizable charts, deciding which measures and parameters to observe, and comparing different laps and sessions. The dashboard is supported by supplementary material and suitable simulations to enhance the analytics process.

The developed interface is a complete web page that allows users to freely navigate among all the various sections. The general layout is basically common to both *Analysis* and *Simulation*, with three main elements: (1) a toggle **sidebar** for app navigation and additional settings, (2) the **header** with possible supplementary information, (3) the actual **visualization area** organized in panels and containers so that the user can decide which ones to show and which ones to hide.

After describing the implementation (Section 5.1) and the data processing (Section 5.2), we present the two main pages composing the system: *Analysis Interface* (see Section 5.3) and *Simulation Interface* (see Section 5.4).

5.1. Implementation

The system is designed as a web application (Fig. 2) [38,39], so that users do not need any particular software installation other than a browser. This overcomes the problems related to system requirements, such as operating system, storage memory, and general computer performance (**G5**). The application is accessible everywhere and with any device (e.g. laptops, tablets, smartphones) over the Internet. All the operations are server-side, avoiding users from the need of specific computational capabilities on their own machines.

We developed our application in Python relying on the Streamlit framework[3]. The interface integrates the Plotly library [40] for Python for charts and plots and Mapbox for map visualization[4]. When a new telemetry is uploaded, the application automatically retrieves weather information according to the specific location and date of the provided data, using the Open-Meteo public Weather API [41] (**G4**). This is important since bike setup and performance are naturally affected by track conditions. Finally, the system hosts the MATLAB Engine to perform advanced calculations and simulations according to different bike parameters. The application provides an intuitive interface to set the desired configurations, so that users are not asked to be experts in this domain (**G6**). When the configuration is submitted, the MATLAB Engine is recalled in the background and the obtained results are returned once completed.

5.2. Telemetry data preprocessing

The telemetry data used in Mine4Race are provided by the racing teams after extracting them from the motorcycle's data acquisition system. These datasets typically include heterogeneous channels recorded at different sampling rates. Mine4Race assumes that the uploaded files follow the structure commonly produced by standard telemetry loggers, containing synchronized time references and clearly identified signal channels.

Upon upload, each file is parsed and converted into a structured dictionary of `pandas` DataFrames, one per lap (e.g., `LAP_01`, `LAP_02`), identified through reset points in the time variable. Metadata are automatically extracted from timing and session information and stored in a companion JSON file, including contextual details such as circuit and bike setup. For each session, the best lap is detected and stored to support reference-based comparative analysis. Signal headers are sanitized to remove encoding inconsistencies, and a general channel mapping aligns variable names and units within a unified schema. Signals sampled at different frequencies are resampled to a common reference rate through linear interpolation, ensuring temporal synchronization and uniform vector lengths across all channels.

5.3. Analysis interface

The *Analysis Interface* is the core page of Mine4Race, providing all the designed tools for data analysis, with several views to investigate telemetry data. It integrates charts, maps, comparisons, and additional information collected by the team.

[3] https://streamlit.io/.

[4] https://www.mapbox.com.

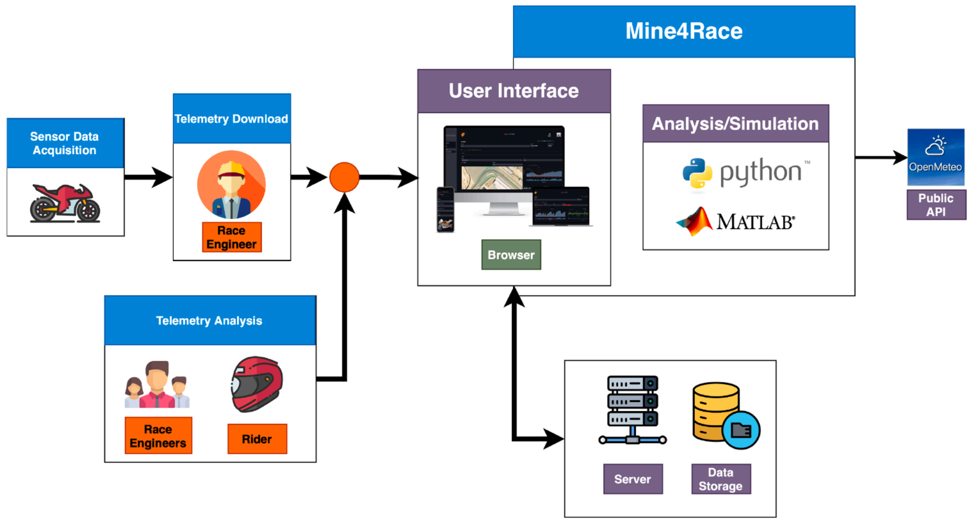

Fig. 2. Architecture overview describing the main components of Mine4Race: users need a simple browser to access the responsive web application without any additional requirements.

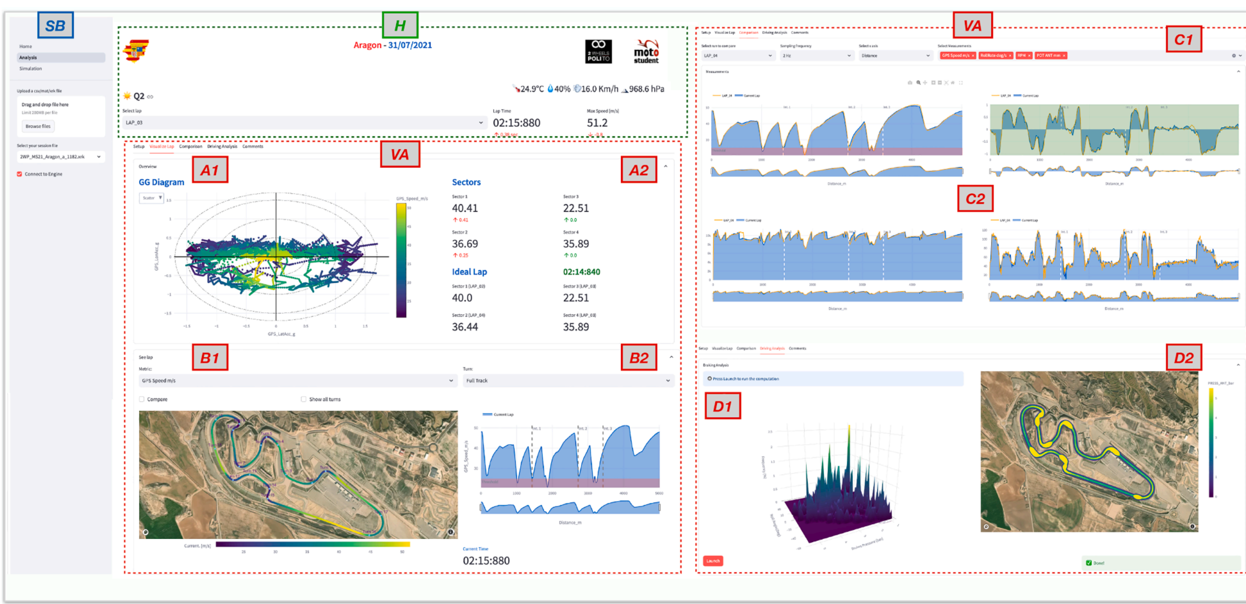

Fig. 3. Mine4Race user interface for data analysis. The interface is composed by three main sections: the sidebar (SB) for options settings, the header (H) showing additional information about the session, and the actual visualization area (VA). The *Visualize lap* view provides a general overview, including the *g-g diagram* (A1) and the *Sector analysis* (A2); the spatio-temporal *Trajectory analysis* (B1,B2). *Comparison* allows to compare different bike measures (C2) according to set filters (C1). The *Driving Analysis* investigates the braking behaviour of the rider (D1, D2).

Layout. Fig. 3 shows the *Analysis Interface*, which can be further investigated according to the following components.

The *sidebar* includes the possibility of uploading a new telemetry data file from the user's personal computer or of choosing from the list of already present ones (Fig. 3 (SB)). The *Connect to Engine* checkbox starts a new MATLAB engine instance server-side for specific computations. By default it is flagged, so that it is loaded only when the application is opened for the first time. However, if this functionality is not needed, the user can disable it to speed up the page loading.

The *header* reports additional information about the selected data file (Fig. 3 (H)) (**G4**). In fact, when a new file is uploaded, the user can specify the session name, track, and date. The title and the icon are then set accordingly, so that switching from a file to another is more intuitive. The weather information is automatically collected and reported based on the given location and time: temperature, humidity, wind, and pressure. Lastly, the lap selector makes immediate move from one lap to another, while the widgets on the right show the lap time and the maximum speed registered, highlighting the positive or negative difference with the best lap of the same session. The color of this metric indicates whether the current lap was better (green) or worse (red).

The *visualization area* reports all the charts and information retrieved by the selected telemetry (Fig. 3 (VA)). It is further divided into five panels: (**G5**): *Visualize lap, Comparison, Driving Analysis, Setup, Comments*.

Visualize lap. This panel provides the most relevant insights at a glance, reporting high-priority charts and information regarding the description of the currently selected lap.

Performance overview: when switching between different laps, it is important for the expert's eye to have a first overview of the performance of the given lap compared to the others of the same session. The *g-g diagram* (Fig. 3 (A1)) plots the longitudinal and lateral acceleration the motorcycle is subjected to, allowing the evaluation of the rider's maneuver abilities [42,43]. The envelope of the *g-g diagram* indicates how much the rider is pushing to the limit and its proper assessment requires sensitivity and expertise. The chart supports both the scatter and the hull to improve the readability of the graph in delimiting the envelope. The right side shows the *Sectors view* (Fig. 3 (A2)). It splits the lap time into the four distinct sectors of the track, highlighting the difference with the best lap (**G2**). The ideal lap is then computed by merging the best absolute sector among all the laps, indicating the reference time and lap for each sector. This representation suggests which lap should be considered for a targeted analysis, and thus understanding the performance variation in a specific part of the circuit.

Trajectory analysis: observing the trajectory plays a key role in identifying possible improvements, especially when approaching turns. It is also important for riders to visualize their behavior aspects that are less evident while riding the bike. We propose a specific view (Fig. 3 (B1)) for studying the rider's trajectories based on the GPS signal and the geo-referenced interactive map (**G1**). Team members and riders can visualize the time series of the sensor signal considered (Fig. 3 (B2)) along with the geographical representation on the map. This supports a better spatial understanding of the session, enabling analysts to discern critical sections where performance variations are most likely to occur, such as tight corners. They can correlate tracked parameters with specific locations on the track, thus including non-trivial factors (e.g., environmental, type of turn, ideal lines) and facilitating the process of detecting issues and causes of poor performances. Especially when data reveal unexpected behaviors, map visualization makes it easier to verify the situation with the rider through a more effective communication. Representing such data on an interactive map also simplifies the process of comparing multiple laps and different riders, especially for beginners (**G2**, **G6**). Following the proper trajectory is imperative for reducing the lap time: our visualization allows to quickly zoom over a desired curve, providing a turn-by-turn analysis (**G3**). Besides the two curves evolution over time, we show the gap curve between them and the specific thresholds for the given metric. For example, users can consult different metrics to see how speed and braking are handled in the track space, how they impact lap time, or whether the rider is fully exploiting the curbs.

Comparison. The comparison view is a panel designed for a further and more detailed inspection, being a special interest of the interviewed experts. It meets the design requirements for having a section devoted to comparisons and a customizable dashboard (**G2**, **G3**). The key focus is about having a more intuitive visualization than other commercial software: (i) get direct access to the data of interest regarding the target analysis; (ii) allow less experienced team members the chance to work on it even without specialized background knowledge; and (iii) make the visual analytics convenient with devices other than computers (**G5**, **G6**). The flexibility of the panel is due to the possibility of choosing special options and organizing the charts according to the user's needs. As shown in Fig. 3 (C1), using the corresponding drop down menus, the top bar allows to select:

- *Lap to compare*, for comparing the current lap (in blue) with one of the other laps of the session (in orange).
- *Sampling frequency*, for choosing between different sampling frequencies which could allow for a better reading of some signals (currently $0.2Hz$, $2Hz$, $20Hz$).
- *X-axis*, for switching from time domain to distance to compare the behaviour in a particular point of the track.
- *Measurements*, for filtering the desired measurements of the acquisition system. The dashboard is automatically updated with a new chart for each measurement.

The reported charts are completely interactive, so that the user can move, zoom and extend the plot. In addition, we represented the different track sections (defined by the three dashed white lines) and two different types of thresholds (set according to the kind of measure, when specified): (i) a red area highlights values which are too low or too high for the given measure; (ii) a green area shows the ideal range in which data are expected for proper performance. Lastly, each chart supports a bottom sliding window to easily move from one data portion to another: this enhance the usability of the application, making it more flexible to advanced data inspections, and constantly provide a total overview of the specific measurement behavior even when a subset of data is actually considered.

Driving analysis. Analyzing telemetry data is important to understand the achieved level of development and condition of the bike, but also to assess the rider's driving style. The engineers usually try to explore the confidence of the rider during tests and races to define the proper strategy.

The *Driving Analysis* panel primarily focuses on braking, as being a *hard braker* is a key characteristic of top riders. The approach to turns is a critical aspect of team strategy, aimed at optimizing the bike-rider combination to reduce lap times. We propose a 3D plot (Fig. 3 (D1)) to provide an overview of the brake usage during the lap versus the roll angle (indicating leaning to the left or right). The leaning is essential for balancing the centrifugal forces acting on the bike and rider during cornering, hence it involves advanced considerations regarding the riding dynamics [4,44]. The corresponding analysis can be affected by several aspects, such as the rider, the characteristics of the track and the geometry of the bike. The proposed visualization is then critical to understand if and how the rider combines the cornering entry phase and the braking phase. It indicates how much brake can be exploited by the rider while leaning. The analyst extracts insights about how aggressive the riding style actually is at cornering, identifying limits or room for operation to exploit the full braking potential of the bike.

To complete the braking view, Mine4Race includes an additional visualization on map (Fig. 3 (D2)), thus providing a geographical representation useful to further explore the driving style (**G1**). Differently from the trajectory analysis in the *Visualize lap* panel (Section 5.3), here the chart is fully dedicated to the braking inspection. For this reason, we do not report the raw scatter plot of the collected data, but rather a heatmap. This choice directly highlights the section of the track in which the rider brakes the most (generally at turns). By taking advantage of the map interactivity (e.g., zoom, move) and the parallel 3D graph linking braking and roll angle, teams have access to a comprehensive picture showing if the limits of either the bike or the rider are reached, while focusing on specific turns.

Supplementary documentation. From the design study conducted with experts, we identified a specific need for annotations to supplement individual telemetry data. Supplementary documentation is particularly necessary when a team collects large volumes of data across multiple sessions and tests. This requirement entails tracking special conditions that occurred and the various configurations that led to the observed results (**G4**). As illustrated in Fig. 4, we designed two additional panels: *Setup* and *Comments*.

1. *Setup:* especially during practices, teams need to try and validate several solutions to solve possible issues, test new updates, and meet the rider's requests to improve the perceived feeling with the bike. The *Setup panel* (Fig. 4 (E)) is intended to (optionally) collect information about the bike setup chosen for the given session. We defined five major categories: *tires, suspension, ECU, geometry, transmission*. Each one has its own expandable container, collecting the different parameters. The user can edit the parameters configuration using the corresponding numeric input widget. The system stores the information associated, so that it is retrieved every time that the telemetry is selected.
2. *Comments:* the final panel is reserved for collecting comments from the team about the selected telemetry file (Fig. 4 (F)). The motivation is to exploit the web-based nature of the application to provide a common platform to easily share useful information from the different team members, including the rider (**G5**). For adding a new comment, the member should specify name and role. The panel shows

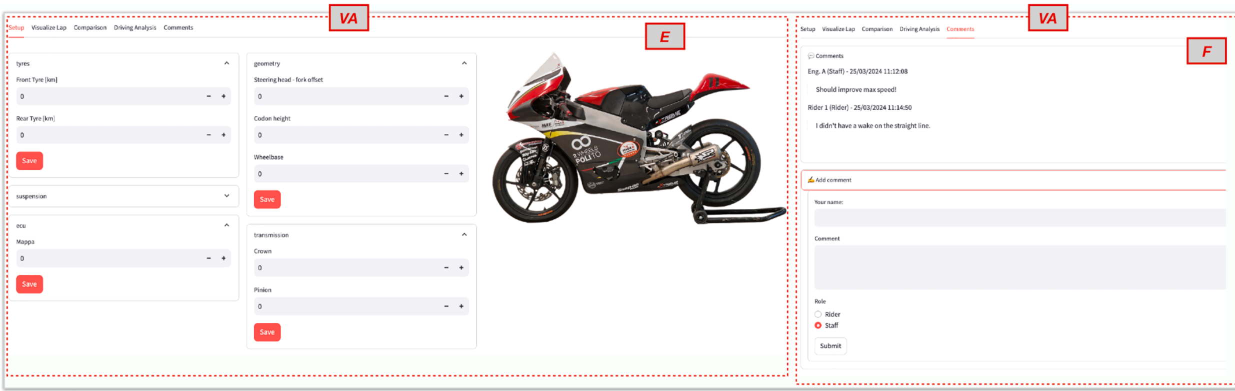

Fig. 4. Supplementary documentation views for storing additional information about the considered telemetry. The *Setup* tab collects the employed setup parameters for the given session (E). *Comments* allows for both riders and team members to annotate and share comments about the telemetry data (F).

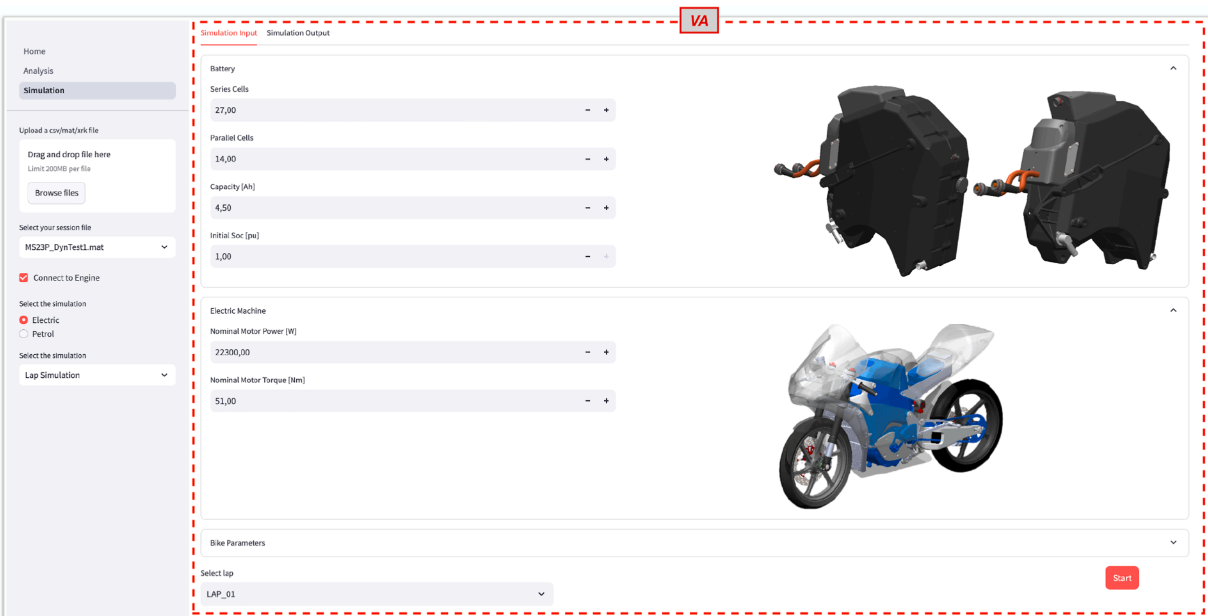

Fig. 5. Mine4Race user interface for Simulation: the sidebar (SB) allows to select the type of simulation, while the visualization area (VA) consists of two tabs for simulation input and output. Several parameters of the bike can be set by the user to test different configurations and perform the simulation accordingly.

the collected comments, thus tracking possible practical evaluations, considerations or issues detected during the session.

5.4. Simulation interface

The *Simulation Interface* was developed as a solid support to directly integrate any potential simulation script of the team within the same platform (**G3**, **G4**), allowing the inclusion of new simulations in the future according to the specific needs. Notice that the focus of our work in this regard was not about the actual development of an accurate simulation system, but rather the investigation apt to satisfy the need of integration under the same system. In fact, simulation tasks are extremely complex and often team-related. During our meetings with the experts, we found out that they are the result of costly efforts and they require specific expertise. Consequently, there is a need for a user-friendly platform to simplify usage outside the development environment. This is especially important for beginners and new team entries (**G6**).

Mine4Race takes charge of handling the computational processes and hiding the more complicated steps from the users, allowing them to focus on analysis. A common challenge in the development of simulation scripts is their deployment, as this often requires creating dedicated interfaces to manage user inputs and make the tools accessible to team members who were not directly involved in their development. This can become a bottleneck for the team's efficiency. To enhance flexibility, we propose that simulation views in our system are not hard-coded but automatically generated based on the specific simulation. This design choice significantly simplifies the inclusion of new features. Each new simulation is accompanied by a JSON file, in addition to the core MATLAB script, which documents the required user inputs. As shown in Table 2, the data structure allows the specification of multiple categories; for each category, a set of parameters; and for each parameter, details such as the name, corresponding variable, and minimum, maximum, and default values. Images are then rendered according to the category name. This approach simplifies the development process, making the extension to new functionalities almost autonomous and minimizing the need for manual intervention.

5.4.1. Layout

The page layout shown in Fig. 5 is slightly different from the one described in Section 5.3. The main aspects are:

- The *sidebar* includes two additional options (Fig. 5 (SB)): a checkbox to select the bike under study (i.e., electric or petrol), and a drop-

Table 2
Portion of input structure for lap simulation to dynamically create the page layout.

Category	Parameter	Variable	Range	Default	Unit
Battery	Series Cells	N_s	0.0 - 100.0	27.0	–
Electric Machine	Nominal Motor Power	P_n	0.0 - 50,000.0	22,300.0	Watt (W)
Bike Parameters	Center of Mass Height	h_g	0.0 - 1.5	0.67	Meter (m)

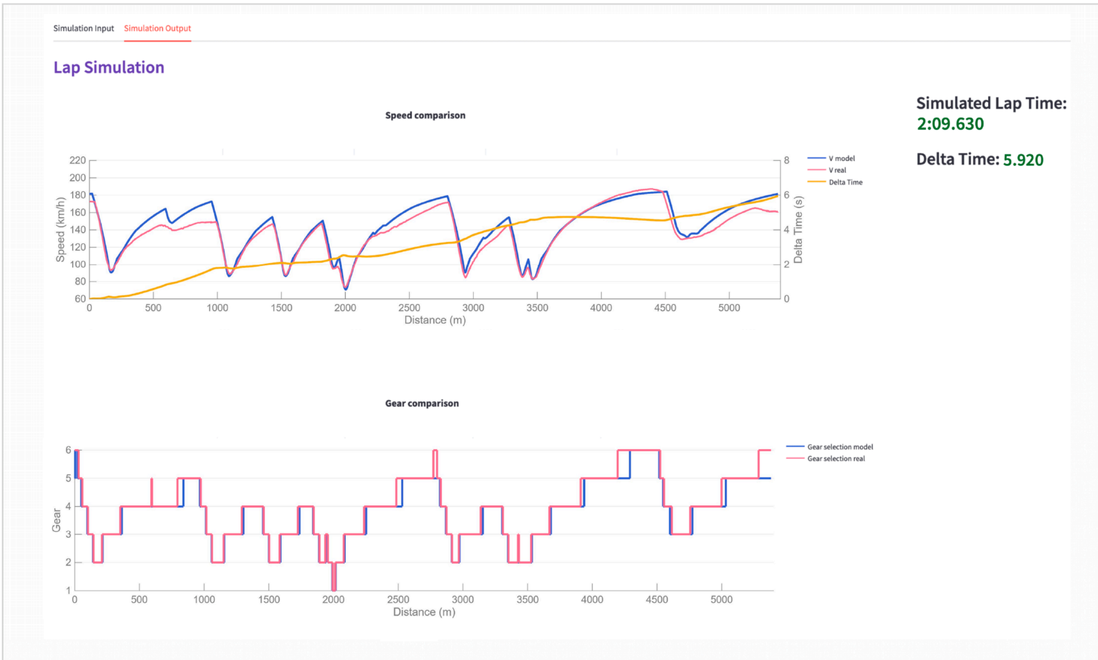

Fig. 6. Example of *Simulation output* for the petrol lap simulation. The system automatically launches the MATLAB instance with the user input parameters and returns the simulated lap time, speed profile and gear comparison between the measured behavior and the model-based one.

down menu to choose the desired simulation to run (e.g., the *Lap simulation*).

- The *visualization area* is divided into two tabs (Fig. 5 (VA)): *Simulation input* and *Simulation output*: the former to set the bike parameters and the general required inputs for the simulation, the latter for showing the results once the simulation has been completed (Fig. 6).

5.4.2. Lap simulation

The *Lap Simulation* assists teams in finding the optimal setup to maximize the performance. In electric motorcycles, for example, the optimal management of the stored energy is crucial to the overall performance and safety of the motorcycle, especially for longer sessions with multiple laps. We use a motorcycle simulator to provide comparison between the ideal (simulated) profile with the actual signals collected by the motorbike.

The simulation module integrated into Mine4Race adopts a quasi-steady-state point-mass modeling approach. This formulation represents the motorcycle as a single point mass moving along a pre-defined trajectory. It was selected to prioritize computational speed over the complexity of models involving multi-body dynamics, making it suitable for rapid strategy planning during race weekends.

Longitudinal dynamics.. The model computes the vehicle acceleration primarily from the balance of longitudinal forces. The fundamental equilibrium equation is defined as:

$$ma_x = F_{engine} - F_{drag} - F_{rolling} - F_{slope} - F_{brake}. \tag{1}$$

where:

- m is the total mass of the motorcycle and rider;
- a_x is the longitudinal acceleration;
- F_{engine}, F_{drag}, $F_{rolling}$, F_{slope}, and F_{brake} are the driving, aerodynamic, rolling, slope, and braking forces, respectively.

The aerodynamic drag and rolling resistance are speed-dependent:

$$F_{drag} = \frac{1}{2}\rho A C_d v^2, \tag{2}$$

$$F_{rolling} = C_{rr}(P, v)mg, \tag{3}$$

where ρ is air density, A the frontal area, C_d the drag coefficient, and C_{rr} the rolling-resistance coefficient, which may depend on tire pressure and speed. The engine force is derived from the nominal torque curve, gear ratios, and wheel rolling radius.

Lateral dynamics.. While the longitudinal behavior is physically rigorous, the lateral dynamics rely on simplified assumptions consistent with point-mass formulations. The simulation assumes separate driving and braking phases using forward and backward integration passes. The intersection of these profiles defines the velocity envelope. Transient behaviors are neglected, including the yaw rate during corner entry, the dynamic roll rate of the motorcycle, and complex trim variations due to suspension oscillations. Instead, the model imposes a grip limit based on a simplified *friction ellipse* concept [45]. The maximum corner speed is derived from the steady-state balance between lateral acceleration and available tire grip:

$$a_y = \frac{v^2}{R} \leq \mu_y g \tag{4}$$

where R is the local cornering radius and μ_y is the lateral friction coefficient. This simplification assumes that the tire force capacity is the primary limiter of performance, rather than the vehicle's transient handling response. For the specific application of energy management (electric) and gear selection (both petrol and electric), this approximation is sufficient as it captures the macro-level velocity profile without requiring complex modeling of the motorcycle and tire system.

Constraints and stability. Geometric constraints are re-introduced to capture essential load-transfer effects, despite the point-mass simplification: (i) *Wheelie Limit*, when the front wheel lifts under acceleration; (ii) *Stoppie Limit*, when the rear wheel lifts during braking.

These are incorporated by enforcing moment equilibrium around the tire contact points based on the wheelbase and center-of-mass height, limiting the acceleration and deceleration phases.

Model calibration. To ensure the simulation provides a reliable baseline for strategy, the model undergoes a calibration phase where physical coefficients are fine-tuned against real-world telemetry. This process isolates modeling errors from vehicle characterization and human factor. Discrepancies in the velocity profile are used to identify specific parameter mismatches, such as the *longitudinal mismatches* and the *lateral mismatches*.

The former occurs if the simulated motorcycle accelerates faster than the physical prototype, implying an underestimation of resistive forces or an overestimation of power. This is corrected by increasing the aerodynamic drag coefficient ($C_d A$) or slightly scaling down the effective engine torque curve to match the measured longitudinal acceleration.

Lateral mismatches occur if the simulation predicts significantly higher cornering speeds than those achieved on the track, suggesting an overestimation of the theoretical limit of the tire. In this case, the lateral friction coefficient (μ_y) is adjusted downward to reflect the actual grip conditions of asphalt and tires.

By iteratively adjusting these coefficients, the simulation converges on a profile that accurately represents the vehicle's physical capabilities, allowing the remaining delta to be correctly attributed to rider behavior or safety margins.

Validation and human factor. The resulting model offers a practical compromise between computational efficiency and physical consistency. However, its validation is inherently challenging in motorsport applications. The simulator computes the theoretical performance envelope of the motorcycle under ideal conditions, assuming perfect traction and adherence to the reference trajectory. Conversely, on-track data reflect rider-induced variability in addition to modeling discrepancies. Factors such as hesitation, variability in braking points, physical fatigue, and deliberate safety margins introduce deviations that must be considered when comparing the simulated and measured profiles. For these reasons, the simulator is not intended to reproduce the exact lap time, but rather to provide a stable physical baseline against which riding quality and powertrain efficiency can be evaluated.

6. Case study

We evaluated our system on field during the Motostudent competition.[5] It is a 2-years international competition in which the attending teams designed and developed their own prototypes. There are two main categories: *petrol* and *electrical*. The main event was held at the "Ciudad del Motor de Aragón", one of the world's leading racetracks (involving, for example, the MotoGP and Superbike world championships), located in Alcañiz, Spain. The competition consisted of five days of tests, practices, qualifying, and races, with jury evaluation on different aspects of the project concerning the motorcycles. The 2WheelsPoliTO race engineers for both the petrol and electric teams used the application as a support for their data analysis throughout the event. In particular, we observed and collected feedback from four members: the two track engineers and the two head of the dynamics division. They all had experience with telemetry data analysis and the team workflow. After each session, data were downloaded from the motorcycle data logger and uploaded to the system, as real-time analysis is not allowed in the competition. Besides a training phase with the engineers to make them familiar with the application, they were free to use it based on their real needs. The panel views were then used to evaluate the laps performance according to the desired focus and especially to provide the rider with a data visualization solution to understand how to improve driving.

6.1. Analytics

When the rider returned to the pit at the end of the session, we observed that access data was a priority for the team. In fact, the riders always needed to rapidly report hot feelings, like grip issues (e.g., "The rear tire is sliding on corner exit") or suspension issues (e.g., "The front feels too stiff during braking, especially in turn one."). They required a solid visualization support to improve communication with the engineers. At the same time, engineers needed to check whether the changes worked and focus on the specific aspects to be examined during the short time between sessions.

6.1.1. Lap time

The team always used the *Visualize lap* panel view (Section 5.3) as the starting point for all the analyses, thus understanding at a glance the trend of the lap under consideration. The lap times reporting (Fig. 3 (A2)) supported the classification of slow and fast laps. This step was critical for tracing the session and figuring out which laps to focus on the most. The rider needs to talk and understand the performance on a specific portion of the track.

During the qualifying session, the study of *LAP_02* (best session lap, $t = 02:15.500$) and *LAP_03* ($t = 02:15.880$) were significantly relevant from the data analysis point of view. Despite the consistent negative gap for the *LAP_03* lap time ($\Delta = 0.380s$), the *Sectors view* (Fig. 3 (A2)) highlighted that the considered lap actually had the best times for Sector 3 and Sector 4, while loosing in Sector 1 and Sector 2. This led to further investigation to assess the strong and weak points of each lap performance. Achieving the right confidence with the track proved to be a long and iterative task, in which the focus was often on improving a single sector of the track.

In addition, the telemetry analysis was supported by the employment of the lap simulation to fully assess the lap time results. As shown in Fig. 6 (petrol bike simulation), engineers studied the simulation output obtained for different configurations of bike parameters, appreciating the intuitive interface. Despite the necessary approximations of the mathematical model of the bike to ensure reasonable run times, the lap simulator showed room for improvement in relation to the simulated lap time, speed profile and rider's use of the gearbox. This was consistent with rider reporting some difficulty in managing frequent downshifts in specific corners. Based on these findings, engineers suggested slightly lengthening the final gear ratio to allow the rider to keep one lower gear before entering certain turns, avoiding an additional downshift and ensuring a smoother corner approach.

Data-driven feedback for the rider. The lap-time and sector analysis revealed that performance gains were not uniformly distributed along the circuit. While the rider achieved optimal pace in the final sectors, the initial portions of the track showed margin for improvement due to less consistent acceleration phases and delayed confidence in corner entry. The integration of telemetry and simulation results helped quantify these discrepancies, enabling the rider to focus on building rhythm earlier in the lap and maintaining a steadier pace through consecutive sectors.

6.1.2. Trajectory and turns

A common procedure for all sessions was to analyze the trajectories of different laps. During the meeting with the driver, the team members were used to have printed maps of the track with the referenced turns. Switching to an interactive computer visualization was found to be natural and intuitive for both sides, thanks to the ability to directly zoom in on the curve of interest. Placing a map for trajectories side by side

[5] https://www.motostudent.com.

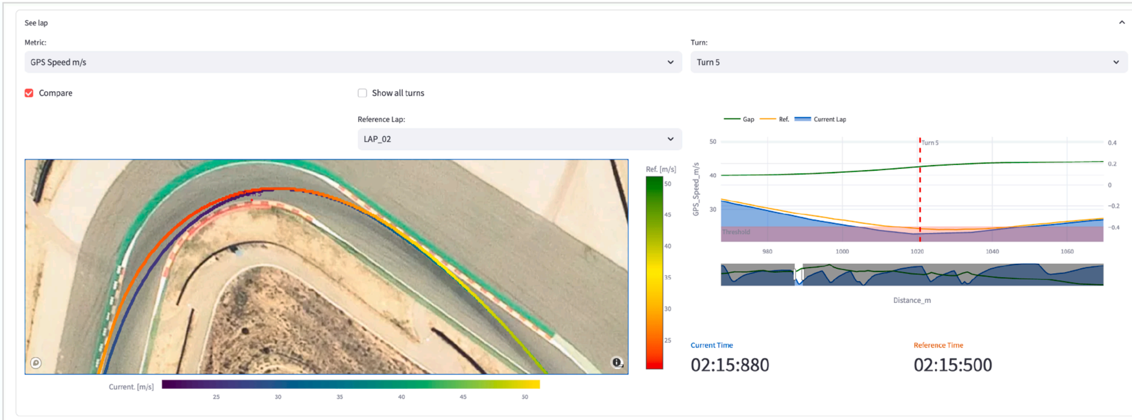

Fig. 7. Focus on turn comparison (Turn 5, Aragón) with spatio-temporal representation of telemetry data using a geo-referenced map and the time-series visualization. The view highlights the different trajectories between the current and the best lap of the session, and how speed is affected during the entire curve.

with corresponding time series proved beneficial for engineers to check the rider's feelings turn-by-turn with data.

Fig. 7 shows the visualization chosen by the team to evaluate the performance of the qualifying session with the rider. The race engineers exploited the *Metric* drop-down menu to select the pertinent sensor signal and the *Compare* option to perform comparison between the current lap (*LAP_03*) and the best one of the session (*LAP_02*), used as reference. By selecting a single turn (*Turn 5*), the engineers were able to visualize the different trajectories and understanding the corresponding feelings of the rider. During *LAP_02*, the whole cornering always showed higher speed (orange line), hence reducing the time. The visualization proved that the difference in speed was caused by the driver's choice of trajectory rather than his level of confidence. In particular, the team data analyst noticed that the blue trajectory could appear to be a more correct trajectory at first, since it was narrow and close to the clipping point (i.e., the closest point to the inside of the track on the kerb at turns, which usually ensures the fastest line). However, the support of data showed that such a close trajectory prevented sufficient speed on corner-exit phase, with the rider having troubles in taking advantage of the entire track and hence in maintaining a higher speed during the whole turn. In fact, a narrow line also implies a higher lean angle which can limit the velocity. The map stressed indeed the effect of the rounder trajectory, suggesting the impact of the different approach to cornering and which one to adopt in future sessions for that turn.

Data-driven feedback for the rider. The trajectory comparison in Turn 5 demonstrated that a wider, more rounded line enabled higher cornering speed and a smoother exit, countering the rider's initial perception that a tighter apex would be faster. This observation provided a clear and data-supported reference for refining the riding line, enabling the rider to intentionally replicate the higher-speed path identified by the analysis in subsequent sessions.

6.1.3. *Advanced insights and comparisons*

After the trajectory analysis during the meeting with the rider, the race engineers used to engage in more in-depth discussions to evaluate the session from multiple bike perspectives that data revealed. In this regard, they exploited the *Comparison view* (Section 5.3) to have an exhaustive perspective of the session.

They found effective the opportunity of customizing the view according to their need, by using the *multiselect* widget (with searching option) to filter the bike parameters of interest and the *frequency* drop-down menu to change the granularity of data. In this way, the team was able to define its own desired layout during the analysis, organizing the different charts for comparison. In evaluating the differences between slower and faster laps (or limited sections of the track), they vertically aligned the Revolutions Per Minute (RPM) and the Throttle Position Sensor (TPS) for a combined analysis of the driving style according to the track position (Fig. 8). For each turn, they compared the laps with the reference one, observing how the different cornering approaches affected the speed carried through the curve and the rider confidence in using the accelerator. The RPM assessed the behavior in gear change and the gear ratio set by the bike configuration. The TPS was used to understand when the rider opened the throttle in advance or without a linear curve. Fig. 8 highlighted a strong difference in the gear change for the two considered laps in the first sector. This observation also reinforced the findings discussed in Section 6.1.1, where combined telemetry analysis and lap simulation suggested a physical adjustment to the bike's gear ratio to improve the rider's confidence and reduce the need for additional downshifts in specific turns. Similarly, they studied the brake behavior at the major braking points, defining with the rider the optimal driving strategy to build the perfect lap.

Data-driven feedback for the rider. The combined analysis of braking, gear shifting, and throttle application allowed the engineers to outline a coherent riding strategy. The optimal approach consisted of applying firm and early braking followed by a controlled, linear release to stabilize front load during corner entry, maintaining the appropriate gear to sustain engine responsiveness, and progressively reopening the throttle just after the apex to maximize traction at the exit. This sequence provided a smoother load transfer throughout the cornering phase and improved the rider's ability to maintain consistent speed and trajectory, translating analytical evidence into actionable performance feedback for the rider.

6.2. *Usability and feedback*

The last aspect we assessed during our experience with the team was related to the usability of the application (**G6**). The interview with the engineers was helpful to collect feedback about the use of the system within the huge variety of possible scenarios that can happen during a race weekend.

6.2.1. *Quantitative assessment*

The usability of the system was quantitatively assessed using the System Usability Scale (SUS), a standardized and technology-agnostic questionnaire widely adopted in Human-Computer Interaction research to evaluate perceived usability [46]. SUS consists of ten statements rated on a five-point scale, alternating between positive and negative formulations. The final score, ranging from 0 to 100, is computed by normalizing each response and summing the item contributions. SUS is particularly valuable in applied engineering contexts because it provides a reliable

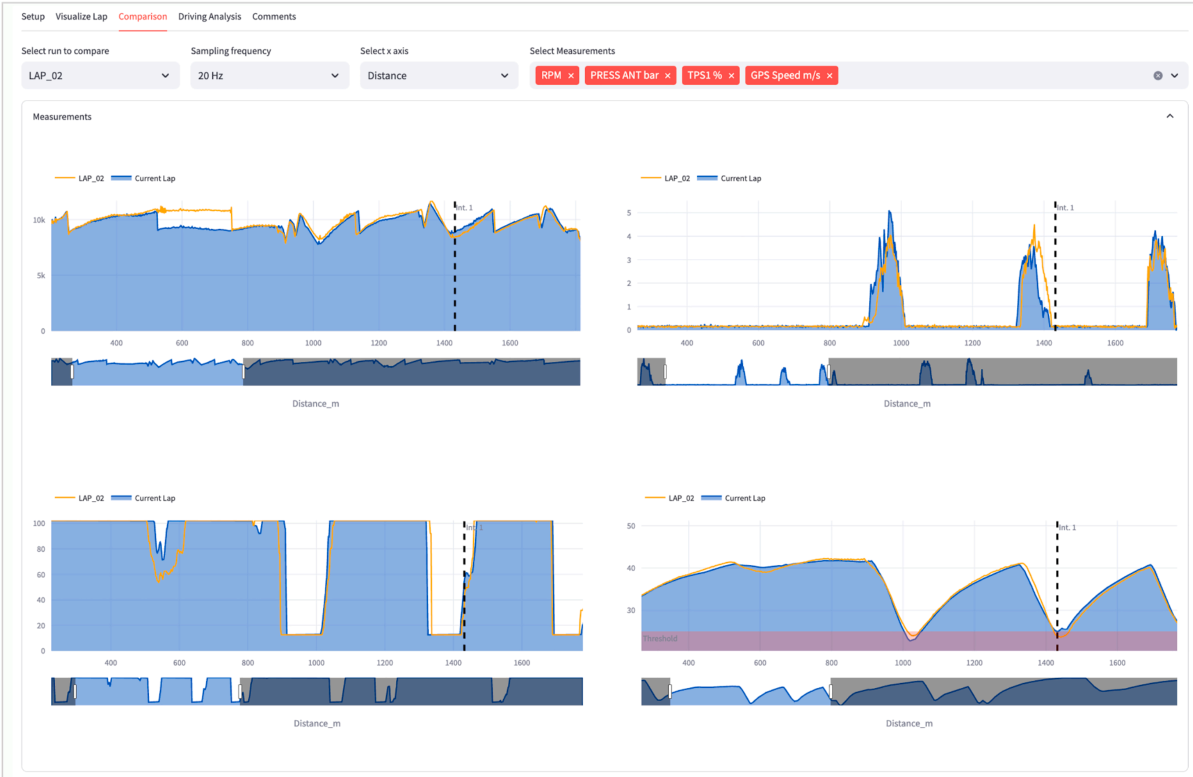

Fig. 8. Effective comparison during telemetry analysis showing *TPS, Braking Pressure, RPM, Speed*. The layout was customized by the engineer to vertically align RPM and TPS, braking and speed. For instance, the relevant difference in the RPM (and TPS) profile in the range 500–600 m indicate the different approach in changing gear.

and robust measure even with small sample sizes, making it suitable for evaluating tools such as Mine4Race.

In our study, the engineers assigned the application an average SUS score of 80 (SD = 8.10). According to the adjective ratings proposed by Bangor et al. [47], this value falls within the *“Good”* usability range. Despite the small sample size, this suggests that Mine4Race is perceived as highly usable, especially considering the demanding operational conditions in which racing engineers typically interact with telemetry software.

6.2.2. Qualitative feedback

The team, particularly the engineers responsible for data analysis, have expressed satisfaction with Mine4Race for the intuitive nature of the application, which eliminates the need to learn complex features. The ability to access visualizations on an interactive map supported by data has proven to be a prominent feature for investigating and comparing performance with the rider. However, they also noted occasional limitations compared to the workflows of the software they are more accustomed to, particularly regarding the ability to create specific charts using custom mathematical functions.

We found appreciation for the flexibility of use in having a web-based solution. The task of uploading new telemetry data to the server was up to a single engineer, ensuring accessibility for everyone on their respective devices. Storing information about bike setup with a graphical interface-featuring numeric widgets and separated containers-was considered smoother compared to their traditional method of managing data in manual, grid-based systems. This facilitated seamless workflow across various simultaneous scenarios. Additionally, they expressed satisfaction with the dynamic nature of the simulation interface, which could automatically adapt to the inclusion of new simulations without the need to design and integrate additional graphical interfaces.

Despite the general appreciation for the layout and ease of use, particularly during high-pressure moments, there were mixed opinions on certain aspects of the interface. For instance, in the "Visualize Lap" module, two experts, unlike others, expressed a preference for prioritizing the *map-based lap visualization* panel over the *performance overview* as the default display. This feedback highlights the importance of increasing the level of customization in terms of layout to better accommodate individual user preferences and workflows. They also suggested a more integrated implementation to facilitate better comparison of laps across different sessions.

Engineers were able to operate from diverse locations and at different times, supplementing the observed telemetry with comments for collective access. The ability to access Mine4Race directly through a web browser, without the need for installation, has become indispensable during crucial moments away from the desktop environment. One significant example was the "track walk", a walking tour of the track for teams before the race. This serves as a vital opportunity to assess the track layout, observe asphalt conditions, and gather valuable insights. In this case, the team members used the application on smartphones comparing the data collected in the previous days with the feeling perceived directly on the track. Specific focus was reserved to check the optimal trajectory on track and plan the ultimate details for the race strategy.

7. Discussion

Motorsport data analysis. The motorsport industry has become increasingly data-driven, where advanced analysis plays a crucial role in optimizing performance and decision making. Modern racing teams rely on telemetry not only to interpret driver behavior but also to guide iterative improvements in mechanical and electronic subsystems. The growing volume and complexity of collected data highlight the need for analytical environments capable of linking rider performance with vehicle dynamics, rather than providing static visual summaries. Mine4Race addresses this need by combining telemetry visualization, spatio-temporal reasoning, and simulation within a single workflow accessible to both engineers and riders. They are indispensable for interpreting extreme behaviors during races, allowing adjustments that can critically influence outcomes.

Findings. The proposed visual analytics environment demonstrated its effectiveness in unifying trajectory-based and time-series analyses, allowing both quantitative validation and intuitive interpretation of performance. They include geographical maps for trajectory observation, comparisons among different laps, charts for driving analysis, integration with additional information (e.g., weather information) and simulations to estimate the optimal lap profile. During the case study, engineers employed the system to isolate sector-specific losses and relate them to trajectory, braking modulation, gear-shifting, and throttle application. This process enabled targeted feedback to the rider, supporting a progressive improvement of lap consistency and cornering technique. The visual evidence was also crucial for translating subjective rider feedback into measurable parameters, closing the gap between perception and data. Visualizing trajectories on maps aids in post-race debriefings and strategy discussions.

The combined use of telemetry and simulation supported a closed-loop workflow in which riding behavior informed mechanical fine-tuning, offering a comprehensive understanding of race dynamics beyond raw time series data alone. The collection of weather information and bike setup was considered useful also for follow-up comparisons, in which contextual data is crucial. Hence, Mine4Race proved to be an effective bridge between on-track performance analysis and mechanical design iteration.

Comparison with existing tools. Unlike commercial telemetry software, Mine4Race introduces an extensible and server-based architecture that integrates simulation and analytical scripting directly into the visualization workflow. This allows customized analyses to be executed and shared without hardware dependencies or proprietary constraints, enhancing reproducibility and collaborative evaluation across team members. Furthermore, while existing platforms offer rich visualization features, they rarely provide an automated interface for defining analytical inputs and outputs, or for dynamically generating front-end components according to the structure of the analytical routine. This design feature distinguishes Mine4Race as both a visual and computational framework.

Limitations. Although engineers reported a generally smooth user experience, they highlighted some limitations that could inform future upgrades. The primary concern is that *customization options are never enough*. Each engineer tends to have unique preferences, particularly regarding control over specific settings such as thresholds and the arrangement of charts. Providing more granular customization options could better accommodate these individual workflows. Additionally, while the intuitive design of Mine4Race is a core strength, some experts noted the absence of certain advanced features commonly available in commercial software, such as the ability to generate custom channels through mathematical expressions derived from raw data. Finally, although the web-based architecture effectively overcomes the computational limitations of personal laptops, Mine4Race depends on network stability and server performance. Scalability for multi-user and high-load conditions will need to be further optimized.

Simulation Model Constraints. The simulation module itself contains modeling assumptions. The quasi-steady-state point-mass formulation does not account for transient roll and yaw dynamics or detailed tire interactions, yet it provides a stable and interpretable reference for reasoning about energy usage, braking efficiency, and trajectory adherence. These simplifications reflect a deliberate trade-off between physical fidelity and computational responsiveness, which is essential for track-side use during race weekends. Future developments of enhanced lateral dynamics or more detailed tire characterizations could enrich the analytical depth of the system while preserving the lightweight nature that enables its practical deployment.

8. Conclusion

Racing competitions represent exciting events where the implementation of the most up-to-date technologies leads to the development of advanced prototypes. The meticulous study of each individual detail is necessary for a team to be competitive, supporting effective decision making for defining the race strategy. During our collaboration with a university motorcycle racing team, we observed that visual analytics, when properly integrated into the engineering workflow, can improve communication between riders and engineers for performance assessment. Our investigation highlighted the complexities behind this kind of analysis, pointing out clear need for intuitive and accessible solutions tailored to the specific requirements of domain experts. The dynamic nature of motorcycle racing presents unique obstacles that require adaptive solutions and methodologies.

Mine4Race contributes to this evolution by providing a unified web-based platform that combines telemetry inspection, trajectory visualization, and simulation analysis within a single reproducible framework. The system enabled engineers to translate quantitative evidence into actionable instructions for the rider while simultaneously identifying parameter-level adjustments for the components of the motorcycle. Beyond immediate racing applications, the proposed approach facilitates a more intuitive and exploratory use of telemetry data for teams, researchers, and institutions with varying levels of expertise and resources. By centralizing analysis within a reproducible web-based environment, Mine4Race reduces technical barriers and promotes a wider engagement with advanced data analysis, supporting the development and validation of machine-learning and predictive models for performance evaluation and optimization.

Moreover, by reporting a real-world case study conducted during race sessions, we collected examples of analyses, engineering discussions, and rider feedback that can serve as valuable indicators for future system developments. These observations highlight how field validation provides not only evidence of usability and effectiveness, but also guidance for the evolution of analytical modules and interface design toward increasingly intelligent and adaptive tools.

This work emphasizes the importance of flexible, server-side analytical infrastructures in motorsport telemetry, capable of managing both human feedback and computational modeling within the same environment. Future work will focus on extending the analytical and simulation modules with predictive and machine-learning components to assist decision making, enable automated anomaly detection, and provide scenario-based recommendations, as well as performing a quantitative validation of analytical reliability to complement the current findings. Furthermore, integrating multi-user version control and expanding the JSON-based definition of analytical routines could facilitate broader reproducibility and collaborative experimentation across teams. The principles demonstrated here also hold promise beyond motorsports, particularly for applications in vehicle optimization, driver-assistance systems, and autonomous control validation.

CRediT authorship contribution statement

Andrea Avignone: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology; **Silvia Chiusano:** Writing – review & editing, Writing – original draft, Validation, Supervision, Formal analysis; **Lorenzo Peroni:** Writing – review & editing, Validation, Supervision, Methodology, Conceptualization.

Data availability

The data that has been used is confidential.

Declaration of interests

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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