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RoboRacer.AI: Hands-on Autonomous Vehicle Design, Testing and Deployment

An Open Course, Competition Series, and Small-Scale Testbed for
Safe Automated Transportation

Project #609

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16. Abstract Project 609 develops RoboRacer.AI, an open platform for teaching, testing, and deploying autonomous vehicle software. It combines a multi-scale autonomous driving course, a global competition series, and an ethics framework for machine learning in life-critical systems. The platform grew from the F1TENTH 1/10-scale racing vehicle and now serves 89 or more universities. This report analyzes RoboRacer.AI against the roadmap for small-scale testbeds for connected and automated vehicles published in IEEE Intelligent Transportation Systems Magazine, and shows how the platform addresses accessibility and diversity, shared best practices, and cross-scale connectivity. Three further research studies on the platform, covering adaptive model predictive contouring control, nonplanar model predictive control, and signal-temporal-logic-guided multi-agent reinforcement learning, show that the platform supports research in control, learning, and safety. Outreach through races at IEEE ICRA and IROS, a learning management system at courses.roboracer.AI, a community of more than 130 publications, and partnerships with industry and the Autoware Foundation extend the reach of the work toward deployment in automated transportation.		
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Contents

1	Project Overview	1
1.1	Project Funding and Matching Funds	2
1.2	Summary of Project Targets and Evidence	2
2	Why Small-Scale Testbeds Matter for Transportation Safety	2
2.1	Challenges Identified by the Roadmap	3
2.2	How the Roadmap Is Organized	4
3	The RoboRacer.AI Platform and Curriculum	4
3.1	Platform	4
3.2	Learning Outcomes and Student Feedback	5
3.3	Open Learning Management System	5
4	Roadmap Part A: Accessibility, Diversity, and Outreach	8
4.1	Cost-Effectiveness and Lightweight Implementation	8
4.2	Competitions and Outreach	8
4.3	Educational Programs, Workshops, and Seminars	9
4.4	International Initiatives and Remote Access	9
4.5	Diversity in Intelligent Transportation Research	9
5	Roadmap Part B: Shared Best Practices	10
6	Roadmap Part C: Global Connectivity and the Path to Full Scale	11
7	Research Enabled by the Platform	12
7.1	Adaptive Differentiable MPCC for Autonomous Racing	12
7.2	Nonplanar Model Predictive Control with Recursive Sparse Gaussian Processes	13
7.3	Multi-Agent Reinforcement Learning Guided by Signal Temporal Logic	13
7.4	What the Three Studies Show About the Platform	14
8	Community and Deployment Impact	14
8.1	Community Reach	14
8.2	Partnerships and Deployment	15
8.3	Workforce Development	15

9 Ethical Framework for Machine Learning in Life-Critical Systems	15
10 Conclusions and Recommendations	16
11 Research Products, Data, and Dissemination	16
11.1 Publications	16
11.2 Software, Course Materials, and Websites	17
11.3 Datasets and Metadata	17
11.4 Awards and Recognition	18
11.5 Research Personnel and ORCID Information	18
A Abbreviations	19

List of Figures

1	Photographs from the 1st Workshop on Small-Scale Testbeds for Connected and Automated Vehicles and Robot Swarms at IEEE IV 2024. Figure from [1].	3
2	Home page of the RoboRacer course portal at courses.roboracer.AI	5
3	Course catalog. Instructors at different universities offer and manage courses side by side. . .	6
4	Instructor workflow from application to the first live class.	6
5	Course-planning tool in the instructor portal.	7
6	A RoboRacer course page (left) and the course outline with modules (right).	7
7	Remote access to a small-scale testbed through a web interface. The roadmap uses CPM Remote as its example. Figure from [1].	10
8	An abstraction layer connecting two different small-scale testbeds, so that one motion planner controls vehicles on both. Figure from [1].	11

List of Tables

1	Project 609 funding sources.	2
2	Project targets and the evidence reported here.	2
3	Challenges of small-scale testbeds identified in the roadmap [1].	3
4	Roadmap parts and the corresponding RoboRacer.AI activities.	4
5	RoboRacer competitions at IEEE ICRA and IROS. Sizes are as reported by the organizers.	8
6	Best practices from the roadmap and the corresponding RoboRacer.AI practice.	10
7	Evaluation dimensions from the roadmap and how RoboRacer.AI measures them.	12
8	AD-MPCC results in the F1TENTH Gym [3].	13
9	Safety rate in the CARLA traffic-jam scenarios [5]. Safety rate is the share of episodes without collisions.	14
10	Partners of the RoboRacer.AI project.	15
11	Publications and research products associated with the project.	17
12	Software, course materials, and websites.	17
13	Project investigators, project-affiliated publication authors, and ORCID information.	18
14	Abbreviations used in this report.	19

1 Project Overview

Safety21 Project 609, RoboRacer.AI, addresses a workforce and technology problem in automated transportation. Automated driving systems must be developed, tested, and trusted before they reach public roads, yet few universities can afford full-size research vehicles, and few engineers receive hands-on training with real vehicles that fail, drift, and sense imperfectly. Led by Principal Investigator Rahul Mangharam and Co-Principal Investigator Insup Lee at the University of Pennsylvania, the project builds a low-cost, open, and scalable platform on which students and researchers can design, test, and deploy autonomous vehicle software, and then carry that software toward full-scale vehicles.

The project has three connected components.

1. **A multi-scale autonomous driving course.** An open curriculum teaches the fundamentals of autonomous driving on vehicles from 1/18 scale through 1/10 and 1/5 scale to full size, and is delivered through an open learning management system at <https://courses.robocer.AI>.
2. **Community activities.** The RoboRacer community spans 89 or more universities. The project supports international competitions, workshops, and open-source releases that give the community shared goals, shared benchmarks, and a reason to contribute.
3. **An ethical framework.** Students and researchers learn how to reason about machine learning in life-critical systems, so that technical training and responsible deployment develop together.

RoboRacer.AI grew out of F1TENTH, a 1/10-scale autonomous racing vehicle and course first described in 2020 as an open-source evaluation environment for continuous control and reinforcement learning [2]. The platform was renamed RoboRacer as it grew beyond racing into a general teaching and research platform. The race series has run since 2016, and the competition at ICRA 2025 was the 24th RoboRacer Autonomous Grand Prix.

This report documents the project in four parts. Sections 2 through 6 analyze RoboRacer.AI against the roadmap for small-scale testbeds for connected and automated vehicles (CAVs) and robot swarms published in IEEE Intelligent Transportation Systems Magazine [1]. That roadmap, written by a group of 14 authors from 11 institutions in eight countries, including the Principal Investigator of this project, identifies the main challenges of small-scale testbeds and proposes three parts to address them: accessibility and diversity, shared best practices, and global testbed connectivity. Section 7 presents three research studies, conducted on RoboRacer-based platforms, that show the platform is effective for transportation research and development. Section 8 describes the community and deployment impact, including the more than 130 publications from the RoboRacer community and the partnerships with industry. Section 11 lists all research products.

Overall project outcome

Project 609 delivered an open course and learning management system, two RoboRacer racing competitions in the project period together with a growing race series, an ethics component, and three peer-reviewed or preprint research studies that use the platform for control, learning, and safety research. The platform directly addresses each of the three roadmap parts for small-scale testbeds. The surrounding community includes 89 or more universities and more than 130 publications, and industry and Autoware partnerships connect the platform to deployment in automated transportation.

1.1 Project Funding and Matching Funds

Project 609 was funded through the Safety21 National University Transportation Center under U.S. Department of Transportation grant 69A3552344811 for the project period July 1, 2025 through June 30, 2026. Table 1 states the source of all project funds. The University of Pennsylvania provided the full non-federal match, equal to the federal award, as institutional cost share. The cost share requirement has been met and is documented in Penn’s sponsored-projects records. No other matching sources were used. The federal share was fully expended by the end of the project period.

Table 1: Project 609 funding sources.
kvoptions-patch[2019/11/29]

1.2 Summary of Project Targets and Evidence

The project proposal set quantitative targets. Table 2 lists each target next to the evidence reported in this document.

Table 2: Project targets and the evidence reported here.

Target	Evidence	Section
Open multi-scale course delivered on a learning management system	Open LMS at https://courses.roboracer.AI with instructor and student portals, course pages, and outlines.	3.3
Community across 89 universities	The RoboRacer community spans 89 or more universities.	4
At least four competitions	Races at ICRA 2025 (hardware and virtual), ICRA 2026, and IROS 2026, within a series of 24 or more grand prix events.	4.2
Ethical framework for machine learning in life-critical systems	Ethics module integrated with the course, with safety-oriented formal and learning-based methods demonstrated on the platform.	9
Reference vehicles from 1/18 scale to full size	1/18, 1/10, 1/5, and full-size vehicles supported through the Autoware integration plan, with 1/10-scale racing as the most mature level.	6
Open-source release of materials	Course content, race software, and research code released openly.	5

2 Why Small-Scale Testbeds Matter for Transportation Safety

Connected and automated vehicles and robot swarms need platforms for testing and validation before they are deployed. Full-scale testing is expensive and risky, while simulation alone cannot capture hardware effects such as sensor noise, actuator limits, and real-time constraints. The roadmap for small-scale testbeds describes small-scale testbeds as a cost-effective, flexible, and scalable solution in controlled settings, and as an intermediate validation layer between simulation and full-scale deployment [1]. RoboRacer.AI is one of the named case studies in that roadmap, under educational programs and competitions.

The roadmap came from the 1st Workshop on Small-Scale Testbeds for Connected and Automated Vehicles and Robot Swarms, held on June 2, 2024 at the IEEE Intelligent Vehicles Symposium in Jeju, South Korea. The workshop included eight invited speakers, four contributed papers, and a survey of more than 25 testbeds,

and it brought together researchers and educators who work with testbeds. Figure 1 shows photographs from the workshop.



Figure 1: Photographs from the 1st Workshop on Small-Scale Testbeds for Connected and Automated Vehicles and Robot Swarms at IEEE IV 2024. Figure from [1].

2.1 Challenges Identified by the Roadmap

The roadmap sorts the challenges into two groups. Table 3 summarizes them, and the text after the table explains each one.

Table 3: Challenges of small-scale testbeds identified in the roadmap [1].

Category	Challenge	Main issues
Transition challenges	Simulation to reality (Sim2Real) gap	Simulation fidelity, dynamic environment complexity, and multi-agent interaction fidelity.
Transition challenges	Small-scale to full-scale transition	Localization, perception, actuation, and uncertainty modeling.
Inherent real-world challenges	Environmental unpredictability	Mixed traffic, anomalous objects, and environmental variability.
Inherent real-world challenges	Distributed computing demands	Resource limits, real-time computing, fault tolerance, communication overhead, and synchronization.

Sim2Real gap. Methods developed in simulation must transfer reliably to hardware. The gap arises from limited simulation fidelity, from dynamic conditions such as weather and lighting that simulators model poorly, and from the difficulty of reproducing interactions among many agents. Digital twins that combine high-fidelity sensor models with real-time feedback help narrow the gap.

Small- to full-scale transition. Moving from a small vehicle to a full-size vehicle changes four things. Localization differs because indoor positioning systems used on small testbeds do not work outdoors. Perception must handle real lighting, obstructions, and objects not seen in training. Actuation differs because small and large vehicles have different dynamics, and a translation layer can adjust control inputs between

scales. Uncertainty modeling must include communication uncertainty, mixed traffic, road friction, payload, and wear.

Environmental unpredictability. Real traffic includes human drivers whose behavior is stochastic, unusual objects such as construction zones and irregular loads, and changing weather. These effects are especially strong in unstructured traffic in developing regions, where lane discipline is loose and many types of road user share the road.

Distributed computing demands. Vehicle computers have limited processing, memory, and energy, so real-time coordination across many vehicles needs algorithms that are efficient, fault-tolerant, and tolerant of communication delay and bandwidth limits.

2.2 How the Roadmap Is Organized

The roadmap has three parts, and Table 4 relates each part to the challenges and to the sections of this report. Parts A and B are foundational and near term, because they lower entry barriers and improve reproducibility and can be adopted by any single testbed. Part C is a long-term direction, because global testbed connectivity requires sustained interoperability and shared interfaces. Parts A and B enable Part C, and Part C in turn raises the value of shared practices and participation [1].

Table 4: Roadmap parts and the corresponding RoboRacer.AI activities.

Roadmap part	Principal RoboRacer.AI activities	Section
A. Accessibility and diversity	Low-cost 1/10-scale vehicle, open course and LMS, international competitions, simulation league for remote participants.	4
B. Shared best practices	Open-source software, modular and containerized stack, pre-configured course modules, Autoware compatibility, continuous updates.	5
C. Global connectivity	Common vehicle interfaces across scales, Autoware integration, simulation and hardware leagues with shared rules.	6

The roadmap itself is a synthesis of community-identified needs and does not report a measurement of RoboRacer.AI. The mapping in Table 4 and the following sections is the analysis of this project, which compares the roadmap recommendations with what the project built and delivered.

3 The RoboRacer.AI Platform and Curriculum

3.1 Platform

The reference platform is a 1/10-scale autonomous race car that carries a LiDAR, a camera, an inertial sensor, and an onboard computer, and that runs the Robot Operating System. It costs a small fraction of a full-size research vehicle, so a classroom or student team can afford several. A common software stack allows teams to run perception, planning, and control code in simulation first and then on the vehicle. The same course is designed to extend to other scales: 1/18-scale vehicles for hand-held and tabletop work, 1/5-scale vehicles that carry heavier computers and automotive-style actuation, and full-size vehicles running the Autoware software stack.

3.2 Learning Outcomes and Student Feedback

Students who take the RoboRacer course build and test the full autonomy pipeline on a real vehicle: perception and state estimation, mapping and localization, planning, and control, followed by head-to-head racing. The proposal for this project cited student survey results from earlier course offerings. More than 80 percent of respondents strongly agreed that the hardware and software modules motivate them to learn, more than 70 percent strongly agreed that the hardware improved their understanding of the material, and more than 80 percent strongly agreed that the competitions motivate them. These results support the premise of the roadmap that small-scale physical platforms give students experience with sensing imperfections, actuator limits, and real-time constraints that simulation-only tools cannot give.

3.3 Open Learning Management System

A central deliverable of this project is an open-source learning management system (LMS) for RoboRacer courses, published at <https://courses.roboracer.AI>. The LMS gives instructors a ready-made path from a new course idea to a first live class, and gives students a single place to follow lectures, tutorials, assignments, and discussions. Figure 2 shows the portal home page, and Figure 3 shows the list of courses offered by different institutions on the platform.

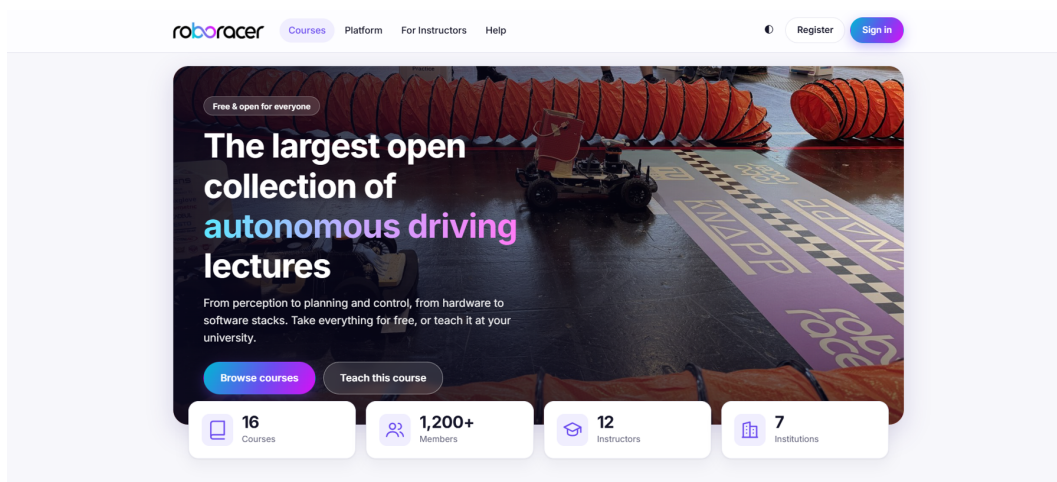


Figure 2: Home page of the RoboRacer course portal at courses.roboracer.AI.

The LMS has separate portals for students and instructors.

- **Open platform.** Lecture slides, lecture videos, interactive tests and hands-on coding, and notes for lecturers are available to all, with related background courses, discussion groups, built-in grading, and monthly content updates.
- **Instructor registration and verification.** Instructors verify their identity and then upload and manage course content in their own portal. Students register with their school identifier and enter the portal of their course.
- **Guided course creation.** Step-by-step tutorials and documentation guide an instructor from application to a first live class: apply, get access, customize, add material, publish, and teach.

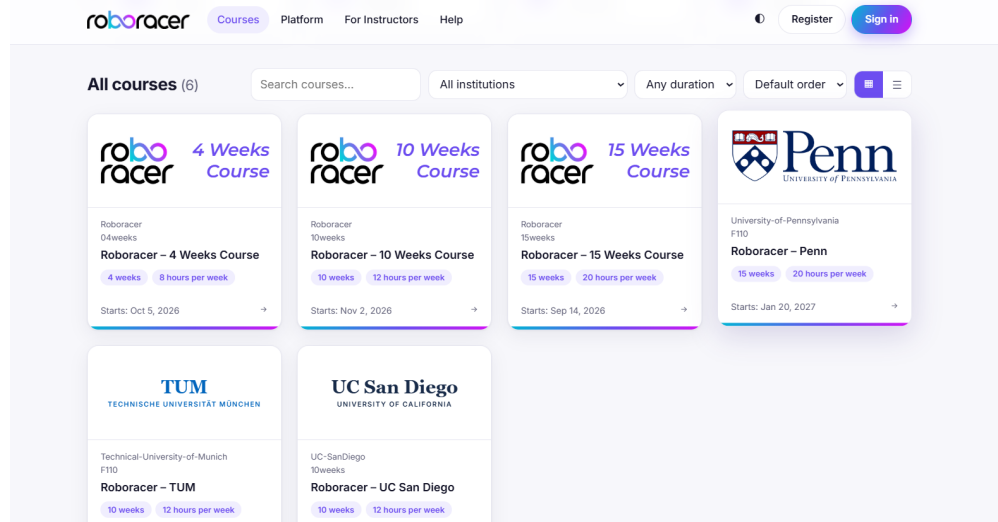


Figure 3: Course catalog. Instructors at different universities offer and manage courses side by side.

- **Course planning.** The instructor sets the course timeline, lecture duration, and content requirements, uploads slides, video tutorials and notes, sets grading templates and rubrics, and brands the course according to university guidelines.
- **Course pages.** Each course page shows the description, prerequisites, outline and modules, instructor and teaching staff, and a frequently-asked-questions section.

Figures 4 and 5 show the instructor workflow and the course-planning view, and Figure 6 shows a course page and its outline.

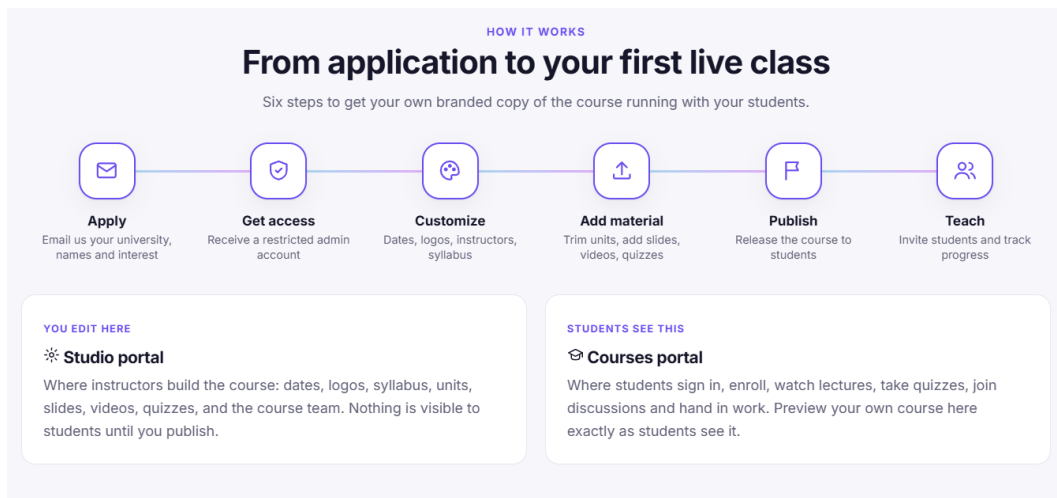


Figure 4: Instructor workflow from application to the first live class.

The course content follows modules that move from the foundations of the vehicle and the Robot Operating System, through reactive methods, mapping and localization, planning, and vision, to special topics and the final race. The courses were taught in January through May of 2025 and again in 2026.

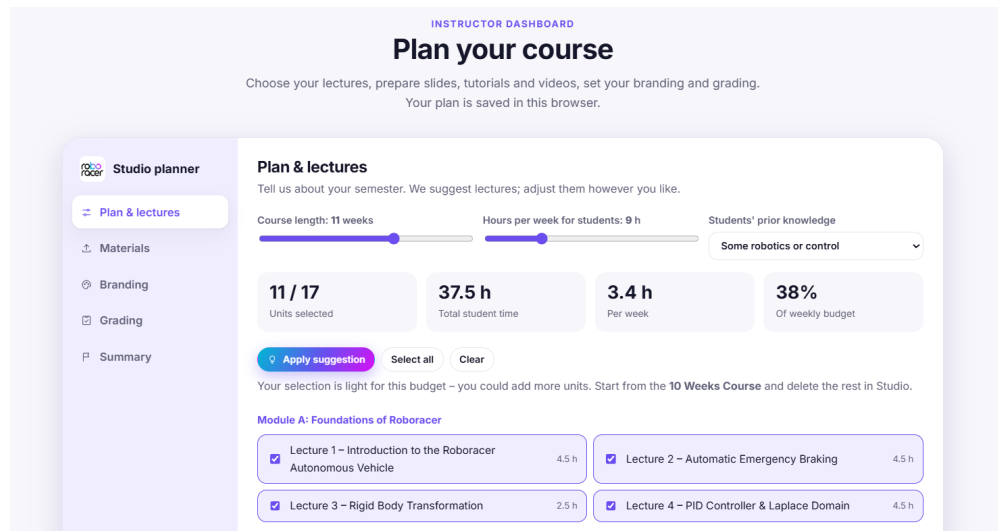


Figure 5: Course-planning tool in the instructor portal.

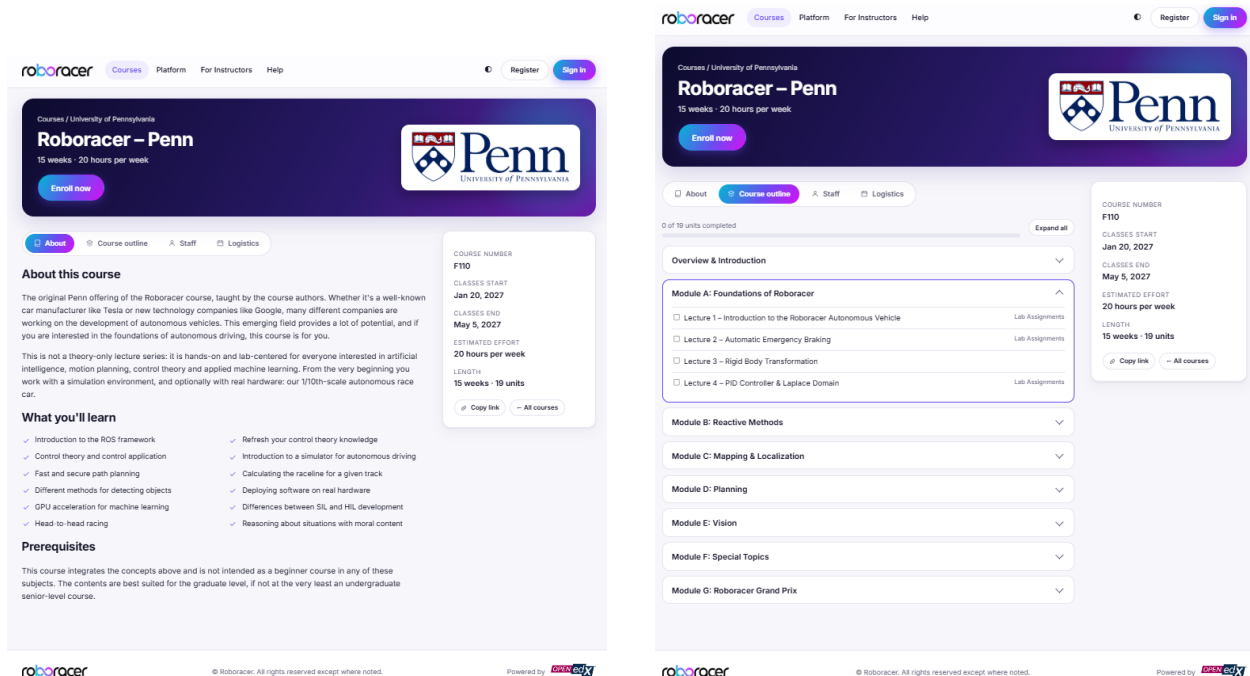


Figure 6: A RoboRacer course page (left) and the course outline with modules (right).

4 Roadmap Part A: Accessibility, Diversity, and Outreach

Part A of the roadmap asks testbeds to broaden participation, especially among underrepresented and geographically distributed communities, through low cost, light-weight implementation, educational programs, competitions, workshops, international initiatives, and remote access [1]. RoboRacer.AI addresses each measure.

4.1 Cost-Effectiveness and Lightweight Implementation

The roadmap names two measures that make a testbed accessible: low cost and a lightweight, simple design. The 1/10-scale RoboRacer vehicle is built from commercial off-the-shelf parts. The open LMS removes a second cost, because a university does not need to develop a course before it can teach one. The simulation league removes a third, because a team without hardware can still take part from anywhere. The roadmap highlights the trade-off between the complexity needed for research and the simplicity needed for access. RoboRacer addresses it with a layered curriculum, in which beginners use reactive methods and advanced teams use model predictive control, learning-based planning, and game-theoretic racing.

4.2 Competitions and Outreach

The roadmap lists competitions as a way to incentivize innovation, creativity, and teamwork, and it names RoboRacer first among its case studies. Competitions are also the most visible outreach activity of this project. Table 5 lists the events, with the recent history of the series for context.

Table 5: RoboRacer competitions at IEEE ICRA and IROS. Sizes are as reported by the organizers.

Event	Period	Reported size and notes
RoboRacer Grand Prix at ICRA 2022, Philadelphia	Series history	20 teams, more than 100 participants.
RoboRacer Grand Prix at ICRA 2023, London	Series history	24 teams, more than 130 participants.
RoboRacer Grand Prix at ICRA 2024, Japan	Series history	19 teams, more than 135 participants.
24th RoboRacer Autonomous Grand Prix at IEEE ICRA 2025	Project period	60 reported by the organizers.
3rd RoboRacer Sim Racing League at ICRA 2025, virtual	Project period	56 teams.
RoboRacer Competition at IEEE ICRA 2026, Vienna	Project period	36 teams (35 international challengers of the winning team). Hardware race and virtual simulation track.
RoboRacer Race at IEEE IROS 2026, Pittsburgh, September 27–30	After project end	Physical competition with 1/10-scale cars and the 6th RoboRacer Sim Racing League. Sponsors include TIER IV and Autoware.

The events share a format. In the physical competition, teams build or bring 1/10-scale autonomous race cars, qualify with time trials, and then compete in multi-car knockout tournaments. In the virtual competition, teams participate remotely in a simulation benchmark. The ICRA 2026 theme was multi-agent dynamic games. At the time of the project proposal, the series had hosted 24 grand prix competitions, and the most

recent one had more than 180 participants from 37 teams. The ICRA 2026 competition was won by the LamarRacing team, which also earned the Best Performance Overall award [7].

These events show the reach of the platform in three ways. First, each race brings together dozens of university teams from different countries, so a single event reaches a large share of the autonomous-driving research community. Second, the virtual league lets teams without a vehicle or without a travel budget take part, which is the roadmap’s accessibility goal. Third, the race at IROS 2026 is held in Pittsburgh, the home city of the Safety21 lead institution, and its organizers include Carnegie Mellon University, Clemson University, West Virginia University, and the University of Pennsylvania [8].

4.3 Educational Programs, Workshops, and Seminars

The roadmap describes educational programs, workshops, and seminars as ways to bring together established experts and early-career researchers. RoboRacer contributes in all three ways. The course supplies the educational program. The Principal Investigator is a co-author of the roadmap that came out of the workshop on small-scale testbeds at IEEE IV 2024, and the community meets through the competitions and an online Slack community. The roadmap’s case studies show that comparable programs exist elsewhere, including the CPM Lab and CPM Academy at RWTH Aachen and the University of the Bundeswehr Munich, the Hands-On Robotics course, and RoboCup. RoboRacer is different in how widely it has been adopted, with 89 or more university users.

4.4 International Initiatives and Remote Access

The roadmap recommends international collaboration, in particular with regions such as India, South Africa, and Egypt, where traffic is non-lane-based and diverse, and it recommends remote access to testbeds for resource-constrained communities. The CPM Remote system, shown in Figure 7, is the roadmap’s example of remote access to a physical testbed. The RoboRacer simulation league and the LMS provide two forms of remote access that already operate at scale: a shared simulator and benchmark in which any team can compete, and a course portal that any instructor can use. Teams from several countries compete at each event, and the roadmap’s authors include researchers from Germany, India, China, Egypt, Bulgaria, Sweden, Belgium, and the United States.

4.5 Diversity in Intelligent Transportation Research

The roadmap identifies a gap between advanced technologies and real-world conditions in developing regions, a lack of dataset diversity, and a need for tailored testbeds. Small-scale vehicles lower the barrier for local researchers to test globally developed algorithms in local conditions. The 1/10-scale RoboRacer vehicle is such a vehicle, and the shared open software allows a team anywhere to reproduce results from another team. By supporting students from universities of very different resources, the open course and simulation league contribute to the roadmap goal of broad participation.

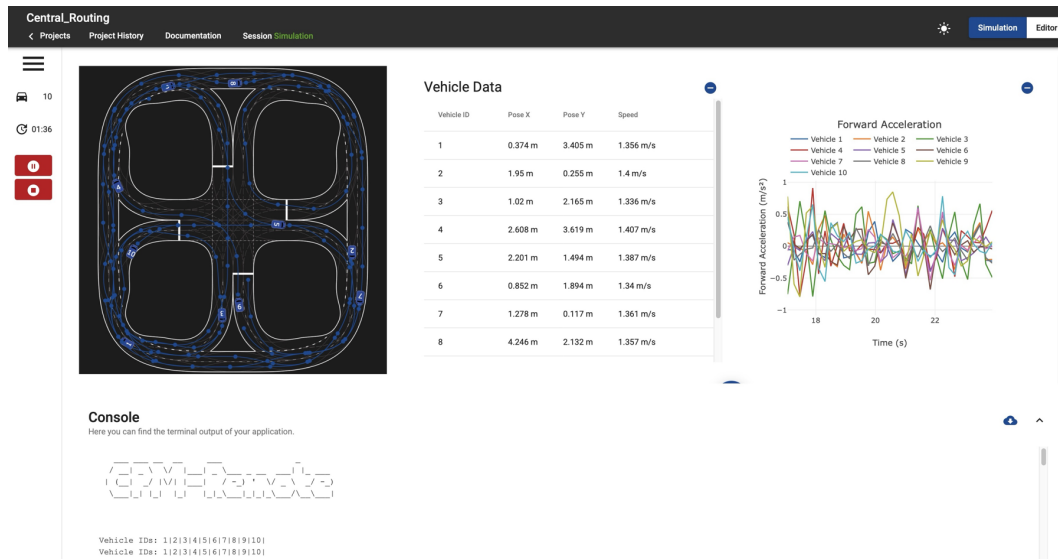


Figure 7: Remote access to a small-scale testbed through a web interface. The roadmap uses CPM Remote as its example. Figure from [1].

5 Roadmap Part B: Shared Best Practices

Part B of the roadmap lists six best practices for developing and maintaining a testbed [1]. Table 6 relates each practice to what RoboRacer.AI does.

Table 6: Best practices from the roadmap and the corresponding RoboRacer.AI practice.

Roadmap best practice	RoboRacer.AI practice
Collaboration and knowledge sharing	A central hub (roboracer.ai, the LMS, the code repositories, and a Slack community) for code, tools, documentation, and standardized race scenarios that allow algorithms to be compared fairly.
Open-source contributions	Course content and software are open. Research code from the project is released openly, for example the AD-MPCC controller and the nonplanar Isaac Sim environment. Community stacks such as the ForzaETH race stack build on the platform [6].
Purpose-driven, modular design	Modular hardware and software based on the Robot Operating System make sensors, planners, and controllers replaceable.
Streamlined usability	Ready-to-use modules, documentation, a pre-configured simulator, and containerized software allow students to focus on experiments rather than setup.
Interoperability and communication	Standard interfaces and middleware. The project integrates with the Autoware stack across vehicle scales.
Continuous development	Course content is updated monthly, the platform has evolved from F1TENTH to RoboRacer, and the competitions raise the technical challenge each year, for example with multi-agent dynamic games.

The roadmap proposes two mechanisms to encourage open-source contributions: a pull mechanism, in which competition tracks or academic recognition reward open releases, and a push mechanism, in which an open release is a condition of eligibility. RoboRacer applies the pull mechanism through its competitions, which reward strong and well-documented approaches, and the community builds on the code that is released. The more than 130 publications described in Section 8 are the clearest evidence that the practice works.

6 Roadmap Part C: Global Connectivity and the Path to Full Scale

Part C of the roadmap calls for an abstraction layer that connects testbeds of different design and location. The roadmap demonstrates the idea by connecting two testbeds, the CPM Lab and the IDS3C scaled smart city. A single motion planner ran unchanged on both testbeds in identical three-vehicle intersection scenarios, with the abstraction layer adding only a few milliseconds of overhead, sub-millisecond message-level delay, and a total control cycle below 40 milliseconds. Figure 8 shows the setup.

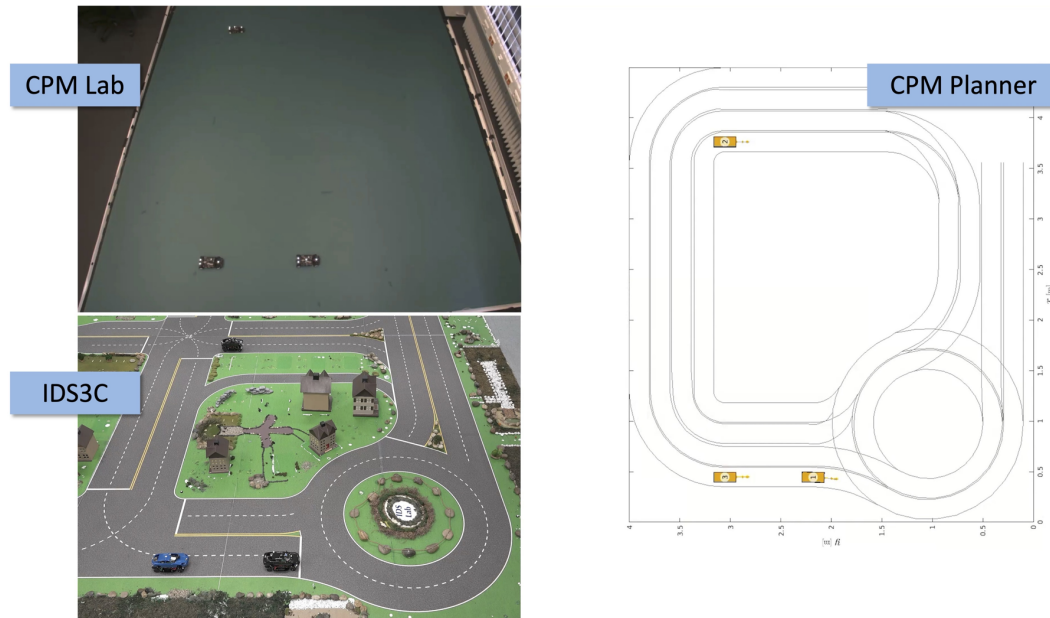


Figure 8: An abstraction layer connecting two different small-scale testbeds, so that one motion planner controls vehicles on both. Figure from [1].

RoboRacer.AI follows the same principle across vehicle scale and across simulation and hardware. Four design choices stand out.

- **One software interface across scales.** The same interface is used on 1/18-, 1/10-, and 1/5-scale vehicles and on full-size vehicles through the Autoware integration. A planner written for the small vehicle can therefore be moved to a larger one with changes limited to parameters.
- **Simulation and hardware with shared rules.** The physical race and the Sim Racing League follow the same race format, with time trials and head-to-head racing, so that results from simulation can be compared with results from hardware.
- **Scale-agnostic control.** The roadmap recommends scale-agnostic control interfaces that compensate for dynamic mismatch between scales. Model-based controllers, such as the MPCC controllers in Section 7, express vehicle dynamics through parameters, so the same formulation can be re-parameterized for another vehicle.
- **Common evaluation metrics.** The roadmap provides example metrics for testbed fidelity, cross-scale transfer, and connectivity, shown in Table 7. Lap time, collision rate, and safety margin are the natural RoboRacer measures of cross-scale behavior.

The Autoware integration is the most direct deployment path from the platform to automated transportation.

Table 7: Evaluation dimensions from the roadmap and how RoboRacer.AI measures them.

Aspect	Dimension	Roadmap example metrics [1]	RoboRacer.AI measure
Testbed fidelity	Sensing, actuation, environment, and communication realism	Noise, latency, dropouts, tracking error, repeatability, packet loss	LiDAR and odometry noise on the vehicle, control latency, tracking error, track and surface variation.
Cross-scale transfer	Behavioral consistency, control performance, sensitivity to uncertainty, transfer effort	Trajectory similarity, collision rate, near-miss distance, deadline misses, code modification	Lap time, collision count, minimum distance to opponents, solver time against the control period, parameters changed between scales.
Global connectivity	Interface generality, runtime overhead, scalability, portability	End-to-end latency, number of agents and testbeds, identical code across platforms	Same stack in simulation and hardware, number of teams per event, number of institutions on the LMS.

Autoware is an open-source stack for automated driving, and the Autoware Foundation is a deployment partner listed in the Safety21 project record [9]. The races at IROS 2026 are sponsored by TIER IV and Autoware. The project plan therefore sets out a path in which algorithms mature on the low-cost 1/10-scale vehicle, are tested in the Autoware ecosystem on larger vehicles, and are evaluated with the metrics above.

The roadmap treats global connectivity as a long-term direction, and Project 609 does not claim to have completed it. The project has contributed the pieces that the roadmap identifies as prerequisites: a broad community (Part A) and shared practices (Part B).

7 Research Enabled by the Platform

A testbed is useful to transportation research only if it supports results that matter beyond the testbed. This section presents three studies that use RoboRacer-based platforms and cover three areas of automated driving: control under changing road conditions, control on uneven terrain, and safe multi-agent learning. All three build on the F1TENTH and RoboRacer platform [2], and the Principal Investigator is a co-author of each. Safety21 is acknowledged in the nonplanar control paper. The other papers acknowledge the sponsors named in their own acknowledgments, and they are included here as evidence of what the platform enables.

7.1 Adaptive Differentiable MPCC for Autonomous Racing

Autonomous racing drives vehicles to their physical limits, which makes it a demanding test of control methods. Model predictive contouring control (MPCC) minimizes contouring and lag errors while it maximizes progress along a path. The dominant uncertainty in racing comes from the interaction of the tire with the road, which the Pacejka tire model describes well. The AD-MPCC study [3] combines online estimation of Pacejka parameters, through a regularized moving-horizon estimator, with a differentiable MPCC that adapts the objective weights, which a Pacejka-informed machine learning model approximates for real-time use. It is evaluated in the F1TENTH Gym simulator.

For transportation, the lesson is that a controller that adapts to a changing road surface avoids a failure that fixed models cannot avoid. Sudden loss of friction, from rain, ice, gravel, or a painted surface, is a hazard

Table 8: AD-MPCC results in the F1TENTH Gym [3].

Scenario	Result	Meaning for safety and performance
Single surface, 10 laps, friction 1.2	Average lap time 64.89 s for AD-MPCC and 64.08 s for Diff-MPCC, against 75.57 s for standard MPCC.	About 11 s faster per lap, with a lateral offset of 0.926 m for AD-MPCC against 1.040 m for Diff-MPCC.
Multiple surfaces, friction 0.7 to 1.2, 1 lap	Only AD-MPCC completes the lap. MPCC, Diff-MPCC, and A-MPCC crash at the first slippery segment.	Online adaptation to sudden friction change is needed for safe operation. Mean speed 11.65 m/s and lateral offset 1.069 m.
Computation time per step	21.21 to 24.18 ms for the new methods, against 20.45 ms for MPCC.	Within the 50 ms control period, so the methods are real-time feasible.

for any vehicle. The code for this study is public at <https://github.com/nxt-lab/AD-MPCC>. The authors note that the results come from simulator data, and that deployment on a physical racing platform is the next step.

7.2 Nonplanar Model Predictive Control with Recursive Sparse Gaussian Processes

Most autonomous-driving research assumes flat terrain, but vehicles in off-road, work-zone, and rural settings travel over slopes, banks, and bumps. The nonplanar control study [4] combines a nominal single-track vehicle model with a residual Gaussian process that takes terrain geometry as an input and that is updated recursively from real-time data. A model predictive path integral (MPPI) controller uses the learned model to track a reference trajectory. The study built a custom NVIDIA Isaac Sim environment with kidney-shaped, L-shaped, and oval tracks that have varying 3D geometry, with vehicle parameters taken from the F1TENTH platform, and open-sourced it at <https://github.com/mlab-upenn/NonPlanarIsaacSim>.

The results show that the recursively updated sparse Gaussian process residual markedly improves tracking compared with the nominal model alone. On the more difficult tracks, the nominal model departs from the track, while the learned model keeps the vehicle on it. The computation time stays below 20 ms, so the controller runs at 50 Hz, which is practical for real-time control. This work illustrates the small-to-full-scale challenge identified by the roadmap, which says that actuation and uncertainty differ between scales, and it shows a method that learns those differences online. The study acknowledges the U.S. DOT Safety21 National University Transportation Center. Future work will move to physical off-road vehicles and add dynamic obstacles.

7.3 Multi-Agent Reinforcement Learning Guided by Signal Temporal Logic

Learning-based control needs reward functions, and it is hard to write a scalar reward that expresses safety rules and task goals for several interacting vehicles. The STL-MARL study [5] uses signal temporal logic (STL), a formal language for time-dependent requirements, to write task and safety specifications, and it uses the robustness value of each specification as reward. It adds an STL-based safety shield. The study is evaluated in the multi-agent particle environment and in the CARLA simulator, including a traffic-jam scenario in which vehicles must pass through the one open lane around broken-down vehicles.

The STL-guided method has both a higher reward and a higher safety rate than the baselines, and the safety shield has a strong effect, since removing it cuts the safety rate in the expansion scenario from 90 percent to 20 percent for the comparison algorithm. This links to the ethics component of the project, because formal

Table 9: Safety rate in the CARLA traffic-jam scenarios [5]. Safety rate is the share of episodes without collisions.

Method	Traffic-jam	Traffic-jam expansion
STL-guided MARL	97%	90%
MAPPO	74%	64%
MAA2C	88%	68%
MAPPO without STL safety shield	65%	20%

specifications state in an auditable way what a learning system is required to do and not to do.

7.4 What the Three Studies Show About the Platform

The three studies address different problems, but together they show the platform is effective for transportation research and development in five ways.

1. **Range of topics.** The platform supports optimization-based control, learning-based modeling, and multi-agent reinforcement learning with formal methods, which are three of the main areas of automated driving research.
2. **Simulation to hardware path.** The F1TENTH Gym and Isaac Sim environments mirror the hardware, which follows the roadmap’s call for high-fidelity simulation that is paired with physical testing.
3. **Safety focus.** Each study centers on a safety question: failure on slippery surfaces, loss of tracking on uneven terrain, and collisions among interacting vehicles.
4. **Open artifacts.** Code and simulation environments are released, which lets others reproduce and extend the work.
5. **Student-led research.** Graduate students lead the studies, which links the research mission of the platform with its training mission.

8 Community and Deployment Impact

8.1 Community Reach

The RoboRacer community includes 89 or more universities in many countries that use the platform for research, teaching, and competition. The community has produced more than 130 publications that use or build on the platform, which is the broadest measure of its research impact. Examples in this report include the control and learning studies of Section 7, the ForzaETH race stack for head-to-head racing on commercial off-the-shelf hardware [6], and the roadmap itself, which credits RoboRacer as a case study of how courses, competitions, and an open stack combine [1]. The publication list is maintained by the community through the project website.

8.2 Partnerships and Deployment

The platform links universities to organizations that build and deploy automated vehicles. Table 10 lists the partners and the connection of each to deployment in automated transportation.

Table 10: Partners of the RoboRacer.AI project.

Partner	Role
Autoware Foundation	Deployment partner of record in the Safety21 project record. Autoware is the open-source automated-driving software stack that the platform integrates across vehicle scales, and Autoware is a sponsor of the IROS 2026 race.
IEEE Robotics and Automation Society	Partner of record, and host of the ICRA conference at which the grand prix has been held.
TIER IV	Sponsor of the IROS 2026 race and a developer of Autoware.
SICK	Industry partner in sensing technology for automated vehicles.
NVIDIA	Industry partner in computing and simulation. The nonplanar control study uses the NVIDIA Isaac Sim simulator.
Quailsys	Industry partner of the RoboRacer community.
NeoBotics spinoff	Industry partner (a NeoBotics spinoff).

These partnerships matter for deployment for three reasons. First, they connect the students who train on the platform with the sensor, computing, and software companies that hire them and that build production systems. Second, they provide hardware, software, and sponsorship that keep the open platform current, which the roadmap identifies as a requirement of continuous development. Third, Autoware gives the platform a common software path to larger vehicles and to the field.

8.3 Workforce Development

The project proposal set a goal of training more than 2,000 people worldwide in the design and testing of autonomous vehicles. The LMS, the course offerings each year at many institutions, and the competitions together serve that goal. The students who learn on the platform enter the automated-vehicle workforce with direct experience of the full autonomy pipeline.

9 Ethical Framework for Machine Learning in Life-Critical Systems

The third component of the project is an ethical framework. Automated vehicles are life-critical systems, and students who learn to use machine learning on them need to learn the consequences of mistakes. The framework in this project has three elements.

- **Safety by specification.** Courses and research teach formal requirements, for example signal temporal logic, as a way to state precisely what a learning-based system must do and must not do. The STL-MARL study of Section 7 is an example.
- **Testing at increasing risk.** The platform lets students test first in simulation, then on a small vehicle where failure is cheap, and later on larger vehicles. This reflects the roadmap’s view of small-scale testbeds as an intermediate validation layer.

- **Inclusion and global fairness.** The roadmap warns that datasets and technology developed in a few countries may not fit unstructured traffic in other regions, and it calls for local researchers to take part. The open course and simulation league are designed to broaden who participates.

10 Conclusions and Recommendations

Project 609 shows that a low-cost, open, and well-organized platform can serve three purposes at the same time: it teaches autonomy to students at many universities, it supports research in control, learning, and safety, and it links to partners who deploy automated vehicles. Measured against the roadmap for small-scale testbeds, the project has delivered the foundational Parts A and B and has built the interfaces on which Part C depends.

The project recommends the following next steps.

1. **Continue the race series and the simulation league** as the main outreach activity, with attention to participation from regions that are underrepresented today.
2. **Complete the cross-scale validation.** Use the common metrics of Table 7 to measure transfer from 1/10-scale vehicles to 1/5-scale and full-size vehicles through the Autoware integration.
3. **Move the research studies to hardware.** Take the adaptive MPCC and the nonplanar controller from simulation to physical vehicles, including low-friction and uneven surfaces.
4. **Grow the LMS.** Add partner-contributed courses and an ethics module that all courses share.
5. **Document outcomes.** Track the number of learners, institutions, and publications each year, so that the effect on the workforce is measured and not only estimated.

11 Research Products, Data, and Dissemination

This section lists the publications, software, datasets, and other outputs associated with the project. Each item is given with its full DOI or URL so the record remains usable in print and with assistive technology.

11.1 Publications

Table 11 lists the research products. Sponsor acknowledgments are as printed in each paper.

Table 11: Publications and research products associated with the project.

Short name	Publication and access	Venue and status
Testbeds roadmap	J. Xu, J. Betz, A. Mokhtarian, A. Mittal, M. Cai, R. Mangharam, O. M. Shehata, C. M. Elias, J.-N. Zaeche, P. Scheffe, F. Jahncke, S. S. Ullhas, K. M. Arfvidsson, and B. Alrifae, “Small-Scale Testbeds for Connected and Automated Vehicles and Robot Swarms: Challenges and a Roadmap.” DOI: https://doi.org/10.1109/MITS.2026.3666681 arXiv: https://arxiv.org/abs/2503.05656 Survey table: https://bassamlab.github.io/testbeds-survey	IEEE Intelligent Transportation Systems Magazine, 2026
AD-MPCC	N. T. Nguyen, B. Nguyen, A. Amine, T. Vo-Duy, R. Mangharam, and T. X. Nghiem, “AD-MPCC: Adaptive Differentiable Model Predictive Contouring Control for Autonomous Racing.” arXiv: https://arxiv.org/abs/2607.00141 Code: https://github.com/nxt-lab/AD-MPCC	IROS 2026
Nonplanar MPC	A. Amine, K. Puri, V.-A. Le, and R. Mangharam, “Nonplanar Model Predictive Control for Autonomous Vehicles with Recursive Sparse Gaussian Process Dynamics.” arXiv: https://arxiv.org/abs/2602.16206 Code: https://github.com/mlab-upenn/NonPlanarIsaacSim	Preprint, February 2026
STL-MARL	J. Wang, S. Yang, Z. An, S. Han, Z. Zhang, R. Mangharam, M. Ma, and F. Miao, “Multi-Agent Reinforcement Learning Guided by Signal Temporal Logic Specifications.” arXiv: https://arxiv.org/abs/2306.06808	IROS 2025

11.2 Software, Course Materials, and Websites

Table 12: Software, course materials, and websites.

Item	Purpose	Access
RoboRacer course portal and LMS	Open learning management system with instructor and student portals, course pages, lectures, tutorials, assignments, and grading.	https://courses.robocer.ai
RoboRacer project website	Competitions, rules, community links, and publications.	https://robocer.ai
IROS 2026 race site	Rules, registration, and organizers for the 2026 race in Pittsburgh.	https://iros2026-race.robocer.ai/
AD-MPCC	Adaptive differentiable MPCC with Pacejka parameter estimation.	https://github.com/nxt-lab/AD-MPCC
NonPlanarIsaacSim	Isaac Sim environment with nonplanar tracks and the sparse-GP MPPI controller.	https://github.com/mlab-upenn/NonPlanarIsaacSim

11.3 Datasets and Metadata

The project produced course content, simulation environments, and experiment records. The course materials are archived in the LMS and the code repositories above. The simulation environment and its track

definitions are public. Experiment data from the research studies are maintained by the authors of each study under the project Data Management Plan. Their descriptive metadata give the simulator and version, vehicle parameters, track geometry, controller settings, random seeds, number of laps or episodes, and the metrics reported in the papers.

11.4 Awards and Recognition

- At ICRA 2026 in Vienna, the LamarRacing team won the Best Performance Overall award in the RoboRacer competition [7].
- The RoboRacer platform is a named case study in the roadmap for small-scale testbeds in IEEE Intelligent Transportation Systems Magazine [1].

11.5 Research Personnel and ORCID Information

Rahul Mangharam and Insup Lee are the project investigators. Table 13 gives ORCID identifiers for the investigators and for the project-affiliated authors of the publications.

Table 13: Project investigators, project-affiliated publication authors, and ORCID information.

Name	Project or publication role	ORCID
Rahul Mangharam	Principal investigator; author of all four publications	https://orcid.org/0000-0002-3388-8283
Insup Lee	Co-principal investigator	https://orcid.org/0000-0003-2672-1132
Ahmad Amine	Publication author (AD-MPCC, nonplanar MPC)	https://orcid.org/0009-0008-6080-8411
Kabir Puri	Publication author (nonplanar MPC)	https://orcid.org/0009-0008-8586-302X
Viet-Anh Le	Publication author (nonplanar MPC)	https://orcid.org/0000-0002-9829-7150
Shuo Yang	Publication author (STL-MARL)	

External co-authors are affiliated with other institutions and are listed in each publication.

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A Abbreviations

Table 14: Abbreviations used in this report.

Abbreviation	Definition
AD-MPCC	Adaptive differentiable model predictive contouring control
ADAS	Advanced driver-assistance system
ADS	Automated driving system
CAV	Connected and automated vehicle
DMP	Data Management Plan
GP	Gaussian process
ICRA	IEEE International Conference on Robotics and Automation
IROS	IEEE/RSJ International Conference on Intelligent Robots and Systems
LMS	Learning management system
MARL	Multi-agent reinforcement learning
MPC	Model predictive control
MPCC	Model predictive contouring control
MPPI	Model predictive path integral
PPMS	Safety21 project and performance management system
ROS	Robot Operating System
Sim2Real	Simulation to reality
STL	Signal temporal logic
USDOT	U.S. Department of Transportation

Abbreviation	Definition
UTC	University Transportation Center
