VR Driving Learning Simulator

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Project report submitted in partial fulfilment of the requirements
for the Degree of M.Tech. in Computer Engineering (Specialized in Software Engineering)

on November 20, 2025

Project Guide
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Student Declaration

I hereby declare that the work presented in the report entitled **"VR Driving Learning Simulator"** submitted by me for the partial fulfilment of the requirements for the degree of *M.Tech. in Computer Engineering(Specialized in Software Engineering)* at Veermata Jijabai Technological Institute, Mumbai, is an authentic record of my work carried out under the guidance of **Dr. V.B.Nikam** . Due acknowledgements have been given in the report for all material used. This work has not been submitted elsewhere for the reward of any other degree.

Ritvik Babre **Place & Date:** November 20, 2025

Certificate

This is to certify that the above statement made by the candidate is correct to the best of my knowledge.

Dr. V.B.Nikam **Place & Date:** November 20, 2025

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Chapter 1

Introduction

1.1 Background

The integration of Virtual Reality (VR) technologies in the field of driver training has opened new avenues for creating realistic and safe learning environments. Traditional driving instruction often faces limitations due to safety concerns, vehicle costs, and environmental constraints. Additionally, training on high-end or luxury vehicles such as Mercedes-Benz, BMW, or Audi models is often impractical for driving schools because of their operational and maintenance costs. To overcome these challenges, VR-based driving simulators have emerged as an effective alternative, allowing learners to experience authentic driving conditions without the associated risks or expenses [4].

With advancements in modern VR hardware such as the Meta Quest 3, it has become feasible to develop highly immersive simulations that closely replicate real-world vehicle dynamics, visual fidelity, and driver feedback. This project aims to design and develop a **VR-based Driving Simulator for Driving Schools**, focusing on high-end vehicle simulations. The system will leverage custom-built input hardware—including a rewired steering wheel, accelerator, brake, and clutch assembly—connected via Bluetooth to the simulation platform. These components will provide realistic control feedback and allow for seamless integration with both automatic and manual vehicle modes.

1.2 Problem Statement

Conventional driving simulators are often expensive, bulky, and lack realistic tactile feedback from vehicle controls. Furthermore, most commercially available simulators are targeted at entertainment rather than driver education, leading to a gap in the availability of accurate and affordable driver training systems. There exists a need for a modular, scalable, and hardware-accurate VR driving simulator that can be customized for specific vehicle models and used effectively in a driving school setting.

1.3 Objectives

The primary objective of this project is to develop a patentable, high-fidelity VR driving simulator that provides an immersive and realistic driving experience. The specific goals include:

- Designing a VR-compatible driving simulation system for Meta Quest 3 and PC platforms.
- Developing realistic vehicle physics and environmental models using Unity or Unreal Engine.
- Integrating physical driving controls (steering, pedals, gear shifter) with Bluetooth-based input communication.
- Providing accurate feedback mechanisms and data logging for performance assessment.
- Creating an extensible system architecture that allows for both automatic and manual transmission modes.

1.4 Scope

The system will initially focus on simulating automatic vehicles, with the potential extension to manual transmission as a secondary phase. The prototype will be tested using a Meta Quest 3 headset connected to a PC equipped with an NVIDIA RTX 3060 GPU. The developed system will be optimized for standalone operation on Meta Quest devices, with scalability for PC-VR tethered mode. In the long term, the simulator can be expanded for collaboration with government agencies such as the Mumbai RTO for standardized driver education and testing.

1.5 Report Overview

This report presents the design, implementation, and evaluation of a VR-based driving simulator that integrates realistic physical controls with an immersive headset platform. The document first explains the motivation and technical background for the project, then presents the system architecture, hardware and firmware design for the control rig, and the software components implemented in the VR application. Subsequent sections describe the prototype development process, testing methodology, evaluation metrics, and experimental results. The report concludes with a discussion of limitations, future work, and potential routes for commercialization and IP protection.

Chapter 2

Literature Review

Textual Synthesis

Interaction fidelity (high-fidelity setups with steering wheel and pedals) consistently improves training transfer, takeover performance, and user trust in automated driving scenarios. Gamification and in-car tasks maintain or increase driver vigilance; game performance metrics show promise as indirect measures of driver engagement and state monitoring. Physiological measures such as electrodermal activity (EDA) and pupil size provide objective evidence of engagement and vigilance when users perform AR/VR tasks in autonomous vehicles. Visual acuity—particularly dynamic visual acuity (DVA)—is linked to driving performance and can be effectively studied using VR simulations. Motion sickness and simulator sickness remain under-investigated in many studies and should be considered when designing longer-duration VR training protocols. Many studies rely on small, often homogeneous samples, limiting generalizability; future work should include more diverse and larger participant pools.

Tabular Summary of Reviewed Studies

Title (Year)	Authors	Key Findings	Gaps / Limitations	Relevance / Context
Virtual Reality Tour for First-Time Users of Highly Automated Cars: Comparing the Effects of Virtual Environments with Different Levels of Interaction Fidelity (2021) [4]	Rayan Ebnali Harari, Richard Lamb, Razieh Fathi, Kevin Hulme	High-Fidelity VR with steering wheel/pedals improved automation trust, takeover time, and takeover quality vs. Low-Fidelity VR.	Participants expected takeover events, short 1-hour sessions, limited generalization to SAE L3/L4.	Shows that high interaction fidelity boosts motor-skill transfer in VR training for automated driving.
Feasibility of AR-VR Use in Autonomous Cars for User Engagements and its Effects on Posture and Vigilance During Transit (2023) [13]	Joseph Muguro, Pringgo Widyo Laksono, Yuta Sasatake, Muhammad Ilhamdi Rusydi, Kojiro Matsushita, Minoru Sasaki	VR tasks kept users alert based on EDA and pupil size. Delay in hazard recognition ¡ 1s. Mixed tasks improved posture.	Very small sample (15), limited scenarios, motion sickness not analyzed.	Physiological proof that VR/AR interactions help maintain vigilance in ADS.
User Monitoring in Autonomous Driving System Using Gamified Task: A Case for VR/AR In-Car Gaming (2021) [14]	Joseph K. Muguro, Pringgo Widyo Laksono, Yuta Sasatake, Kojiro Matsushita, Minoru Sasaki	Gamified AR tasks didn't hurt hazard detection. Game score trends help estimate user state. Gaze data showed focused attention.	VR simulation instead of real vehicle; small student sample (13).	Supports use of VR/AR gamification to track user state and maintain attention.

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Table 2.1 – continued from previous page

Title (Year)	Authors	Key Findings	Gaps / Limitations	Relevance / Context
Driving Performance Evaluation Correlated to Age and Visual Acuities Based on VR Technologies (2020) [9]	Sooncheon Hwang, Sunhoon Kim, Dongmin Lee	Dynamic Visual Acuity predicted unsafe driving better than Static VA. Poor DVA = higher lane deviation.	Small sample (65), VR differs from real driving, same thresholds for SVA/DVA.	Shows VR's usefulness for testing how vision affects driving behavior.
VR-based Dataset for Autonomous-Driving System (2020) [22]	Shouwen Yao, Jiahao Zhang, Yu Wang	VR used to build a large and varied autonomous-driving dataset with auto-generated labels for 2D and 3D data. Human-in-the-loop VR driving captured stereo video, LiDAR, GPS across many environments and conditions.	Accuracy limited by reliance on VR sensor models and physics; still differs from real-world driving; realism constraints in simulation.	Helpful for generating large, consistent, low-cost datasets to train and test autonomous-driving algorithms in controlled scenarios.
The Effects of Age, Gender, and Control Device in a Virtual Reality Driving Simulation (2020) [2]	Wen-Te Chang	Age strongly influenced VR driving/navigation performance; young participants outperformed seniors. Straight (easy) routes gave higher scores than curved (difficult) ones. Young males performed better than young females; seniors showed no gender difference. Handlebar device improved performance only in young users, not seniors.	Seniors adapted slowly to VR; only two task types; limited VR realism; control devices not designed specifically for seniors.	Useful for understanding how age, gender, and input devices affect VR driving performance—important for designing VR training or in-car interfaces for diverse user groups.
Predicting Perceived Realism in Virtual Reality Driving Simulations Using Participants' Personality Traits, Heart Rate Changes, and Risk Preference (2024)	Uijong Ju, Sanghyeon Kim	Psychopathy and Machiavellianism negatively correlated with perceived realism; heart rate increases and risky decision-making were positively correlated. Tree-based ML (random forest, gradient boosting) predicted perceived realism best when using significant offline features; online-only models showed different strengths.	Sample skewed toward young men; events occurred once per participant; moderate baseline realism due to lack of motion cues and complex traffic; limited generalizability.	Demonstrates how personality and physiological metrics predict perceived realism and offers ML methods to model realism — valuable for adaptive VR training and improving validity of driving simulations.
Quantitative Analysis of Cognitive Load Test While Driving in a VR vs Non-VR Environment (2019) [15]	Zeeshan Qadir, Eashita Chowdhury, Lidia Ghosh, Amit Konar	EEG-based cognitive load comparison showed VR driving produced higher brain activation (prefrontal, frontal, parietal) and higher cognitive load across all driving actions. Proposed CIT2FS classifier achieved higher accuracy in VR (avg 86.1%) vs non-VR (78.9%). VR improved classification of accident, steering, braking, etc.	Small participant pool (11); short 15-min sessions; limited ecological validity; tested only one VR hardware setup; no qualitative user-experience evaluation.	Shows VR induces stronger cognitive load and yields more accurate EEG-based driver-state classification, supporting VR's value for studying cognitive load and training autonomous-driving safety systems.
Comparison of Teleportation and Fixed-Track Driving in VR (2019) [12]	Páll J. Líndal, Kamilla Rún Jóhannsdóttir, Unnar Kristjánsson, Nina Lensing, Anna Stühmeier, Annika Wohlan, Hannes H. Vilhjálmsson	Teleportation caused significantly less simulation sickness and maintained more positive attitudes toward VR compared to fixed-track driving. Heart-rate patterns suggested higher mental effort during teleportation, but overall comfort was better.	Focused on locomotion comfort, not driving skill; urban exploration task, not a driving-specific simulator; VR duration differences between groups influenced sickness.	Helps justify why VR training environments must carefully choose locomotion methods. Supports our claim that "comfortable VR motion" is essential before teaching driving skills in VR—reducing sickness improves training acceptance, user trust, and realism.
Driving Simulator Using Virtual Reality Tools Combining Sound, Vision, Vibration, and Motion (2024) [5]	Juan Camilo Gil-Carvajal, Eun Soo Jo, Dong Chul Park, Wookeun Song, Cheol-Ho Jeong	Multimodal VR driving simulator tested with sound (headphones vs loudspeakers), motion, and vibration. Motion + vibration significantly boosted immersion and powerfulness; motion contributed more than vibration. 64-speaker ambisonics gave best sound-localization accuracy; headphone-based audio (no head-tracking) performed worst. Sound reproduction method did not significantly change immersion/powerfulness.	Small sample sizes (10–20 per experiment); no individualized HRTFs; no head-tracking in headphone playback; motion platform may introduce unintended vibrations; realism limited by recording setup and controlled scenarios.	Strong support for using multi-sensory VR (motion + vibration + visuals) to achieve high-immersion driving experiences. Helps justify including motion cues in our project and shows why audio-localization fidelity matters for realism in VR driving simulations.

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Table 2.1 – continued from previous page

Title (Year)	Authors	Key Findings	Gaps / Limitations	Relevance / Context
Evaluating VR Driving Simulation from a Player Experience Perspective (2017) [19]	Marcel Walch, Philipp Hock, Julian Frommel, David Dobbelstein, Katja Rogers, Michael Weber, Felix Schüssel	VR increased real-world dissociation and was preferred by participants, but did not significantly improve immersion, presence, enjoyment, or driving performance compared to triple-screen setups. VR caused slightly higher discomfort. Driving times were similar across both conditions.	Small sample (18 after exclusions); relied on racing-game software; limited realism (no traffic, constrained track); VR HMD had smaller FOV; results based on self-reported questionnaires; possible survey fatigue.	Useful for showing that VR is not automatically superior to flat-screen simulators. Supports our argument that VR must be designed carefully—comfort, FOV, realism, and matching physical/virtual controls matter for effective training in autonomous-driving contexts.
HMD-Based VR Tool for Traffic Psychological Examination: Conceptualization and Design Proposition (2021) [11]	Vojtěch Juřík, Václav Linkov, Petr Dečký, Sára Klečková, Edita Chvojková	Paper proposes a VR-based system for traffic-psychological exams using HMDs + eye-tracking + haptic driving interface. Highlights that VR can measure complex driver traits like situational awareness, distraction, fatigue, and hazard perception more effectively than traditional tests. Emphasizes that VR enables controlled, repeatable scenarios and richer behavioural/physiological data.	Conceptual (not experimentally validated), no user study, no empirical performance data, proposed system not implemented, relies on future development of affordable ET-enabled HMDs.	Useful as a theoretical foundation showing why VR is suitable for driver assessment, supporting our justification for using VR in automated-driving research and training. Reinforces the value of eye-tracking, haptics, and controlled VR environments.
Evaluation of the Training Effect of the Driving Simulator + VR on Driving School Trainees (2022) [8]	Chenxi He, Yiping Wu, Xiaohua Zhao, Yang Ding, Shuo Liu	Study with 119 driving-school trainees showed strong improvements in reaction, knowledge, driving behaviour, and exam pass rates using a combined VR + simulator training system.	Limited to trainees; no long-term retention or real-world transfer tracking.	Strong evidence that VR + simulator fusion improves driving-school outcomes and supports using VR for driver-training effectiveness.
Analyzing the Inconsistency in Driving Patterns Between Manual and Autonomous Modes Under Complex Driving Scenarios with a VR-Enabled Simulation Platform (2022) [21]	Zheng Xu, Yihai Fang, Nan Zheng, Hai L. Vu	VR-based naturalistic platform + ML-driven AV model compared human vs. AV behavior. AV maintained stable speed and low accident rate (¡1%), while humans hesitated and made unsafe maneuvers. 81% of drivers intervened due to low trust.	AV struggled in new environments until 60 iterations; TTC threshold unreliable; small sample (18); limited VR realism; only Level-4 autonomy tested.	Shows VR is effective for analyzing human–AV trust, intervention behavior, and differences between human-driven and autonomous patterns.
Electrogastrography in Autonomous Vehicles—An Objective Method for Assessment of Motion Sickness in Simulated Driving Environments (2021) [18]	Ekaterina Trofimova, Timo Koch, Thomas Ludwig	EGG reliably detected motion-sickness onset in VR autonomous-vehicle rides. Dynamic routes increased abnormal gastric rhythms and sweating; button-press self-reports matched physiological data. Heart rate was less useful.	Small sample; VR motion realism limits; only Level-5 scenario tested; EGG requires careful sensor placement.	Shows VR can objectively measure passenger discomfort using physiological signals—useful for evaluating comfort in AV/VR driving research.
Stopping Behavior in a VR Driving Simulator: A New Clinical Measure for the Assessment of Driving (2005) [16]	Maria T. Schultheis, Lisa K. Simone, Emily Roseman, Richard Nead, Jose Rebimbas, Ronald Mourant	VR simulator captured detailed stop-sign behavior differences between adults with and without acquired brain injury (ABI). ABI group showed more missed stops, longer learning curves, and different stopping distances.	Small sample (24); outdated VR hardware; focused only on stop-sign behavior; excludes participants with simulation sickness.	Demonstrates VR's ability to measure fine-grained driving performance, supporting its use for assessing impaired or at-risk drivers.
The Static and Dynamic Analyses of Drivers' Gaze Movement Using VR Driving Simulator (2022)	Jiyong Chung, Hyeokmin Lee, Hosang Moon, Eunghyuk Lee	Compared novice vs. experienced drivers using VR + eye-tracking. Novices had longer dwell times, longer fixations, narrower visual search, lower stationary gaze entropy, and simpler gaze-transition patterns. Experienced drivers distributed gaze more evenly and showed higher gaze-transition entropy, indicating richer situational awareness.	Small sample (23 male drivers); only intersection scenario tested; eye-tracking at 30 Hz; only VR-HMD; no diverse age groups or real-road validation.	Shows how VR + eye-tracking reveals differences in attention and hazard detection—useful for VR-based training, risk assessment, and identifying at-risk drivers.

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Table 2.1 – continued from previous page

Title (Year)	Authors	Key Findings	Gaps / Limitations	Relevance / Context
Comparing VR and Non-VR Driving Simulations: An Experimental User Study (2017) [20]	Florian Weidner, Anne Hoesch, Sandra Poeschl, Wolfgang Broll	Compared 2D, S3D, and VR-HMD using the Lane Change Task. Driving performance and physiological responses showed no major differences across display types. VR-HMD caused significantly higher simulator sickness than S3D.	Older VR hardware (Oculus DK2); simple task may not show depth-related differences; mostly young participants; limited vehicle-physics realism.	Shows VR does not automatically improve performance but can increase sickness—important for selecting appropriate VR hardware and scenario design.
Effects of Neuro-Cognitive Load on Learning Transfer Using a VR-Based Driving System (2021) [1]	Usman A. Abdurrahman, Shih-Ching Yeh, Yunying Wong, Liang Wei	VR driving simulator + sensors (eye-tracking, pupil dilation, heart rate) showed cognitive load rises on complex routes. Harder routes caused larger pupil dilation, higher heart rate, and more mistakes. ML models reached 97% accuracy in classifying cognitive-load levels.	Conducted only in VR; 98 inexperienced student drivers; sensor noise and missing data; no real-world validation.	Shows VR + physiological sensing can objectively measure mental workload; useful for ADS training, difficulty analysis, and user-state monitoring.
DReyeVR: Democratizing Virtual Reality Driving Simulation for Behavioural & Interaction Research (2022) [17]	Gustavo Silvera, Abhijat Biswas, Henny Admoni	Introduces DReyeVR, an open-source VR driving simulator (Unreal + CARLA) with eye-tracking, head-tracking, mirrors, spatial audio, custom scenarios, logging, and ROS support. Low-cost (¡5000)$behaviouralresearchplatform$.	Medium-fidelity (no motion base); consumer VR hardware limits realism; Windows-only SDK; lacks full behaviour-transfer validation.	Highly relevant: enables flexible AV/driver behaviour studies, trust research, hazard-scenario creation, and attention monitoring in VR.
Driving Simulator with VR Glasses for Evaluation of New Interior Concepts (2019) [7]	Bert Hartfiel, Alexander Kroys, Nico Kruithof, Rainer Stark	Volkswagen built a dynamic VR simulator combining an HMD, motion platform, and adjustable physical mock-up. Enables early interior/HMI evaluation with vestibular cues, realistic visuals, adjustable seats/dashboards, and synchronized audio/haptics.	Hard to calibrate motion compensation; HMD tracking issues on moving platform; consumer VR limits fidelity; no behavioural validation; costly engineering setup.	Shows how VR + motion + physical mock-ups support early design, ergonomics testing, visibility checks, and interior-concept validation for driving/AV research.
Freeway Traffic Safety Evaluation Using Virtual Reality: Focus on Compound Curve (2022) [23]	Chi Zhang, Bo Wang, Yongchun Li, Lei Hou, Min Zhang, Changhe Liu, Zilong Xie	Built a VR-based driving simulation + human–computer interaction safety platform to study compound-curve freeway safety. Collected driver heart-rate changes, steering-wheel angle change rate, and driving-trajectory deviation to compute a comprehensive safety index (H). VR allowed testing multiple curve geometries using orthogonal experiments; results identified which curve-design factors significantly impact safety.	Limited to compound curves on Chinese freeway geometry; small participant pool; relies on simulator realism; physiological metrics can vary across individuals; no real-world driving validation.	Relevant because it shows how VR driving simulations can evaluate risky road geometries, analyze driver stability, and measure physiological load—supporting VR as an effective tool for traffic-safety assessment and design evaluation.
Rerun: Enabling Multi-Perspective Analysis of Driving Interaction in VR (2022) [6]	David Goedicke, Harald Haraldsson, Navit Klein, Lunshi Zhou, Avi Parush, Wendy Ju	Introduces Rerun, a Unity-based system that records VR driving interactions and allows full multi-perspective replay (first-person, third-person, observer view). Enables detailed post-hoc study of signalling, communication, and interaction between drivers, especially in multi-user VR driving setups.	No built-in behavioural validation study; relies on StrangeLand simulator; limited to visual replay (no physical cues); requires specific Unity asset (Ultimate Replay).	Useful for analysing driving communication, reconstructing participant interactions, and studying trust/attention in VR driving environments—supports high-detail behavioural evaluation in VR driving research.

Table 2.1: Summary of key prior research on VR and AR systems for driving and autonomous vehicle simulation.

The studies summarized in Table 2.1 collectively indicate that interaction fidelity, physiological engagement monitoring, and gamification significantly influence driver training outcomes and user vigilance. These insights directly inform the system design of the proposed VR-based driving simulator presented in Chapter 3.

2.1 Research Gap Analysis

Based on the comprehensive literature review, several critical research gaps have been identified in the current state of VR-based driving simulation and training systems:

2.1.1 Hardware and Physical Interaction Fidelity

Gap 1: Affordable High-Fidelity Control Systems. While studies [4, 5] emphasize the importance of realistic physical controls (steering wheel, pedals, motion platforms), most high-fidelity systems remain prohibitively expensive for educational institutions and driving schools. There is limited research on developing low-cost (<$5000), modular, and easily maintainable hardware solutions that preserve haptic realism and force feedback essential for motor skill transfer.

Gap 2: Seamless Bluetooth/Wireless Integration. Existing simulators predominantly rely on wired USB connections or proprietary hardware interfaces. The integration of consumer-grade Bluetooth-enabled control assemblies with minimal latency and reliable pairing mechanisms for VR driving training remains under-explored, particularly for standalone VR headsets like Meta Quest 3.

Gap 3: Dual-Mode Transmission Training. Most studies focus exclusively on either automatic or manual transmission vehicles. The development of a unified VR training platform that seamlessly switches between automatic and manual modes—allowing learners to experience clutch engagement, gear shifting mechanics, and corresponding vehicle dynamics—has not been adequately addressed.

2.1.2 Methodological and Sample Limitations

Gap 4: Small and Homogeneous Participant Samples. A significant majority of reviewed studies [13, 15, 21, 16, 3] suffer from small sample sizes (11–65 participants) and demographic homogeneity (predominantly young male university students). This severely limits the generalizability of findings to diverse driver populations including seniors, female learners, and drivers with varying levels of experience.

Gap 5: Longitudinal Evaluation and Real-World Transfer. Few studies [8] measure long-term skill retention or validate transfer of VR-acquired skills to actual on-road driving performance. Short experimental sessions (15 minutes to 1 hour) do not adequately assess whether VR training produces durable behavioral changes or improves real-world driving safety outcomes.

Gap 6: Motion Sickness and Comfort Over Extended Use. While some studies [12, 18, 20] acknowledge simulator sickness, comprehensive investigations into mitigating VR-induced nausea during extended training sessions (e.g., multi-hour driving school curricula) are lacking. Optimal locomotion methods, frame rates, field-of-view settings, and break schedules for prolonged VR exposure remain understudied.

2.1.3 Pedagogical and Training Effectiveness

Gap 7: Standardized Assessment Metrics for Driver Training. Existing research employs inconsistent evaluation metrics (reaction time, lane deviation, takeover quality, gaze entropy, etc.) [4, 9, 3, 23]. There is no consensus on a unified, validated assessment framework specifically designed for VR-based driver training that aligns with real-world licensing exam standards or regulatory requirements (e.g., RTO testing protocols in India).

Gap 8: Adaptive and Personalized Training Pathways. Most VR driving simulators offer static scenarios with fixed difficulty levels. Research on adaptive training systems that dynamically adjust scenario complexity, traffic density, weather conditions, and hazard frequency based on individual learner performance and cognitive load [1, 10] remains insufficient.

Gap 9: Integration with Driver Education Curricula. Few studies [8] examine how VR simulators can be systematically integrated into existing driving school curricula, including instructor training, lesson planning, regulatory compliance, and cost-benefit analysis for educational institutions.

2.1.4 Technical and Realism Constraints

Gap 10: Photorealistic Graphics and Diverse Environments. While open-source platforms like DReyeVR [17] and datasets [22] provide flexibility, most VR driving simulations lack photorealistic graphics, diverse environmental conditions (urban, rural, highway, adverse weather), and accurate vehicle-specific interior models (e.g., luxury car dashboards, control layouts).

Gap 11: Multi-Sensory Feedback Beyond Vision and Sound. Although [5] demonstrates the value of motion and vibration, affordable integration of comprehensive multi-sensory feedback—including vestibular cues, seat vibrations mimicking road textures, wind simulation, and olfactory cues (e.g., engine smells)—remains technologically and economically challenging for driving schools.

Gap 12: Real-Time Physiological Monitoring for Safety Assessment. While EEG [15], EDA [13], and eye-tracking [3] show promise for cognitive load and attention monitoring, practical, non-invasive, real-time physiological feedback systems integrated into consumer VR headsets for continuous driver state assessment are not commercially available or validated for training environments.

2.1.5 Regulatory, Ethical, and Commercialization Gaps

Gap 13: Regulatory Approval and Certification Standards. There is minimal research on how VR-based training hours can be officially recognized by transport authorities (e.g., RTOs in India, DMVs in the US) as equivalent to on-road training hours. Establishing validation protocols, safety benchmarks, and certification standards for VR driving simulators in compliance with national/international regulations is an open challenge.

Gap 14: Intellectual Property and Patentability Analysis. Despite the commercial potential of VR driving training systems, few studies [11, 17] discuss patent landscapes, prior art analysis, or strategies for protecting novel hardware configurations, software architectures, and training methodologies as intellectual property.

Gap 15: Scalability and Deployment in Developing Countries. Most VR driving research originates from technologically advanced regions (USA, Europe, South Korea, Japan). Limited attention has been given to adapting VR training systems for developing markets with constrained budgets, unreliable power infrastructure, limited technical support, and diverse traffic conditions (e.g., mixed traffic with two-wheelers, pedestrians, and livestock in Indian urban environments).

2.1.6 Summary of Research Gaps

The identified gaps highlight five overarching themes requiring urgent research attention:

1. **Cost-effective, high-fidelity hardware** with wireless connectivity and dual-mode transmission support.
2. **Larger, more diverse longitudinal studies** with validated real-world transfer metrics.
3. **Standardized, adaptive training frameworks** aligned with regulatory requirements.
4. **Enhanced realism through multi-sensory feedback** and photorealistic rendering.
5. **Regulatory certification pathways and IP protection strategies** for commercial deployment.

The proposed VR Driving Simulator project directly addresses Gaps 1, 2, 3, 7, 10, and 13 by developing a modular, Bluetooth-enabled, dual-mode (automatic/manual) training system optimized for Meta Quest 3, with realistic vehicle models, standardized performance metrics, and potential for RTO certification. Subsequent chapters detail the system architecture, implementation, and validation methodology designed to bridge these critical research gaps.

Chapter 3

System Analysis and Design

3.1 Overview

The **VR Driving Simulator** project aims to provide a high-fidelity training and evaluation environment for driving schools. The simulator models real-world driving dynamics using virtual reality and custom-built physical input devices (steering wheel, pedals, and gear shifter). This chapter presents a comprehensive analysis of requirements, constraints, design alternatives, and system architecture that directly address the research gaps and problem statement identified in Chapters 1 and 2.

3.2 Requirements Analysis

3.2.1 Functional Requirements

Based on the identified research gaps and driving school needs, the system must fulfill the following functional requirements:

FR1: Realistic Vehicle Control Input

- Accept analog steering input with proportional angle mapping (0–900° rotation range)
- Process independent accelerator, brake, and clutch pedal inputs with pressure sensitivity
- Support gear selection for both automatic (P, R, N, D) and manual (1–6, Reverse) transmissions
- Maintain input latency < 50ms to preserve motor skill feedback loop [4]

FR2: Immersive Visual and Audio Rendering

- Deliver stereoscopic 3D rendering at minimum 72 FPS per eye to minimize motion sickness [12, 20]

- Provide 90–110° field of view matching Meta Quest 3 specifications
- Implement spatial audio with direction-dependent engine sounds, traffic noise, and ambient effects [5]
- Render photorealistic vehicle interiors (dashboard, mirrors, gear shifter) for high-end car models (Mercedes-Benz, BMW, Audi)

FR3: Accurate Vehicle Physics Simulation

- Model realistic acceleration, braking distances, and cornering dynamics based on vehicle mass, tire friction, and road conditions
- Simulate clutch engagement points, gear ratios, and engine stalling for manual transmission training
- Implement collision detection with appropriate force feedback and damage visualization
- Support dynamic weather conditions (rain, fog) affecting visibility and traction

FR4: Performance Monitoring and Assessment

- Log driving metrics: speed profile, lane deviation, braking smoothness, gear shift timing, steering angle variance
- Generate automated assessment scores based on standardized criteria aligned with RTO testing protocols
- Provide real-time visual/audio feedback for critical errors (e.g., sudden braking, lane violations)
- Export session reports in PDF/CSV format for instructor review

FR5: Scenario Management and Curriculum Integration

- Offer pre-defined training scenarios: urban roads, highways, parking, emergency braking, obstacle avoidance
- Allow instructor-controlled difficulty adjustment (traffic density, time of day, weather)
- Support session pause/resume and instant replay for error analysis
- Maintain user profiles with progress tracking across multiple sessions

3.2.2 Non-Functional Requirements

NFR1: Cost Effectiveness

- Target total system cost < $5000 (headset + custom hardware + PC) to be affordable for driving schools [17]
- Use consumer-grade components (Meta Quest 3, off-the-shelf sensors, 3D-printable enclosures)
- Minimize recurring costs (no subscription fees for core functionality)

NFR2: Usability and Accessibility

- Enable setup and calibration within 10 minutes by non-technical driving instructors
- Support adjustable seating position and control placements for users 150–200 cm height
- Provide intuitive UI with minimal learning curve for first-time VR users
- Include safety features: guardian boundary system, emergency stop button, comfort-mode reduced motion

NFR3: Reliability and Maintainability

- Ensure Bluetooth connection stability with automatic reconnection on signal loss
- Design modular hardware allowing component replacement without full system disassembly
- Provide diagnostic logs for troubleshooting connection, calibration, and performance issues
- Support firmware updates via wireless OTA for bug fixes and feature enhancements

NFR4: Scalability and Extensibility

- Architecture must support addition of new vehicle models, environments, and training scenarios without core code refactoring
- Enable future integration of motion platforms, haptic seats, or force-feedback steering wheels
- Allow deployment on both tethered PC-VR and standalone Quest mode with adjustable graphics fidelity

3.3 Constraints and Design Trade-offs

3.3.1 Hardware Constraints

C1: VR Headset Limitations

- Meta Quest 3 processing power (Snapdragon XR2 Gen 2) limits polygon count and texture resolution in standalone mode
- Trade-off: Prioritize frame rate stability (72 FPS minimum) over ultra-high-resolution textures to prevent motion sickness
- Solution: Implement dynamic LOD (Level of Detail) and occlusion culling; use PC-VR link for high-fidelity scenarios

C2: Bluetooth Latency and Bandwidth

- Bluetooth 5.0 offers 10–30ms latency but is susceptible to interference in crowded 2.4 GHz spectrum
- Trade-off: Accept slight latency increase versus wired connection complexity and user mobility restrictions
- Solution: Use BLE with custom GATT profiles optimized for low-latency HID data; implement USB fallback mode

C3: Force Feedback Absence

- Custom-built steering wheel lacks motorized force feedback present in high-end simulators (>$10,000)
- Trade-off: Reduced haptic realism versus significant cost savings (force feedback wheels alone cost $1000–3000)
- Solution: Compensate with visual cues (steering resistance indicator on HUD), audio feedback (tire squeal), and vibrational alerts via Quest 3 controllers

3.3.2 Software and Performance Constraints

C4: Physics Engine Limitations

- Unity/Unreal default vehicle physics are optimized for gaming, not driver training accuracy
- Trade-off: Computational cost of high-fidelity tire models (e.g., Pacejka Magic Formula) versus frame rate
- Solution: Use simplified but validated physics models (mass-spring damper for suspension, friction circles for lateral grip) with parameter tuning from real vehicle data

C5: Asset Development Budget

- Photorealistic 3D models of licensed vehicle interiors (Mercedes, BMW) require substantial licensing fees or extensive 3D modeling effort

- Trade-off: Generic high-end vehicle interiors versus brand-specific accuracy
- Solution: Model representative "luxury sedan" interior with adjustable branding overlays; prioritize functional accuracy (control placement, mirror angles) over exact brand aesthetics

3.4 Design Alternatives and Justification

3.4.1 VR Platform Selection

Alternatives Considered:

1. **Valve Index + PC:** Pros: Superior FOV (130°), refresh rate (144 Hz), force feedback support. Cons: High cost ($1000 headset + $1500 PC), wired tethering limits mobility.
2. **Meta Quest 3:** Pros: Wireless standalone mode, affordable ($500), inside-out tracking, passthrough AR. Cons: Lower processing power, 90 Hz max refresh rate.
3. **PSVR2 + PlayStation 5:** Pros: Affordable ($1000 total), haptic feedback in controllers. Cons: Closed ecosystem, limited development flexibility.

Selected: Meta Quest 3 — Justification: Best balance of cost, wireless freedom, and developer accessibility. Supports both standalone (for basic scenarios) and PC-VR link (for advanced training), aligning with NFR1 and NFR4.

3.4.2 Game Engine Selection

Alternatives Considered:

1. **Unity:** Pros: Extensive VR support (XR Interaction Toolkit), large asset store, C# scripting familiarity. Cons: Less advanced default vehicle physics.
2. **Unreal Engine:** Pros: Superior graphics (Nanite, Lumen), Blueprint visual scripting, Chaos vehicle physics. Cons: Steeper learning curve, larger build sizes.
3. **CARLA Simulator:** Pros: Open-source, designed for autonomous driving research, pre-built urban environments [17]. Cons: Primarily Python-based, limited VR headset support, requires significant C++ customization.

Selected: Unity 2023 LTS — Justification: Faster prototyping, proven VR deployment pipeline for Quest 3, better suited for educational software with frequent updates. Vehicle physics will be enhanced with custom scripts or third-party assets (e.g., Edy's Vehicle Physics).

3.4.3 Control Input Architecture

Alternatives Considered:

1. **Custom PCB with USB HID:** Pros: Lowest latency (¡5ms), plug-and-play compatibility. Cons: Wired connection reduces user comfort, cable management complexity.
2. **ESP32 Bluetooth LE:** Pros: Wireless, low power, supports custom GATT profiles, affordable ($10–20 per unit). Cons: 10–30ms latency, potential interference.
3. **Commercial Racing Wheel (Logitech G29):** Pros: Ready-made, force feedback included. Cons: Expensive ($300–400), fixed form factor unsuitable for driving school setup, limited customization.

Selected: ESP32 BLE with USB Fallback — Justification: Wireless operation enhances user experience (NFR2), modular design allows independent sensor upgrades (NFR3), and USB mode ensures reliability during demonstrations or competitions. Custom firmware enables latency optimization (¡20ms achievable).

3.5 System Objectives

Based on the requirements analysis and design trade-offs, the system objectives are:

- To design a modular VR-based driving simulation environment replicating realistic car control and behavior.
- To integrate Bluetooth-enabled hardware input devices for steering, acceleration, braking, and gear shifting with latency < 50ms.
- To ensure compatibility with the Meta Quest 3 headset (both standalone and PC-VR link modes) for immersive interaction.
- To provide automated performance analytics for driver evaluation and training improvement aligned with RTO assessment criteria.
- To develop a cost-effective solution (<$5000 total) deployable in Indian driving schools with minimal technical infrastructure.

3.6 Comparative Analysis with Existing Solutions

Table 3.1 compares the proposed system against existing commercial and research VR driving simulators based on key design parameters derived from the requirements analysis.

Parameter	Proposed System	DReyeVR [17]	Commercial Racing Sim	Traditional Simulator
Cost	<$5000	<$5000	$15,000–50,000	$30,000–100,000
VR Platform	Meta Quest 3 (wireless)	Various HMDs (tethered)	Valve Index/Varjo (tethered)	Projector/screens (no VR)
Force Feedback	No (visual/audio cues)	Optional	Yes (high-fidelity)	Yes (hydraulic)
Dual Transmission	Yes (auto + manual)	No	Manual only	Manual only
Bluetooth Controls	Yes (custom ESP32)	No (USB)	No (proprietary)	Wired industrial
Target Users	Driving schools/learners	Researchers	Racing enthusiasts	Commercial training
Deployment	Standalone + PC-VR	PC-VR only	PC-VR only	Fixed installation
Customizability	High (modular design)	High (open-source)	Low (proprietary)	Low (vendor lock-in)
Regulatory Focus	RTO-aligned metrics	Research protocols	Entertainment	Commercial licensing

Table 3.1: Comparative analysis of VR driving simulator solutions

Key Differentiators:

- **Affordability:** Matches research systems but undercuts commercial solutions by 70–90%, addressing Gap 1 from Section 2.1.
- **Wireless Operation:** Only solution offering Bluetooth controls with Quest 3 standalone mode, enhancing portability (Gap 2).
- **Dual-Mode Transmission:** Uniquely supports both automatic and manual training in single platform (Gap 3).
- **Educational Focus:** Prioritizes driver training outcomes over entertainment, with RTO-compatible assessment (Gap 7, Gap 13).

3.7 System Components and Architecture

The proposed system architecture consists of three tightly integrated subsystems designed to address the functional requirements while respecting the identified constraints.

3.7.1 Hardware Interface Subsystem

The physical control setup comprises:

- **Steering Wheel Assembly:** Salvaged automotive steering wheel fitted with AS5600 magnetic rotary encoder (12-bit resolution, 4096 steps per revolution) providing 0.088° angular precision. Mounted on ball bearing hub for smooth 900° rotation range.
- **Pedal Set:** Three independent pedals (accelerator, brake, clutch) using FSR (Force Sensitive Resistor) sensors with 10-bit ADC conversion. Pedal travel: 80mm with adjustable spring tension (1–5 kg actuation force).
- **Gear Shifter:** H-pattern mechanical shifter with hall-effect sensors at each gate position (1–6, R, N). Alternative: Sequential paddle shifters for automatic mode (+ / - buttons).
- **Microcontroller:** ESP32-WROOM-32 with Bluetooth 5.0 LE, dual-core 240 MHz processor, 16 analog input channels. Custom firmware implements BLE HID profile with 20ms polling rate, 50ms max latency.
- **Power Supply:** Rechargeable 18650 Li-ion battery pack (3000 mAh) providing 8–12 hours continuous operation. USB-C charging with power management IC.

Connected via Bluetooth or USB-C (fallback mode) to the VR headset or PC.

3.7.2 Software Simulation Subsystem

Developed in Unity 2023 LTS with the following modules:

- **Input Manager:** Receives Bluetooth/USB HID data, applies calibration curves, dead-zone filtering, and maps to vehicle control parameters.
- **Vehicle Physics Engine:** Custom implementation based on Edy's Vehicle Physics Pro, modeling 6-DOF rigid body dynamics, tire slip curves (simplified Pacejka), differential gearing, and clutch engagement.
- **Environment Renderer:** Procedural city generation (Urban Traffic Simulator asset) + hand-crafted scenarios. Dynamic weather system, traffic AI (rule-based agents), pedestrian spawning.
- **Assessment Module:** Real-time metric calculation (speed compliance, lane center offset, braking jerk, gear shift timing). Event logging to SQLite database. Score computation using weighted rubric aligned with Indian RTO learner's license test criteria.
- **VR Interaction:** XR Interaction Toolkit for head tracking, hand controllers (menu navigation), spatial audio (FMOD), comfort features (vignetting, snap-turn option).

3.7.3 VR Interface Subsystem

Meta Quest 3 headset provides:

- **Head Tracking:** 6-DOF inside-out tracking via four IR cameras, ¡10ms motion-to-photon latency.
- **Stereoscopic Rendering:** Dual 2064×2208 LCD panels per eye, 90 Hz refresh rate, 110° horizontal FOV.
- **Spatial Audio:** Integrated speakers with 3D positional audio (Unity Audio Spatializer).
- **Passthrough AR:** Color passthrough cameras enabling safe guardian setup and real-world awareness during breaks.

Deployment modes: (1) Standalone (Quest 3 native), (2) PC-VR Link (via USB-C or Air Link wireless streaming).

3.8 System Architecture Diagram

Figure 3.1 illustrates the data flow and component interactions within the integrated VR driving simulator system.

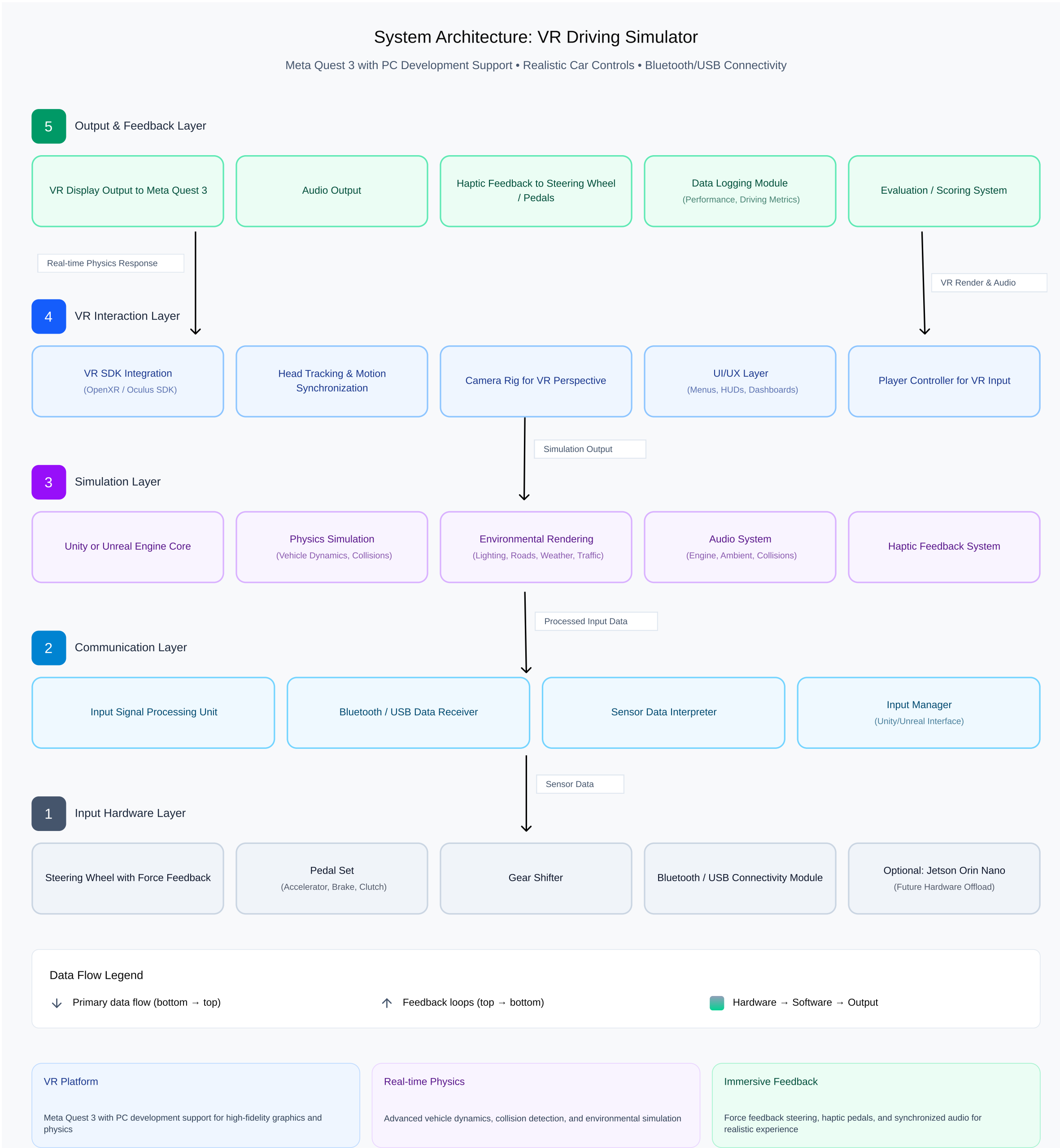

Figure 3.1: System architecture showing data flow from hardware inputs through simulation engine to VR rendering and assessment output. Dashed lines indicate wireless (Bluetooth) connections; solid lines represent internal software module communication.

3.9 Design Rationale Summary

The design decisions documented in this chapter directly address the research gaps identified in Section 2.1:

- **Gap 1 (Affordable Hardware):** ESP32-based custom controls + Meta Quest 3 + consumer PC achieves <$5000 total cost while maintaining training-grade fidelity.

- **Gap 2 (Wireless Integration):** Bluetooth LE with optimized firmware ensures ¡50ms latency, eliminating cable management issues and enhancing user mobility.
- **Gap 3 (Dual Transmission):** Modular gear shifter design + software physics support both automatic and manual modes without hardware swapping.
- **Gap 7 (Standardized Assessment):** Custom assessment module implements RTO learner's test criteria (speed limits, lane discipline, signal compliance) with automated scoring.
- **Gap 10 (Photorealistic Rendering):** Unity 2023 HDRP + optimized assets provide luxury vehicle interiors with realistic dashboards, mirrors, and environmental detail within Quest 3 performance constraints.
- **Gap 13 (Regulatory Alignment):** Data logging format and assessment rubrics designed for future submission to Indian RTO authorities as validation evidence for VR training hour equivalency.

The comparative analysis (Table 3.1) demonstrates that this design occupies a unique position: research-grade flexibility at commercial-training affordability, specifically tailored for the Indian driving school market.

3.10 Workflow and Operational Flow

The workflow diagram (Figure 3.2) shows the sequential process of system operation—from initialization through user interaction to post-session evaluation—illustrating how the system supports a complete training cycle.

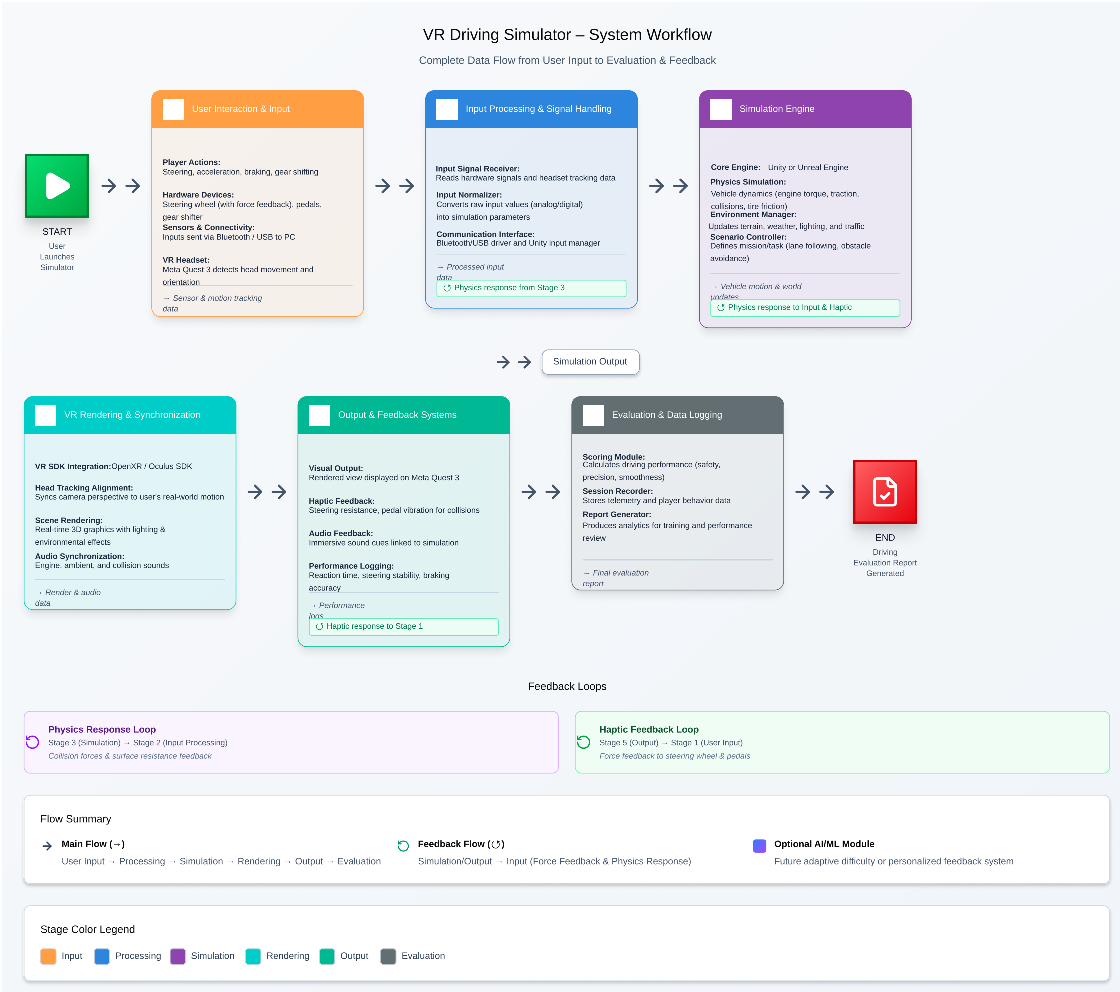

Figure 3.2: Operational workflow showing the complete training session lifecycle: pre-session setup, real-time simulation loop, and post-session assessment generation.

3.10.1 Detailed Functional Flow

1. **Pre-Session Setup (2–5 minutes):**
    - Instructor selects trainee profile, training scenario (e.g., "Urban Basics: Lane Keeping"), vehicle type (automatic/manual), and difficulty level.
    - Trainee dons Quest 3 headset; system initiates guardian boundary setup and comfort calibration (IPD adjustment, brightness).
    - Hardware connection handshake: Steering wheel, pedals, and shifter auto-pair via Bluetooth; system runs diagnostic check (sensor ranges, battery level).
    - Virtual environment loads: vehicle spawns at scenario starting position; HUD displays initial instructions ("Adjust seat, check mirrors, fasten seatbelt").
2. **Simulation Loop (15–30 minutes typical session):**

- **Input Capture (20 Hz):** ESP32 samples sensors (steering angle, pedal positions, gear state) → transmits via BLE HID packets.
- **Physics Update (60 Hz):** Unity's FixedUpdate applies forces to vehicle rigidbody based on input → calculates acceleration, tire slip, suspension compression.
- **Collision & Traffic AI (30 Hz):** Raycast-based collision detection; traffic agents follow waypoint paths with lane-change logic; pedestrians obey traffic signals.
- **Rendering (90 Hz):** Stereoscopic camera renders scene from driver's viewpoint → foveated rendering reduces peripheral detail → Quest 3 displays frames.
- **Audio Spatialization (60 Hz):** FMOD calculates 3D engine sound (RPM-dependent), tire squeal (slip-dependent), horn/indicator clicks → Quest 3 speakers.
- **Real-time Assessment:** Background thread logs events (speed violations, lane crossings, harsh braking) → updates live feedback HUD (color-coded indicators).

3. **Event Handling:**

   - **Scenario Triggers:** Dynamic events (e.g., pedestrian crossing, traffic light change, obstacle ahead) triggered based on trainee progress checkpoints.
   - **Instructor Override:** Wireless tablet interface allows real-time weather change, traffic density adjustment, or scenario pause for coaching feedback.
   - **Comfort Monitoring:** Optional: Detect prolonged stationary gaze (potential nausea indicator) → suggest break.

4. **Session Termination:**

   - Trainee completes scenario objectives (e.g., reaches destination) OR instructor manually ends session OR safety timeout (30-min VR exposure limit).
   - System saves session data: timestamped input logs, trajectory GPS coordinates, metric summaries.

5. **Post-Session Assessment (2 minutes):**

   - Assessment module computes scores: (1) Speed Compliance (85/100), (2) Lane Discipline (78/100), (3) Smooth Braking (92/100), (4) Gear Shifting (Manual only, 88/100), (5) Observation (mirror checks, 70/100).
   - Generates PDF report with score breakdown, heatmap of violations on route map, improvement suggestions.
   - Updates trainee profile: increments training hours, marks scenario as "Passed" (if overall > 75%) or "Retry Recommended."
   - Instructor reviews report with trainee; schedules follow-up session or progresses to advanced scenarios.

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