Design and Evaluation of a Scalable Educational Testbed for Autonomous Vehicle Instruction

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Abstract

Abstract - This paper presents the design, development, and validation of a next-generation autonomous vehicle testbed to succeed the MIT RACECAR Neo platform. While the Neo has served as the global standard for autonomous systems education, its long-term scalability is hindered by mechanical fragility, inter-vehicle inconsistency, and supply-chain obsolescence. In response, we developed a fully custom, 1:14-scale vehicle platform engineered for geometric repeatability, classroom-grade durability, and supply independence. The system integrates a fully custom structural base and chassis fabricated via 3D printing and laser-cut polycarbonate, along with upgraded actuators and electronics. Design decisions were guided by simulation-driven methods, including parametric force modeling and finite element analysis, and refined through iterative prototyping. Key performance improvements include a 65% reduction in toe play (unintended angular displacement of a wheel around its vertical steering axis that occurs independently of any steering input) and drivetrain velocity stability within ±1% of setpoint. However, evaluation also revealed that the selected motor—REV Robotics Neo 550—delivers excessive and dangerous torque relative to drivetrain capacity, emphasizing the importance of actuator-to-structure matching. The final platform supports full compatibility with the RACECAR Neo sensor suite while offering a mechanically consistent and extensible foundation for autonomy instruction. Future work includes powertrain respecification, long-term durability testing, and a redesigned, low-profile payload architecture with integrated CAN-based communication. This platform redefines the baseline for accessible, high-performance AV education, enabling scalable deployment, hands-on learning, and robust experimentation in autonomous systems.

1 Introduction

As the past decade has witnessed an extreme growth of scaled AV testbed offerings aimed at lowering the entry barrier for robotics education and research, reliable, consistent testbeds are essential for hands-on learning and research on autonomous vehicles (AVs). Popular examples include F1TENTH, AWS DeepRacer, and Donkey Car. Yet, despite their educational value, each platform suffers from structural, technical, or economic constraints that limit adoption in secondary and undergraduate-level classrooms (Table 1). Consequently, instructors who wish to teach state-of-the-art perception, planning, and control on physical hardware often confront a stark choice between cost, consistency, and curricular breadth.

Table 1: Comparison of Popular AV Learning Platforms

Platform	Approx. Hardware Cost	Principal Sensors	Classroom Shortcomings
F1TENTH [1]	≈$3000 per car	2-D LiDAR + RGB camera	High cost, large 1:10 chassis complicating storage, lack of standardization.
Donkey Car [2]	$250 – $300 kit	Single RGB camera	Extremely limited sensing and compute; designed for tight indoor tracks and low speed, not dynamic outdoor courses
AWS DeepRacer [3]	$399 + $3.50/hr Cloud Fees	Stereo RGB cameras	Proprietary ecosystem, recurring costs, no on-board TPU/GPU, limited sensor suite.

By contrast, the MIT RACECAR Neo—a 1:14-scale Ackermann-steered platform designed and maintained by the Beaver Works Summer Institute (BWSI)—has emerged as the standard for hands-on autonomy instruction worldwide. Two main characteristics distinguish RACECAR Neo from other options:

1. **Open-source hardware & software.** A complete CAD, bill-of-materials, and ROS-based software stack are freely available, eliminating vendor lock-in and enabling iterative hardware improvement.
2. **Wide and Flexible Sensor Suite.** A reference sensor suite (Raspberry Pi 4, RGB camera, 360° LiDAR, 9-DoF IMU) and a common software image ensure that educators and students have extensive opportunities in terms of both algorithms to implement and topics to teach.

Given the lack of comparably priced, feature-complete, and educator-ready platforms, the RACECAR Neo currently represents the only viable option for educators seeking a rigorous, open, and globally supported hardware testbed for autonomous-vehicle research and instruction. However, several important issues with the MIT RACECAR Neo, solely due to its mechanical and electrical design, are significant detriments to the educational experience provided by these cars:

- **Inter-vehicle variability:** Identically assembled Neo cars differ in steering alignment, speed, and drivetrain backlash. Algorithms tuned on one unit seldom transfer without significant retuning, making teaching extremely difficult when example programs do not work.
- **Mechanical fragility:** Due to low-quality manufacturer parts and design, components such as the suspension, steering servo, and power transmission often suffer premature failure, interrupting classroom and laboratory activities.
- **Supply-chain obsolescence:** The commercial chassis on which the RACECAR Neo relies has been discontinued, restricting the long-term scalability of educational programs that depend on fleet expansion or replacement parts.

Accordingly, this study advances a successor platform defined by three primary objectives. The first objective is *vehicular geometric consistency* so that wobble in toe angle remains within ±1 mm, and commanded linear velocity stays within ±1% of the setpoint over a sixty-second interval. The second objective is *classroom-grade durability*, pursued through a re-engineered mechanical and electrical architecture so that instructional time is not lost to repairs. The third objective is *supply-chain independence*, achieved by making all major subsystems fully custom and open-source while relying only on widely available commodity components, thus eliminating dependence on any single specialized manufacturer. Beyond these three primary objectives, the new chassis must accommodate the unmodified RACECAR Neo sensor suite and compute module (the payload), to maximize compatibility with existing systems and simplify the design. Together, these objectives define the benchmark against which subsequent design decisions and experimental evaluations are measured.

2 Experimental Methodology

2.1 Theoretical Analysis

To confirm that a candidate motor–gearbox–wheel combination can meet the vehicle's dynamics targets—namely the required speed and acceleration (9 m/s and 7 m/s^2, respectively)—we implemented a parametric calculator. The user supplies seven inputs: motor stall torque, throttle fraction (the duty cycle needed to hit the desired acceleration), input gear teeth, wheel radius, vehicle mass, gravitational acceleration, and a coefficient of static friction. The calculator propagates these values in a table through a chain of closed-form expressions.

Table 2: Vehicle Dynamics and Performance Calculations

Parameter	**Value**	**Result**	**Value**
Stall torque (Nm)	0.97	Effective stall torque (Nm)	0.97
Max RPM	11000	Output torque (Nm)	3.95
Throttle fraction	100.00%	Torque per wheel (Nm)	0.99
Motor Pinion	27	Force per wheel (N)	23.52
Total Gear ratio	4.07	Normal force per wheel (N)	11.13
Wheel radius (m)	0.042	Rolling resistance per wheel (N)	0.42
Vehicle mass (kg)	4.54	Safety margin	55.89
Gravity (m/s^2)	9.81		
Friction coefficient (μ)	0.90		
Final Performance Metrics			
Acceleration at 100% Throttle	20.73 m/s^2		
Max Speed	11.88 m/s		

At full throttle, this system achieved an acceleration of 20.72 m/s^2 and a maximum speed of 11.88 m/s.

Based on these calculations and constraints, we selected a REV Robotics Neo 550 Brushless Motor, a REV Robotics SPARK MAX Motor Controller, a 2200mAh 3S 50C lithium polymer (LiPo) Battery, and a high-power 45kg servo for the new car. Power transmission was handled by a widely available 1/14th scale double differential system. All of these parts were significant upgrades to their counterparts on the RACECAR Neo. The brushless motor offered improved efficiency, reliability, and consistent torque output compared to the brushed variant previously used. The SPARK MAX controller featured robust fault protection and integrated sensor support, addressing the fragility and limited functionality of the earlier ESC. The upgraded servo delivered significantly higher torque and faster actuation, solving many of the mechanical limitations encountered with the original system. With components selected, we advanced to design and simulation.

As the new vehicle was fully custom, with no Commercial Off-The-Shelf (COTS) chassis, a fully parametric solid model was developed in Fusion 360, where wheelbase and track width were exposed as editable parameters to accelerate iterative refinement. The steering system was redesigned around a dual bell-crank linkage with Ackermann geometry and used the full range of the steering servo's rotation with a 2-bar linkage, ensuring the highest mechanical advantage.

Finite Element Analysis (FEA) and structural simulation were employed across several key components during the design process to identify stress concentrations, guide material selection, and optimize part geometry. Among these, a new front bumper, designed with elastic crumple zones to absorb impacts and protect the sensor payload, underwent a detailed simulation. A 280N force was applied to model a head-on collision scenario, representing a 4kg car decelerating from 7 m/s to rest in 0.1 seconds. The resulting maximum deformation was 2.33 mm, concentrated within the intended crumple regions. These results demonstrated sufficient energy absorption and structural integrity, justifying the decision to proceed with physical prototyping without further structural analysis.

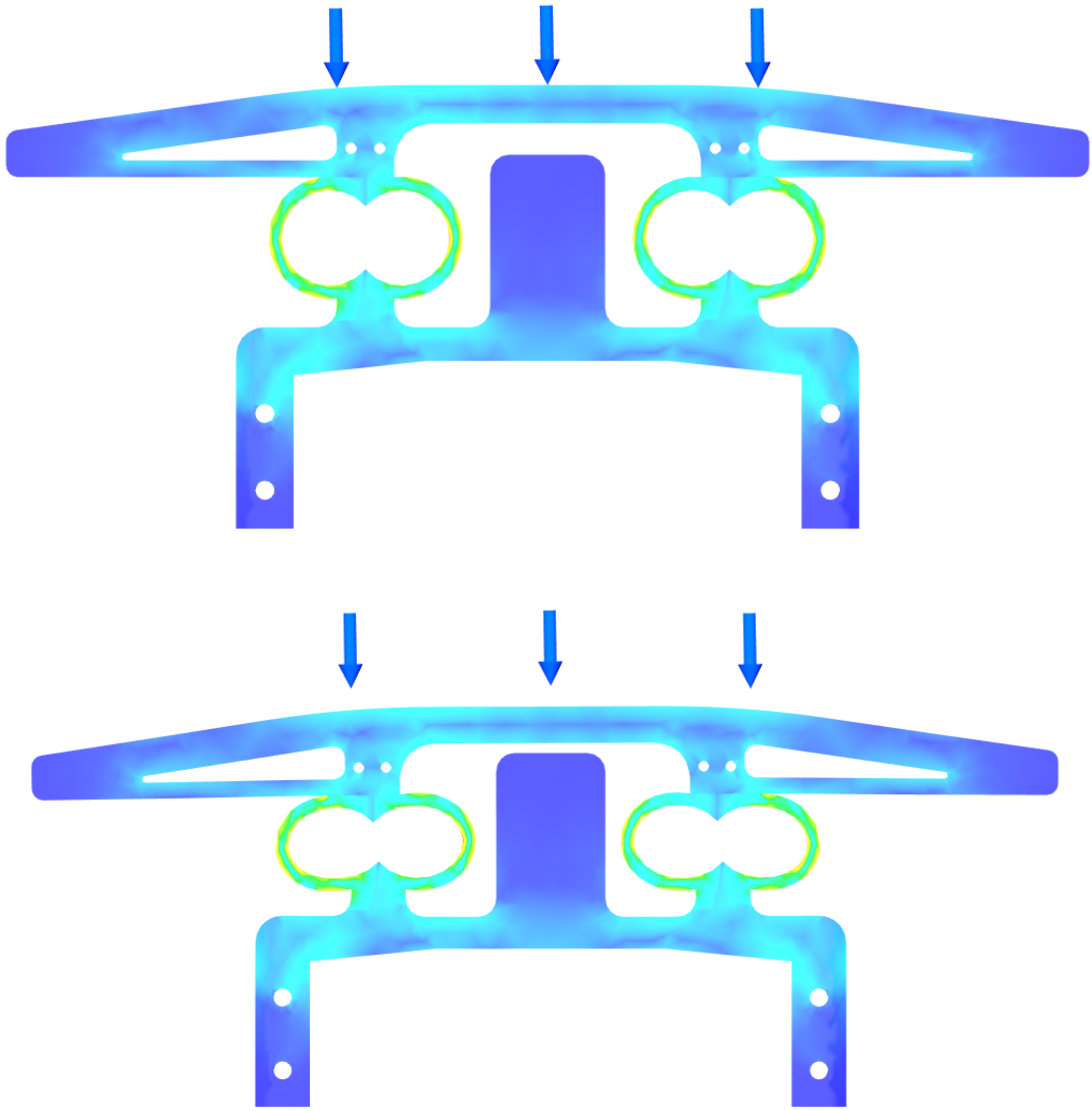


Figure 1: Finite Element Analysis (FEA) of the shock-absorbing bumper. The color map indicates stress distribution under a simulated 280N impact force, with the top image showing the original geometry and the lower image showing the expected deformation.

2.2 Prototyping & Testing

Once the CAD model was finalized, physical prototyping followed a structured print–test–refine process. All custom structural components were manufactured using 3D-printed PLA and TPU, and laser-cut polycarbonate, with tolerances tightened to provide the most secure fit while still being structurally strong and reducing internal strain. Dimensional accuracy was verified post-printing using digital calipers, and minor dimensional deviations were corrected through mechanical rework.

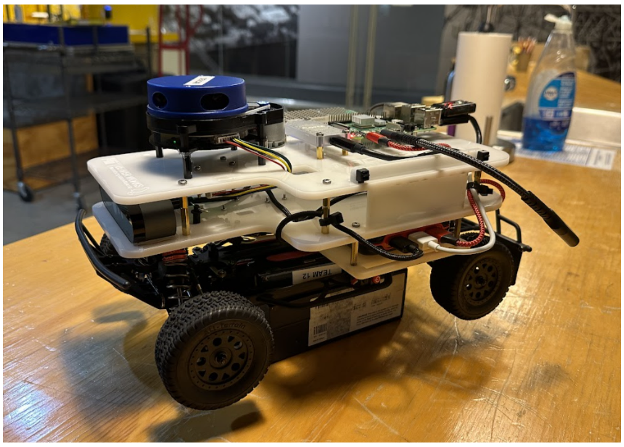
The drivetrain and steering assemblies were constructed and bench-tested before full integration. The Neo 550 motor was installed in a custom enclosure, powering the double-differential drivetrain with a gear ratio of

27:44, where various aspects of the system, such as the gear meshings and fabrication tolerances, were measured. The dual bell-crank steering system was assembled with reference to an alignment fixture that ensured symmetric servo range and minimized mechanical play across the full steering range

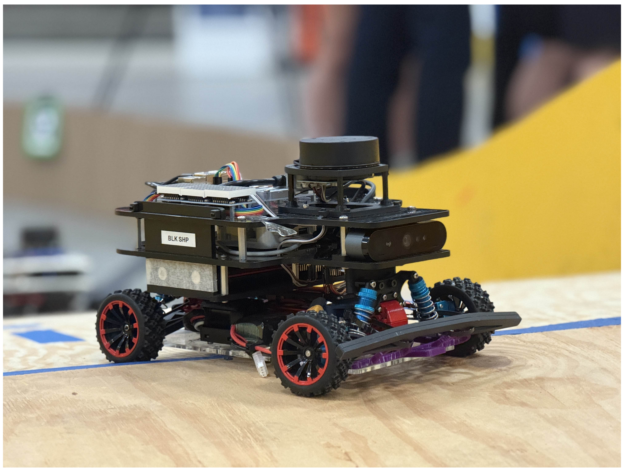
Following the testing of the core components, all remaining subsystems—–such as the suspension arms, shock towers, impact-absorbing bumpers, and sensor payload supports—–were fabricated, iteratively refined, and eventually integrated onto the car. Each part was evaluated for fit, assembly time, and mechanical reliability. Adjustments were made across print iterations to reduce friction in moving joints, correct minor interference fits, and improve structural rigidity without increasing mass.

Preliminary testing focused on verifying mechanical alignment and validating the integration of electrical and software systems. The drivetrain was powered through a PWM signal while encoder feedback was logged using a supplemental computer to observe velocity response and motor performance. The steering linkage was actuated through its full range under varying load conditions to identify points of friction or deflection, and adjustments were made to horn angles and servo limits as necessary.

After preliminary testing, we entered a focused iteration phase where nearly every subsystem was reevaluated and refined based on observed performance. Components that showed signs of wear, misalignment, or unexpected friction were modified in CAD, reprinted, and retested in system context. Steering geometry, drivetrain spacing, servo horn angles, and sensor mount positions were among the areas adjusted to improve mechanical efficiency, alignment reproducibility, and serviceability. This process of testing, redesigning, and revalidating continued until all systems consistently met performance expectations, resulting in a final prototype that was mechanically reliable, easy to assemble, and well-suited for future autonomous development.



(a) The original MIT RACECAR Neo platform which this work aims to succeed.



(b) The new vehicle.

Figure 2: A side-by-side comparison of the two chassis.

3 Problems & Solutions

During the iterative build-test-refinement phase, several major challenges arose that were not fully captured during the initial modeling and simulation stages. These issues, arising from complex interactions between mechanical tolerances, material properties, and system integration, prompted a series of targeted design modifications and engineering interventions. The following section outlines the most significant problems encountered and the solutions developed to address them, with an emphasis on maintaining performance, reliability, and manufacturability across repeated iterations.

3.1 Gear Skipping at High Torque Loads

Problem: Under high torque conditions, the gear mesh between the motor and the differential driveshaft exhibited skipping, severely affecting drivetrain performance. Initially, the differential itself was suspected, but no internal wear or damage was observed. However, fine metal particulates were found beneath the motor–driveshaft interface, indicating gear wear at the external mesh.

Solution: To address this, the drivetrain structure was reinforced by adding a full-length crossbar that constrained the differential housings along the chassis. This structural element reduced flex in the driveshaft and improved axial alignment, significantly mitigating gear skipping under moderate to high load.

3.2 Gear Damage Due to Torque Spikes

Problem: Even after addressing mechanical misalignment, the drivetrain remained vulnerable to instantaneous torque spikes—particularly when motor power increased by $> 2\%$ in a single control cycle (running at 30Hz). These rapid changes generated destructive forces that damaged the steel pinion and spur gears.

Solution: A recursive motion profiler and acceleration limiter were implemented in software to smooth all motor commands. These tools applied time-based ramping and rate-limiting to motor inputs, preventing sudden torque jumps and preserving drivetrain integrity under dynamic driving conditions.

3.3 Inconsistent Fits Between COTS Wheel Hubs & Wheels

Problem: Although the chosen wheel hubs and wheels were both COTS, they originated from different manufacturers and exhibited incompatible tolerances. This resulted in loose fits that impaired wheel alignment and introduced variability across builds.

Solution: Custom 3D-printed inserts were designed and press-fit into the hubs to create a tight, reproducible interface with the wheels. This solution eliminated incompatibility between components and standardized the hub–wheel connection across all units.

3.4 Insufficient Mechanical Advantage in Steering Linkage

Problem: The initial steering linkage lacked the mechanical advantage necessary to provide full articulation under dynamic load. This reduced steering torque and limited the effective range of motion, especially during high-speed cornering.

Solution: A redesigned spatial multi-axis two-bar linkage was implemented to maximize leverage and match the servo's full rotational range. In addition, a buck converter was introduced to provide the servo a voltage of 8.4V, stepped down directly from the LiPo, in contrast to the previous 4.8V provided through the old ESC, enabling the use of a high-torque servo and ensuring consistent steering performance under load.

3.5 Insufficient Ground Clearance

Problem: The vehicle's initial suspension setup yielded inadequate ground clearance, limiting its ability to traverse uneven surfaces and increasing the risk of underbody impacts during normal operation.

Solution: The suspension system was updated by replacing the stock springs with stiffer variants, increasing the spring constant by approximately 70%. This modification raised the ride height and resulted in a ground clearance of 14.5 mm, improving terrain compatibility and reducing acceleration squat.

4 Results and Analysis

The development process resulted in several measurable improvements to mechanical performance, component alignment, and system integration compared to the RACECAR Neo. The transition to a fully custom chassis—with 32 components fabricated via 3D printing and laser-cut polycarbonate—significantly improved the platform's modularity and reproducibility.

One of the most substantial mechanical gains was in toe play, which dropped from 2.28 mm on the legacy platform to 0.82 mm in the new system—a 65% reduction. This improvement reflects tighter control over wheel hub tolerances, steering linkage geometry, and assembly reproducibility. Dimensional accuracy was verified using digital calipers with 0.001 mm resolution.

Drivetrain consistency was evaluated through high-speed encoder tests. When operated at 10,000 RPM for 60 seconds, the motor maintained rotational velocity within a window of 9,920 to 10,095 RPM. This corresponds to a maximum deviation of $+0.95\%$ and a minimum deviation of –0.80%, both within the design specification of $\pm 1\%$. These results confirm that the combination of a brushless motor and an improved motor controller yielded a stable, precise drive system.

Additionally, the choice to replace legacy COTS chassis elements with custom parts proved effective not just in performance, but in logistics. The remaining COTS components in the new car are limited to high-precision, widely available parts where replication would be cost-prohibitive. This balances performance, reproducibility, and accessibility for large-scale deployment.

Despite these gains, one critical mismatch was identified: the REV Robotics Neo 550 motor consistently delivered more torque than the drivetrain could reliably handle. Even with physical constraints and software acceleration limitations, high-torque spikes damaged gears and introduced excessive mechanical strain. This exposed an imbalance in the system—excess power at the actuator level can damage components downstream that are difficult to resolve through mechanical reinforcement alone.

Overall, the analysis demonstrates that system-level coherence—across mechanical, electrical, and software domains—is essential for sustainable performance at scale. The improvements seen here are not solely the result of stronger components but of tighter integration between subsystems.

5 Educational Impact

The end product of this research—a fully custom, reproducible autonomous vehicle platform—offers significant advancements for robotics and autonomy instruction at the secondary and undergraduate levels. By resolving the critical limitations of the RACECAR Neo, the platform enables more structured, scalable, and effective hands-on learning experiences in autonomy education.

5.1 Mechanical Consistency and Algorithm Transferability

One of the most common barriers to teaching autonomy with physical testbeds is mechanical variability between vehicles. In the RACECAR Neo, even minor differences in steering linkage, drivetrain backlash, or assembly tolerances led to divergent behavior across units. As a result, students often found that algorithms developed on one car failed when deployed on another, leading to unnecessary debugging and reduced confidence in the software stack.

The redesigned platform mitigates this issue by enforcing tight mechanical tolerances across all structural and drivetrain components. Toe play, a primary contributor to inconsistent steering response, was reduced by 65%, and drivetrain velocity stayed within $\pm 1\%$ of the target RPM under sustained load. These improvements allow instructors to design assignments that work identically across multiple vehicles, enabling students to focus on core topics such as perception, control, and planning, rather than troubleshooting hardware inconsistencies. This uniformity also supports more rigorous assessment, collaborative debugging, and instructional reproducibility across years and classrooms.

5.2 Supply Chain Independence and Long-Term Deployability

Sustainability and scalability are essential for any educational platform intended for long-term use. The RACECAR Neo's reliance on a discontinued commercial chassis created significant logistical challenges, especially for programs attempting to expand their fleet or replace damaged units. The custom platform presented here eliminates that dependency. All critical mechanical components are open-source and fabricated from widely available materials using accessible tools such as fused filament fabrication (FFF) 3D printers and low-cost laser cutters.

This allows schools to produce spare parts in-house, maintain consistency across batches, and avoid being locked into specific vendors or part lifecycles. As a result, programs can maintain their fleets for multiple semesters, even in low-resource settings, and scale deployments to support larger classes or new cohorts without significant increases in cost or logistical complexity.

5.3 Compatibility with Existing Curriculum

Because the new chassis was designed around the RACECAR Neo payload—including the sensor suite, Raspberry Pi 4 compute module, and LiDAR—the platform integrates seamlessly into existing software and curriculum infrastructure. Programs currently using the Neo can transition to the new vehicle without rewriting course materials or retraining instructors. The familiar ROS-based stack remains fully supported, preserving students' exposure to industry-relevant tools while providing a mechanically superior vehicle that reduces failure modes and instructional interruptions.

In combination, these contributions position the new platform as a long-term successor to the RACECAR Neo, offering improved reliability, instructional consistency, and scalability. It supports not just autonomous driving projects, but also the broader educational goal of providing students with meaningful, systems-level experience in engineering design, analysis, and real-world implementation.

6 Conclusion

This work presents a complete reengineering of the MIT RACECAR chassis, transitioning from a legacy COTS-based drivebase to a fully custom, tightly toleranced, and structurally rigid system. The final vehicle integrates 32 custom-fabricated components and maintains mechanical reproducibility across builds, while improving steering precision, reducing drivetrain variability, and simplifying future iteration through parametric design. Quantitative evaluation confirmed key performance gains: toe play was reduced by 65% and velocity error during sustained high-RPM operation stayed within ±1%. However, a deeper analysis reveals key insights into the interaction between actuator specification and system-level mechanical integrity. While the REV Robotics Neo 550 provided ample performance headroom, its torque output was excessive for this application. Even with structural reinforcements and acceleration-limiting software, the drivetrain remained vulnerable to physical damage under sudden load application. This highlights a broader design lesson: excess power is not inherently beneficial when the rest of the system is not designed to absorb it. In this case, the burden of mitigating this excess power shifted downstream—onto gears, crossbars, and software motion profiling algorithms—rather than being addressed at the source through proper actuator sizing. The development process also illuminated the importance of early-stage consideration for supply chain resilience and part lifecycle. By eliminating reliance on hard-to-source components and adopting a design language based on manufacturable geometries and standard materials, the resulting platform is more sustainable for classroom and research environments, where consistency and ease of repair are critical.

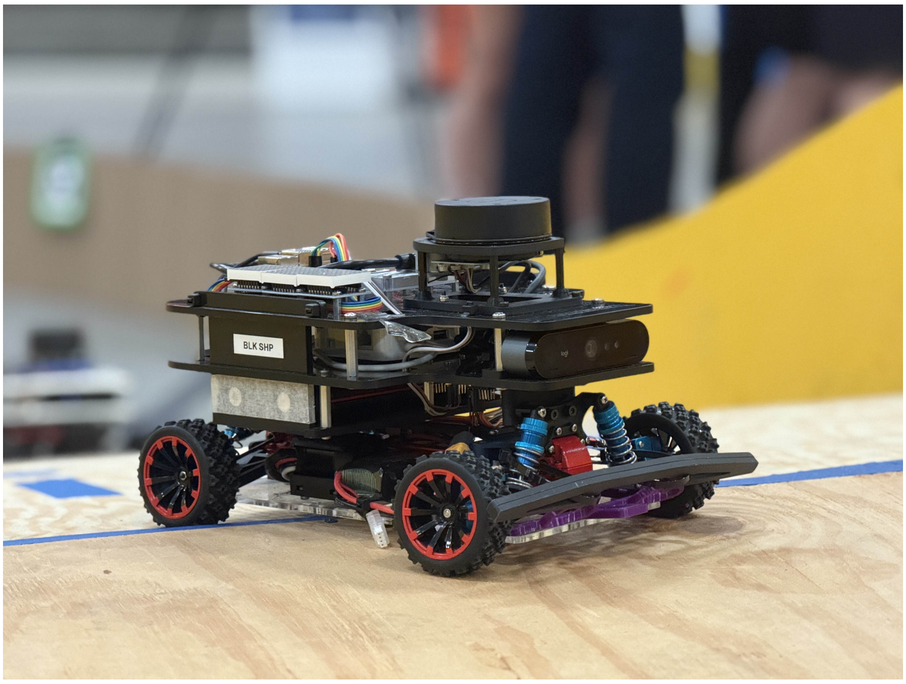


Figure 3: The new vehicle and chassis.

7 Future Considerations

To build on this foundation, future development efforts should focus on:

Powertrain Respecification: Replacing the Neo 550 with a lower-torque, more efficiency-optimized motor that matches the mechanical durability of the rest of the system would reduce the damage done to the gears, lower system stress, and allow more aggressive use of lightweight materials.

Durability Testing: Extended-use testing over varied terrain and operating conditions to characterize wear, mechanical drift, and service intervals is essential to ensure reliability across time or multiple student classes.

Inter-Vehicular Consistency Metrics: Fabricating and testing multiple instances of the platform to assess variation in steering response, drive alignment, and component fit across prints would help further develop a statistical understanding of the platform's manufacturability.

Integrated Payload Redesign and System Architecture: While the current chassis was designed around the existing payload, the payload itself limits mass distribution, compactness, and system integration. Future work will focus on a redesigned perception and compute stack with a lower center of gravity, greater mechanical robustness, and a more compact footprint. This redesign also enables a transition from PWM to a unified CAN-based architecture, improving signal integrity and expanding our car's sensor suite and abilities. By embedding wireless and power management into the control stack, the chassis and payload can function as a tightly integrated system rather than loosely coupled modules.

By combining mechanical reproducibility, open-source accessibility, and system-level design thinking, this platform sets a new baseline for the educational and prototyping vehicles that succeed the RACECAR Neo. Its development offers not only a technical foundation but also a framework for engineering education built on iteration, analysis, and real-world constraints.

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