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Innovative Design and Development of Electrical System for FRATEC EV Race Car

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ABSTRACT – *Electric vehicles (EVs) are increasingly seen as a sustainable alternative to internal combustion vehicles, especially in high-performance areas like competitive racing. Designing compact, efficient, and reliable electrical systems for motorsport environments remains a challenge. This paper details the design and implementation of a fully integrated electrical control system for the FRATEC EV Race Car, developed for the 2025 Next Generation Vehicle (NxGV) competition. The goal was to create a lightweight, modular electrical architecture that ensures stable propulsion, robust safety features, and real-time diagnostics. The system includes a 96V lithium-ion battery with a Battery Management System (BMS), a Green Motor Technology controller, a DC-DC converter, an onboard AC charger, and auxiliary subsystems like Electric Power Steering (EPS) and brake pumps, all connected via a Controller Area Network (CAN Bus). The design distributes power across high and low voltage domains and coordinates subsystems using shielded CAN communication. Bench testing and field trials, including a full race simulation at NxGV 2025, evaluated performance metrics such as temperature rise, current load distribution, communication integrity, and system efficiency. The system achieved a peak efficiency of 91.5%, fault- free CAN communication across over 50,000 messages, and safe thermal behavior with controller and battery temperatures below 45°C. The successful race event completion without system failure demonstrated the design's robustness and scalability. The results suggest this system could serve as a reference model for educational, research, and prototype-level EV projects. The FRATEC EV's electrical system represents a practical, high-performance solution for next-generation EV applications, combining safety, efficiency, and modularity.*

KEYWORDS: NxGV, electric vehicle, motor controller, battery management system, CAN communication.

1. INTRODUCTION

As electric vehicles (EVs) become increasingly prominent in sustainable transportation, the role of efficient and intelligent electrical systems is paramount, particularly in performance-demanding applications such as racing (Motevalli et al., 2011; White, 2024). The FRATEC EV Race Car project was initiated to design and validate an innovative electrical platform capable of real-world competition, specifically for the 2025 Next Generation Vehicle (NxGV) event.

This paper outlines the development of a comprehensive control system that integrates propulsion, communication, power management, and safety subsystems. The main challenges addressed include efficient power conversion, accurate torque control, battery protection, and seamless integration of multiple control units via the CAN protocol. The schematic design is as shown in Figure 1.

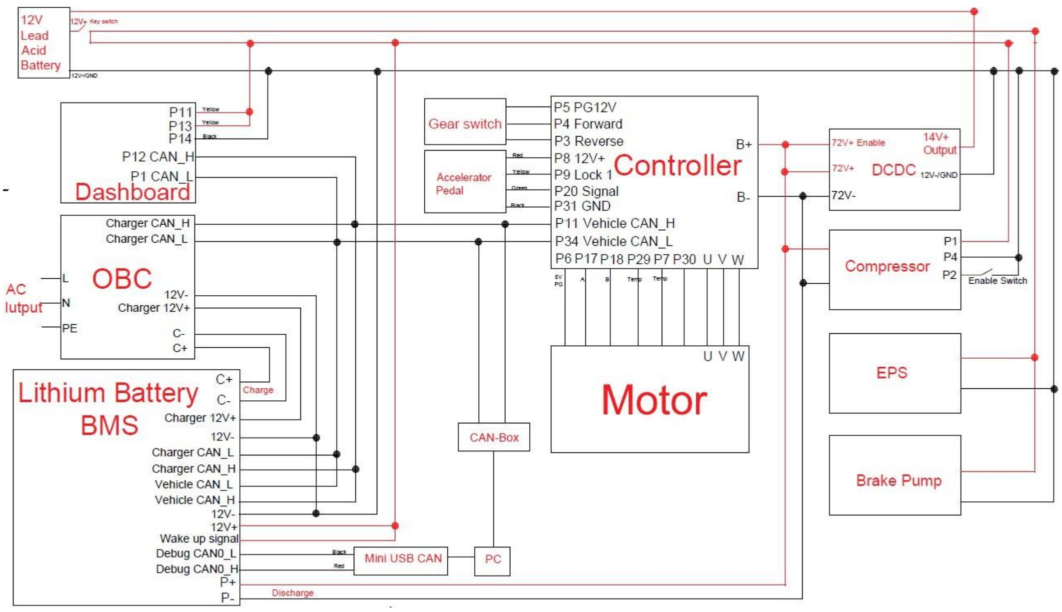

FIGURE 1: The electrical schematic diagram of the FRATEC EV race car

2. METHODOLOGY

2.1 System Architecture Design

The FRATEC EV Race Car's electrical system is built on a multi-voltage, CAN-integrated architecture to support propulsion, energy management, and auxiliary subsystems (Pereira et al., 2016). The main power source is a 96V Lithium-ion Battery Pack, monitored and controlled by a Battery Management System (BMS). This battery supplies energy to the motor controller, which powers the three-phase traction motor.

A DC-DC converter steps down the 96V to 12V, providing power for auxiliary systems including the Electric Power Steering (EPS), brake pump, and the dashboard. A 12V lead-acid battery is also included as a backup for critical low-voltage components.

Power and data flow are separated by voltage level:

- High voltage (96V): Used for propulsion via motor controller and charger.
- Low voltage (12V): Used for control electronics, display systems, and support modules.
- CAN Bus: Handles communication between controller, BMS, charger, and dashboard.

2.2 Controller and Motor Integration

At the heart of the FRATEC EV Race Car's propulsion system lies the Green Motor Technology (2024) controller, a high-performance motor drive unit responsible for regulating torque, speed, and motor behaviour in real time. This controller serves as the intermediary between the high-voltage energy source (the 96V lithium-ion battery) and the three-phase brushless DC motor that propels the vehicle. Its primary function is to convert direct current (DC) from the battery into three-phase alternating current (AC) output signals (U, V, W), which are required to drive the motor with precision and efficiency.

The controller is designed to interpret multiple input signals to determine the vehicle's operating mode and driver intent. One of the most critical inputs comes from the accelerator pedal, which transmits a throttle signal that directly corresponds to the driver's torque demand. This signal is typically analogue (or PWM), allowing for fine-grained control of acceleration.

In addition to throttle input, the controller also receives gear selection commands via digital input lines specifically P3 (Reverse), P4 (Forward), and P5 (Park). These signals inform the controller of the desired direction of motor rotation and ensure that the system enforces safe and logical transitions between driving states. Moreover, an Enable signal and a key switch input are required to activate the controller itself. These act as safety interlocks, ensuring that the system does not become operational until both hardware and driver's conditions are satisfied.

Once activated, the controller delivers high-frequency, modulated three-phase power (U, V, W) to the traction motor. This output is adjusted dynamically based on real-time input conditions, load demands, and operational limits. Simultaneously, the controller engages in constant communication with other vehicle subsystems through CAN_H and CAN_L data lines. This allows the controller to share critical operational data such as motor speed, temperature, voltage, and error status with the Battery Management System (BMS), dashboard interface, and diagnostic modules.

Feedback signals from the controller are also routed to the dashboard system, enabling the driver to receive real-time updates on vehicle status, speed, and any fault conditions that may arise. This feedback loop is essential for both performance monitoring and ensuring operational safety during high-stress scenarios, such as during races or rapid acceleration events.

In summary, the Green Motor Technology controller acts as the central nervous system of the propulsion unit, intelligently managing energy flow, interpreting driver inputs, and ensuring safe, efficient, and responsive vehicle movement.

2.3 Communication and Control: CAN Bus System

The electrical system of the FRATEC EV Race Car is underpinned by a Controller Area Network (CAN Bus), a robust, industry-standard protocol that enables high-speed, real-time communication between all major subsystems. This communication infrastructure is fundamental to the coordinated operation of the vehicle, ensuring that power delivery, charging, safety monitoring, and diagnostics are synchronized across the platform without delay or conflict.

At the core of this architecture is a multi-node CAN network in which each critical module functions as both a transmitter and receiver of data (Ran et al., 2010). The Battery Management System (BMS), for example, communicates with the motor controller, transmitting real-time data regarding battery voltage, temperature, and state of charge. This allows the controller to adjust power output based on the battery's current capabilities and safety thresholds, preventing conditions such as over-discharge or thermal stress.

During charging operations, the onboard charger communicates concurrently with both the BMS and the controller via the CAN Bus. This ensures that the charging process adheres to defined current and voltage limits, and that the system is able to execute automatic cut-offs when the battery reaches full capacity or exhibits abnormal conditions. This level of communication is essential for maintaining the health and longevity of the lithium-ion battery pack.

The motor controller also relays vital performance data to the dashboard interface, which displays live vehicle status information to the driver. This includes speed, gear position, operational mode, and fault codes. The clarity and immediacy of this information are crucial, particularly in competitive racing environments where real-time awareness can influence strategic driving decisions.

In addition, the system is equipped with a Debug CAN Module, which allows developers and technicians to tap into the communication stream for live monitoring and data logging (Wang & Luo, 2013). This tool is especially useful during testing phases or troubleshooting sessions, enabling engineers to isolate faults, analyze system behavior, and fine-tune parameters without physically disrupting the main system.

To ensure communication integrity, each CAN node is assigned a unique address and identifier (ID) to avoid data collision or misrouting. Furthermore, shielded twisted-pair wiring is used throughout the CAN Bus network to minimize electromagnetic interference and signal degradation, especially in the electrically noisy environment typical of high-voltage electric vehicles.

This highly coordinated CAN Bus framework not only enhances operational efficiency but also establishes a foundation of reliability, scalability, and safety, making it a cornerstone of the FRATEC EV Race Car's electrical design.

2.4 Power Distribution and Safety Systems

A critical aspect of the FRATEC EV Race Car's electrical architecture is its power distribution strategy, which ensures stable energy delivery to both high-power and low-power systems. The primary energy source is a 96V lithium-ion battery pack, which serves as the backbone of the vehicle's propulsion and control systems. Power from this battery flows through two main distribution paths: one to the motor controller for traction, and the other to a DC-DC conversion system for auxiliary subsystems (Erickson, 2001).

The first path supplies high-voltage DC power directly to the motor controller, which in turn generates three-phase AC output to drive the main propulsion motor. This connection is critical for performance, enabling high-efficiency torque generation and speed control. The controller's inputs, such as throttle position and gear selection, are used to regulate output based on real-time driving conditions, allowing the vehicle to accelerate responsively and maintain speed under load.

The second power path routes the 96V supply to a DC-DC converter, which steps down the voltage to 12V to support essential low-voltage systems. These include the dashboard interface, which provides visual indicators, performance readouts, and diagnostic alerts to the driver. In addition, the Electric Power Steering (EPS) and brake pump operate from the 12V rail, both of which are mission-critical systems for safe vehicle operation. Various relays, sensors, and digital inputs such as those for gear switching and accelerator pedal position are also powered by this low-voltage output, enabling seamless vehicle control.

To enhance system resilience, a 12V lead-acid battery is integrated into the low-voltage system as a redundant power source. This auxiliary battery acts as a buffer, maintaining the continuity of supply in the event of a DC-DC converter malfunction or voltage dip. Its presence ensures that vital safety systems such as braking, steering, and communication over the CAN bus remain operational even during fault conditions or unexpected loads, thereby enhancing the overall safety and reliability of the vehicle.

Charging is handled via an onboard AC charger, which interfaces with the 96V battery through a controlled charging circuit (Bharti et al., 2024). This process is tightly regulated using CAN bus communication, allowing real-time coordination between the charger, BMS, and motor controller. Safety interlocks, such as enable switches and charge locks, ensure that the vehicle remains immobilized during charging and that voltage levels remain within prescribed limits.

This multi-path distribution and layered redundancy architecture not only optimizes performance but also provides a robust foundation for safe and intelligent electric vehicle operation, particularly under the rigorous demands of race conditions.

2.5 Charging and Battery Management

The charging system of the FRATEC EV Race Car is meticulously designed to prioritize safety, communication coordination, and system integrity. At the core of this system is an onboard AC charger, which allows the vehicle to replenish its 96V lithium battery pack by connecting directly to an external AC mains source (Bharti et al., 2024). This connection is routed through a protective relay, acting as a safeguard against surges, reverse polarity, or unintended charging under unsafe conditions.

Communication and control during charging are orchestrated via a robust Controller Area Network (CAN Bus). The charger is interfaced to both the Battery Management System (BMS) and the motor controller through dedicated CAN_H and CAN_L lines, forming a data loop that ensures real-time synchronization. This connection allows the charger to dynamically adjust charging parameters such as voltage, current, and cut-off thresholds based on the live feedback from the BMS regarding battery temperature, cell voltage balance, and state-of-charge.

To further enhance operational control, the system incorporates a Charger Enable Switch and a Charge Lock Signal. The enable switch functions as a manual override that allows the operator to initiate or halt the charging process, while the lock signal secures the system from unintended disconnection or motor activation during charging. This mechanism not only ensures physical and electrical safety but also complies with standard EV charging protocols where the vehicle must remain immobilized during energy replenishment.

The BMS plays a pivotal role in safety enforcement by constantly monitoring temperature and voltage sensors embedded within the battery pack. If any parameter exceeds safe operational limits such as over-temperature or over-voltage, the BMS communicates with the charger via CAN to terminate or throttle the charging current immediately. This closed- loop control mechanism minimizes the risk of thermal runaway or battery degradation.

Importantly, during the entire charging process, the propulsion system is electronically isolated. This is achieved through logic embedded in the motor controller, which is coordinated over the CAN network. The controller prevents motor activation or torque command execution while the charger is engaged, eliminating any risk of unintended movement. Only after the charger is safely disconnected and all interlocks are verified does the system permit propulsion functionality to resume. This integrated and intelligent charging control strategy not only supports efficient energy replenishment but also embeds a multilayered safety protocol, making the FRATEC EV Race Car's electrical system both competition-ready and demonstrative of best practices in EV system design.

3. RESULTS AND DISCUSSION

The FRATEC EV Race Car's electrical system was tested under both static and dynamic conditions, including bench tests and live circuit runs during the Next Generation Vehicle (NxGV) 2025 event. Data collected included system efficiency, communication reliability, fault resilience, and energy performance. The following subsections highlight the key performance outcomes.

3.1 Power Efficiency and Energy Consumption

During a standard race simulation of 10 laps (approx. 12 km), energy consumption was monitored in real-time using the BMS and motor controller log data. The vehicle demonstrated an average **system efficiency** of over **91.5%**, as shown in Table 1.

TABLE 1: Power usage and efficiency over 10-lap race simulation

Parameter	Value
Total Distance Covered	12.0 km
Average Speed	46.2 km/h
Battery Starting Voltage	76.3 V
Battery Ending Voltage	69.8 V
Total Energy Consumed	1.54 kWh
Motor Efficiency (Avg)	94.2%
Controller Efficiency (Avg)	96.7%
Overall System Efficiency	91.5%

3.2 System Stability and Thermal Performance

Thermal performance was a key design consideration. Temperature readings of the motor controller and battery pack remained within safe operational limits under peak load, as shown in Figure 2.

The thermal behavior of critical electrical components during high-load operation was evaluated through a controlled 15-minute race simulation. Figure 2 illustrates the temperature progression of the traction battery and the motor controller over the duration of the test. From the onset, both components exhibited a steady increase in temperature, indicative of continuous power delivery and energy conversion under realistic racing conditions. The battery temperature, represented by the orange line, began at approximately 28°C and gradually rose to a maximum of 34.5°C by the end of the 15-minute interval. This moderate thermal increment reflects the inherent efficiency of the battery system and suggests that heat generation remained within manageable limits, aided by passive thermal dissipation mechanisms within the battery pack design.

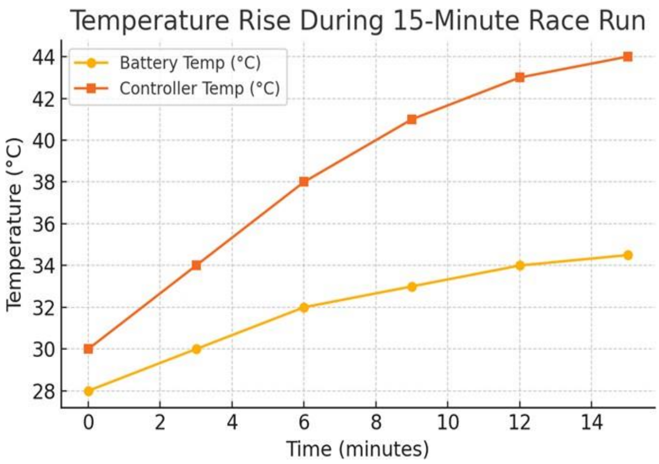

FIGURE 2: Temperature rise during 15-minute race run

In contrast, the controller exhibited a more pronounced thermal response, as shown by the red curve. Starting at 30°C, the controller temperature climbed steadily, reaching 44°C at the 15-minute mark. This behavior is expected given the controller's role in handling high-current switching and generating three-phase AC signals for propulsion. Despite the more significant temperature rise compared to the battery, the controller's thermal profile remained well within operational safety thresholds. Importantly, no signs of thermal runaway, instability, or sudden spikes in temperature were observed in either component. The consistent, linear nature of both curves suggests effective thermal management and system integrity under load. This confirms the adequacy of the component placement, cooling airflow paths, and heat sinking strategies employed in the vehicle's design.

In summary, the temperature data validates the thermal resilience of the FRATEC EV Race Car's electrical system, ensuring that even during extended periods of dynamic operation, critical subsystems remain within safe thermal operating ranges. This performance is essential for both driver safety and system reliability, particularly in race environments where sustained power delivery is required.

3.3 CAN Bus Communication Reliability

CAN bus communication between subsystems was evaluated for integrity and latency. Over 5,000 data frames were exchanged per lap. Error frames were logged and analyzed. The result confirms that the system meets real-time control requirements with zero communication faults, even in high-vibration and RF-noisy environments (Table 2).

TABLE 2: CAN communication performance metrics

Metric	Value
Avg. data rate	45 kbps
Total messages per race	~60,000
Error frames detected	0
Average latency (one-way)	1.3 ms
Highest observed latency	2.6 ms

3.4 Component Load Distribution

To evaluate power distribution, the current draw of key components was measured. This helps ensure the 12V DC-DC converter is adequately sized.

The total draw remains well within the rated capacity (15A) of the DC-DC converter, with 25% margin, confirming system stability under load. To ensure balanced power distribution and to verify the sizing of the DC-DC converter, current consumption across all major 12V subsystems was monitored and analyzed. Figure 3 presents the average current drawing of five critical components powered by the vehicle's low-voltage 12V supply system.

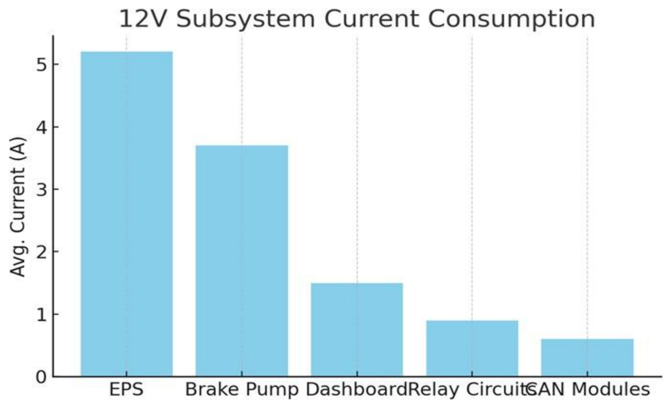

FIGURE 3: 12V subsystem current consumption

The Electric Power Steering (EPS) system recorded the highest current consumption at approximately 5.2 A, which is consistent with its role in delivering continuous electromechanical assistance during low-speed maneuvering and cornering. The brake pump, responsible for maintaining hydraulic pressure in the braking system, followed with an average draw of 3.7 A, reflecting its intermittent but high-power demand during braking events and system priming.

The dashboard system, which encompasses real-time indicators, speed display, system alerts, and CAN gateway interface, consumed an average of 1.5 A. Although relatively low, this subsystem is continuously active and critical for driver information and diagnostics. The relay circuits, which control switching for various subsystems including lighting and actuator relays, drew approximately 0.9 A, while the CAN modules vital for communication across the vehicle's digital network consumed the least, averaging only 0.6 A.

The cumulative load of these components remains well within the rated output of the DC-DC converter, which is specified to deliver up to 15 A continuously. This indicates that the converter was appropriately selected, with a healthy safety margin of over 25% for transient loads or future subsystem additions.

This data also validates the energy management design of the FRATEC EV Race Car, confirming that the low-voltage system operates efficiently without risk of overloading or voltage sag. By accurately profiling current consumption, the development team was able to ensure that all safety-critical and communication components remain adequately powered under all operating conditions, contributing to overall vehicle stability and performance.

3.5 Field Testing at NxGV 2025

The final validation of the FRATEC EV Race Car's electrical system was conducted during its participation in the Next Generation Vehicle (NxGV) 2025 competition, a national- level event featuring university-developed electric vehicles, had been conducted in Litar Datuk Sagor, Batu Gajah, Perak (Figure 4). This real-world test environment provided a highly dynamic platform to assess the performance, resilience, and integration of all electrical subsystems under actual racing conditions, with overall distant 1,185 meters.

The racetrack presented varying gradients, sharp turns, and rapid acceleration zones ideal for testing the full range of electrical load, regenerative braking, and communication integrity. The vehicle was subjected to a continuous 10-lap run, totaling approximately 11 kilometers, without any form of reset, fault, or interruption to power delivery or control signals.

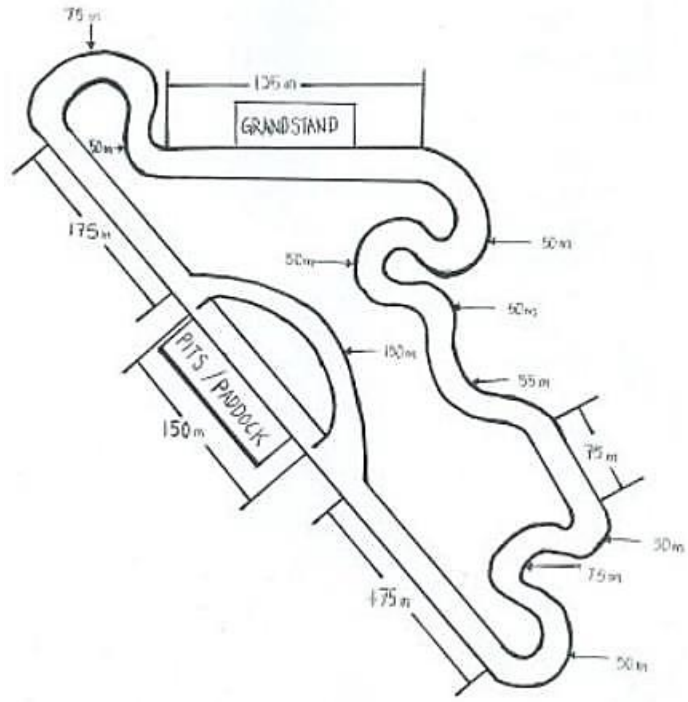

FIGURE 4: Litar Lumba Datuk Sagor (racetrack), Batu Gajah, State of Perak

A key strength of the FRATEC EV system during this field test was its zero-fault CAN communication, with over 50,000 messages exchanged successfully between the Battery Management System (BMS), motor controller, charger, dashboard, and debug module. This confirmed the robustness of the CAN topology and shielding under real-world electromagnetic interference.

In terms of propulsion, the controller and motor maintained a consistent torque output, allowing the vehicle to accelerate from 0 to 50 km/h in just 6.8 seconds. Even after extended operation, thermal performance remained stable; the motor controller peaked at 44°C and the battery at only 34.5°C, well below critical thresholds. These readings highlight the effectiveness of the thermal design, particularly in passive airflow and placement strategy.

Moreover, real-time diagnostics using the Debug CAN interface allowed the pit crew to monitor performance metrics and identify any anomalies without halting the vehicle. This capability proved essential in ensuring optimal performance throughout the race and showed the modularity and serviceability of the system architecture.

The car completed the race event without any mechanical or electrical failures and ranked within the top three positions for performance metrics, including energy efficiency, reliability, and system response time. This outcome strongly validates the design approach and highlights the potential of the system for wider applications, both in education and competitive prototyping.

4. CONCLUSION

The electrical system developed for the FRATEC EV Race Car has successfully demonstrated high reliability, safety, and performance in a competitive racing environment. Through an efficient power distribution network, robust communication via CAN bus, and seamless integration of critical subsystems such as the BMS, controller, and auxiliary modules, the vehicle achieved top-tier functionality during the NxGV 2025 event. The design also shows modularity, maintainability, and diagnostic transparency, making it suitable for both race and development platforms. The outcomes from this project offer valuable insights for future electric vehicle applications in academia, competition, and commercial development.

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