

## Integrating AI, VR, CAD, and Rapid Prototyping for Multi-Utility Electric Vehicle Cabin Design



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### ABSTRACT

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This study develops and validates an integrated digital workflow for multi-utility electric vehicle (EV) cabin design in an emerging-market manufacturing context. The workflow links AI-assisted concept exploration, SolidWorks Computer-Aided Design (CAD) modelling, Virtual Reality (VR) ergonomic evaluation, Computational Fluid Dynamics (CFD) simulation, and rapid prototyping in a continuous feedback loop from concept generation to physical validation. The cabin requirements differ from passenger EVs because the platform must support mixed cargo-passenger use, frequent ingress-egress, robust dashboard and door-panel packaging, driver visibility in urban logistics operations, and low-cost manufacturability. The study generated 12 AI-assisted styling variants, evaluated the cabin through VR with 5 representative participants covering the 95th anthropometric percentile range, and analyzed 1 CFD case at 80 km/h. CFD analysis produced a drag coefficient of approximately 0.404, within the expected 0.35-0.50 range for utility EV bodies. Physical validation used a 1:10 exterior prototype and 1:1 dashboard and door-panel mockups fabricated through 3D printing/manual finishing, with dimensional checks against CAD data. The workflow also supported an underfloor cargo innovation registered as IPR No. S00202511613. The findings show that early VR feedback reduces downstream ergonomic rework, CFD-guided refinement improves aerodynamic behavior, and rapid prototyping confirms manufacturability, offering a scalable model for EV design by small and medium manufacturers in Indonesia and similar emerging markets.

## 1. INTRODUCTION

The accelerating global transition toward sustainable transportation has intensified the need for advanced electric vehicle (EV) technologies capable of supporting diverse mobility functions across urban and peri-urban regions [1]. For emerging economies such as Indonesia, EV development is not only a strategic component of national electrification policies but also an essential pathway for strengthening technological sovereignty and reducing dependence on imported components [2]. Within this broader agenda, multi-utility EVs differ from conventional passenger EVs because they must support variable passenger-cargo configurations, frequent stop-and-go logistics, public-service deployment, operator comfort during extended work cycles, simplified maintenance, and affordable production for small and medium manufacturers. These requirements make the cabin more than a comfort-oriented passenger compartment; it becomes a work interface that integrates visibility, reachability, cargo access, dashboard robustness, ingress-egress efficiency, and manufacturable modularity [3-6].

Recent literature indicates that the enabling technologies for this task have advanced rapidly but remain unevenly integrated. Virtual simulation tools have improved automotive

human-machine interaction and ergonomic assessment by allowing users to evaluate cockpit layout, sightlines, posture, and interface accessibility before physical fabrication [7-11]. Generative AI and AI-assisted (Vizcom AI for Education) design have expanded the ideation space for automotive interiors and intelligent cabins, but most applications remain focused on styling images, seat concepts, or component-level optimization rather than Computer-Aided Design (CAD)-ready full-cabin engineering models [12-17]. Similarly, CAD-additive manufacturing workflows and rapid prototyping have become important for shortening prototype cycles, but they are often positioned as downstream validation tools rather than as active feedback nodes linked with ergonomic and aerodynamic simulation [18-24].

However, current EV design workflows remain constrained by sequential development processes [25], lengthy iteration cycles [26], and high prototyping costs [27]. These challenges are particularly acute for small and medium-scale manufacturers in developing countries, who lack the extensive resources and infrastructure typically available to global automotive firms. Existing attempts to combine digital tools have generally emphasized either model-based EV engineering, CAD-cloud transformation, virtual prototyping, or AI-CAD integration [19, 23, 25, 28-30]. They provide

valuable foundations, but few studies explicitly connect image-based generative concept exploration, parametric CAD reconstruction, Virtual Reality (VR) ergonomic testing, Computational Fluid Dynamics (CFD) aerodynamic evaluation, and physical rapid prototyping within one traceable cabin-design workflow for a multi-utility EV. Therefore, the novelty of this study is not the isolated use of AI, VR, CAD, CFD, or prototyping, but the operational integration of these tools into a repeatable feedback ecosystem that supports design decisions under emerging-market manufacturing constraints.

A systematic review of existing literature reveals four fundamental gaps. First, CAD studies overwhelmingly prioritize structural and aerodynamic performance but seldom incorporate early-stage ergonomic or human-centered parameters, causing misalignment between engineering feasibility and user requirements [8, 9]. Second, VR-based ergonomic evaluations, despite their growing relevance, are typically implemented after major design decisions are finalized, limiting their influence on upstream conceptual development [10, 11]. Third, AI-driven generative design remains underutilized in automotive cabin research and is often limited to generative styling or image-based concept exploration rather than direct geometry generation for CAD-ready production [12, 13, 16, 17]. In this study, AI is positioned specifically as image-based generative styling that supports early concept exploration; it does not automatically generate manufacturable CAD geometry. Fourth, rapid prototyping processes commonly function as isolated validation steps rather than integrated nodes within an iterative digital feedback loop [18, 19, 24]. Collectively, these shortcomings highlight the absence of a cohesive digital methodology capable of unifying ergonomic, aesthetic, structural, aerodynamic, and manufacturability considerations in a single continuous design cycle.

Addressing these gaps, this study introduces a unified digital design workflow that integrates AI-assisted generative concept exploration, parametric CAD modelling, VR-based ergonomic evaluation, CFD-based aerodynamic simulation, and rapid prototyping into an iterative, fully interconnected development framework. This workflow is implemented through a multi-year collaboration between Universitas Pembangunan Jaya and PT Spora Teknika Indonesia, supported by a research ecosystem that includes prior micro-EV platforms, hybrid solar-electric carts, and cargobike prototypes [31, 32]. The integrated framework enables real-time feedback between conceptual, ergonomic, structural, aerodynamic, and manufacturability assessments, significantly reducing design errors and compressing development timelines, outcomes that are crucial to enhancing EV innovation capacity in emerging economies.

This study contributes to EV design and engineering literature in four major ways: (1) Methodological contribution: It proposes a novel end-to-end digital workflow that merges AI, VR, CAD, CFD, and rapid prototyping into a continuous co-design cycle, closing the methodological fragmentation prevalent in existing research. (2) Empirical contribution: The study demonstrates the real-world implementation of this workflow through the complete development of a multi-utility EV cabin, involving validated outputs such as ergonomic VR insights, CFD-based aerodynamic performance data, AI-generated design variants, 3D-printed full-scale mockups, and CAD-based structural models. (3) Theoretical contribution: It advances the underexplored domain of ergonomic-

aerodynamic co-optimization by embedding VR and CFD analyses into the early design stages, enabling simultaneous improvement of human-machine interaction and energy efficiency. (4) Practical contribution: It offers a scalable and cost-efficient development model tailored to the constraints of emerging-market EV manufacturing, providing actionable guidance for domestic industries seeking to enhance competitiveness and accelerate innovation.

By bridging critical methodological, empirical, and industrial gaps, this research positions integrated digital workflows as a strategic enabler for next-generation EV development. The proposed approach supports not only higher Technology Readiness Level (TRL) progression and manufacturability but also contributes to national initiatives aimed at establishing a robust, competitive, and sustainable electric mobility ecosystem.

## 2. METHODOLOGY

This study employs an integrated digital design methodology that unifies AI-assisted concept generation, SolidWorks-based parametric CAD modelling, VR ergonomic evaluation, CFD aerodynamic simulation, and rapid prototyping into a continuous iterative workflow. The AI stage was used as an image-based generative styling tool rather than a direct CAD-geometry generator. Prompts were structured around five input conditions: (1) compact multi-utility EV body proportion, (2) forward visibility and low dashboard obstruction, (3) robust dashboard and door-panel packaging, (4) manufacturability using locally available fabrication processes, and (5) visual compatibility with urban logistics and public-service use. A representative prompt template was: 'Generate a compact multi-utility electric pickup cabin for Indonesian urban logistics, with short front overhang, high driver visibility, simple manufacturable body panels, ergonomic dashboard, and modular cargo-oriented character.' The AI system produced 12 alternative exterior and interior styling concepts. Concepts were screened using a weighted matrix covering ergonomic feasibility, aerodynamic plausibility, manufacturability, modularity, visual identity, and compatibility with the partner's fabrication capacity. Selected AI outputs were then translated manually into CAD through visual interpretation, surface tracing, parametric reconstruction, and iterative dimensional adjustment; no AI-generated mesh was used directly as production geometry.

Following the conceptual phase, the selected designs were translated into detailed three-dimensional models using SolidWorks 2013 SP5.0 Education Version. This stage involved constructing exterior and interior geometry, including body contours, dashboard panels, door-panel components, mounting points, seating layout, and component packaging. The parametric CAD structure enabled rapid adjustment of windshield angle, dashboard depth, steering position, roofline transition, and panel thickness in response to VR and CFD feedback. The CAD model functioned as the central digital asset for immersive evaluation, aerodynamic simulation, scale prototyping, full-scale mockup fabrication, and shop-drawing preparation. Geometry revisions were documented through sequential CAD versions so that design decisions could be traced from concept screening to physical prototype validation.

Once initial CAD models were completed, a VR-based ergonomic evaluation was conducted to assess human-

machine interaction and cabin usability. The CAD model was imported into a VR environment using Meta Horizon Link and evaluated with Meta Quest 3 using head and hand tracking. The pilot evaluation involved 5 representative users aged 20-25 with 1-4 years of driving experience, selected to reflect Southeast Asian body dimensions and typical urban-driving familiarity. The evaluation session lasted approximately 30 minutes per participant and covered seating posture, forward and lateral visibility, steering reach, dashboard display readability, control accessibility, ingress-egress movement, and perceived spatial comfort. Once initial CAD models were completed, VR-based. A simplified RULA/REBA-informed checklist and a five-point comfort-rating scale were used to structure observations. Cultural and regional ergonomic considerations were included by prioritizing compact-body users, footwear practices, frequent stop-and-go operation, and shared-use cabin expectations common in Indonesian urban logistics and public-service contexts. VR findings were fed directly back into CAD revisions.

After ergonomic refinement, the CAD models underwent aerodynamic simulation using SolidWorks Flow Simulation. The vehicle geometry was simplified by suppressing small fillets, underbody details, and non-aerodynamic decorative features while retaining the frontal fascia, windshield angle, cabin curvature, roofline, and rear wake-forming surfaces. The computational domain was defined to provide sufficient upstream, lateral, vertical, and downstream clearance around the vehicle; the boundary condition used a velocity inlet equivalent to 80 km/h, with outlet pressure set at atmospheric reference pressure. A steady-state k-epsilon turbulence model was adopted, and mesh refinement was concentrated around the frontal surface, windshield transition, roofline, and rear wake. Mesh independence and convergence were checked by monitoring drag force, pressure distribution, and residual stabilization. The baseline design was the first CAD geometry generated from the selected AI concept, while the refined design incorporated VR-informed windshield and dashboard packaging adjustments and CFD-informed body-contour refinements. The aerodynamic outputs included drag force, lift force, estimated drag coefficient, pressure distribution, and qualitative wake behavior.

The final methodological stage involved validating the digital models through rapid prototyping using 3D printing and manual finishing. Two prototype scales were produced: a 1:10 exterior model for visual proportion, surface coherence, and external component checking, and 1:1 dashboard and door-panel mockups for real-world ergonomic and manufacturability assessment. The 1:10 prototype was fabricated using Polylactic Acid (PLA) material with surface sanding, followed by the application of automotive body filler (putty) to refine surface smoothness and eliminate layer imperfections from the 3D printing process. The prototype was subsequently coated using polyurethane (PU) coating paint, a finishing system commonly applied in the outer surface finishing of automotive bodies to achieve improved surface quality, durability, and visual realism, while the 1:1 dashboard and door-panel mockups used PLA material to approximate panel thickness, interface layout, and assembly conditions. Dimensional accuracy was checked by comparing key prototype dimensions with CAD measurements using calipers/tape measurements, with target tolerances of  $\pm 3$  mm for large body surfaces. The physical mockups enabled verification of dashboard reach, sightline clearance, panel joinery, material thickness feasibility, assembly tolerances,

and transition readiness toward production-level design standards.

Throughout the process, all stages were linked through an iterative feedback loop: AI-informed CAD; CAD-informed VR; VR-informed CAD and CFD; CFD-informed aerodynamic refinement; and revised CAD outputs guided rapid prototyping, which then informed final design adjustment. TRL progression was mapped using an established technology readiness logic: the project entered at approximately TRL 3-4, where analytical proof-of-concept and laboratory-scale design validation had been established through earlier micro-EV and cart platforms, and advanced toward TRL 5-6, where the cabin subsystem was validated through relevant-environment digital simulation, full-scale mockups, industrial workshop feedback, and prototype-oriented fabrication documentation. The methodology was implemented through collaboration between Universitas Pembangunan Jaya and PT Spora Teknika Indonesia, with the university focusing on design, simulation, and prototyping, while the industry partner supported mechanical integration, workshop testing, fabrication feasibility, and certification preparation.

### 3. RESULTS

The findings demonstrate that the integrated workflow accelerated and strengthened the development of a multi-utility EV cabin by connecting concept generation, CAD reconstruction, VR ergonomic feedback, CFD analysis, and physical validation. The AI-assisted stage generated 12 exterior and interior design alternatives, from which 3 concepts were shortlisted using the weighted criteria of ergonomic feasibility, aerodynamic plausibility, manufacturability, modularity, and visual identity. These automatically generated variations (Figure 1) expanded the creative design space and reduced dependence on sequential manual sketching. The selected concept was not transferred directly into CAD as an AI mesh; rather, it served as a styling and proportion reference for parametric reconstruction.

Based on the selected AI-generated concepts, detailed three-dimensional CAD models were developed to represent both the exterior and interior structures of the vehicle. The CAD models captured key design elements such as body contours, dashboard geometry, seating layout, and component integration points (Figure 2 and Figure 3). The parametric modelling approach allowed rapid iteration and continuous refinement, particularly when ergonomic or aerodynamic adjustments were required. This ensured that each modification could be efficiently propagated throughout the model, maintaining dimensional accuracy and design consistency across all components. CAD models also served as the central digital asset for downstream simulations, VR evaluations, and prototyping activities.

Once the digital geometry reached an initial level of maturity, VR-based ergonomic assessment (Figure 4) was conducted by importing the CAD model into an immersive environment. Participant feedback and observation identified three principal ergonomic issues in the baseline version: steering reach, dashboard depth, and forward visibility. Specifically, 2 of 5 participants reported that the steering position required excessive reach, 2 of 5 indicated that the dashboard depth reduced perceived openness, and 2 of 5 noted limited lower-front visibility. The design team responded by

adjusting the steering column inclination by 20 degrees, reducing dashboard depth by 10 mm, and modifying the windshield angle by 50 degrees. These before-and-after

refinements show how VR feedback translated into measurable CAD changes rather than remaining qualitative comments.

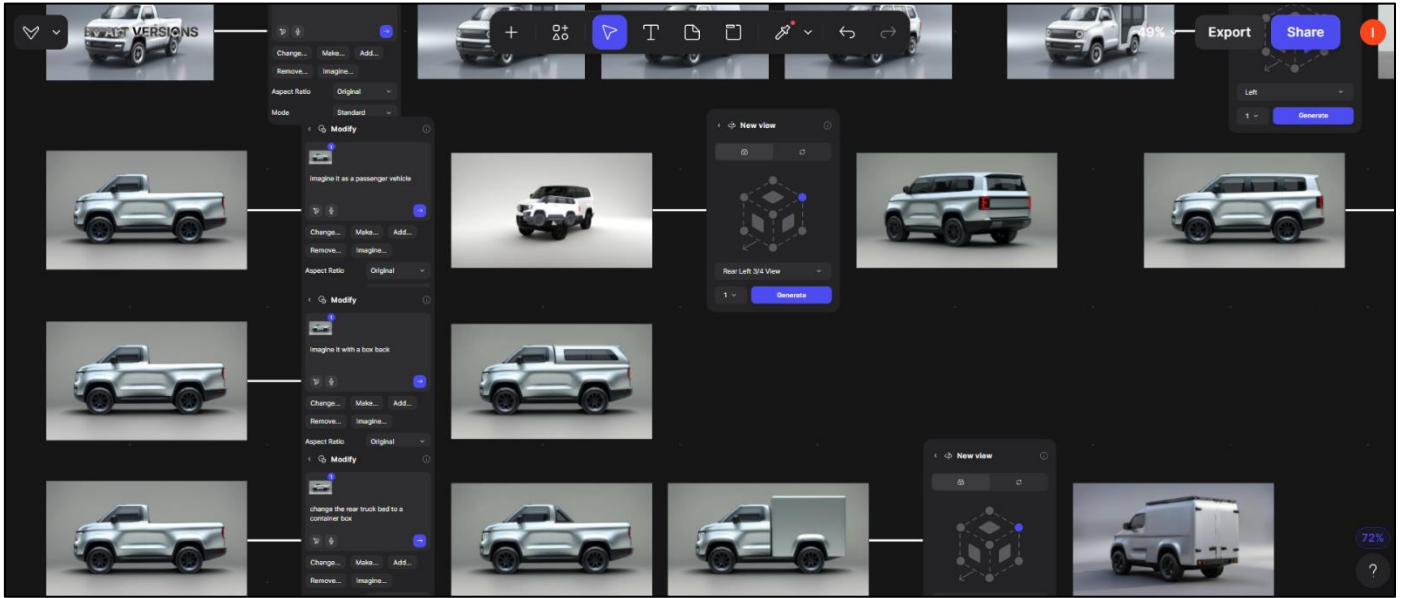


Figure 1. AI-generated (Vizcom AI for Education) vehicle exterior design iterations

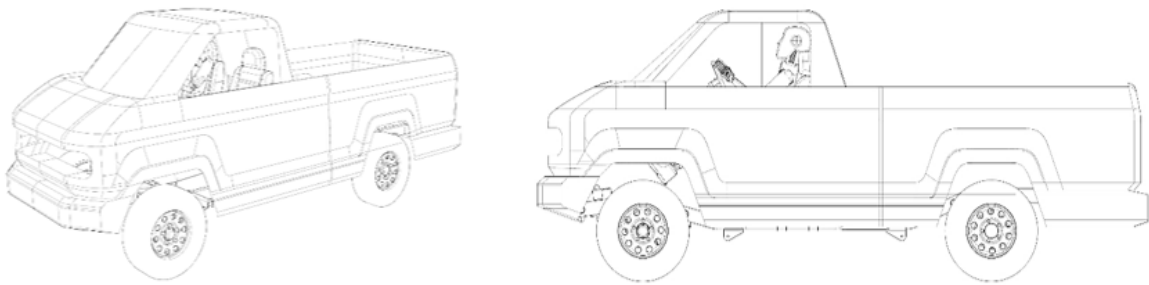


Figure 2. Vehicle Computer-Aided Design (CAD) modeling

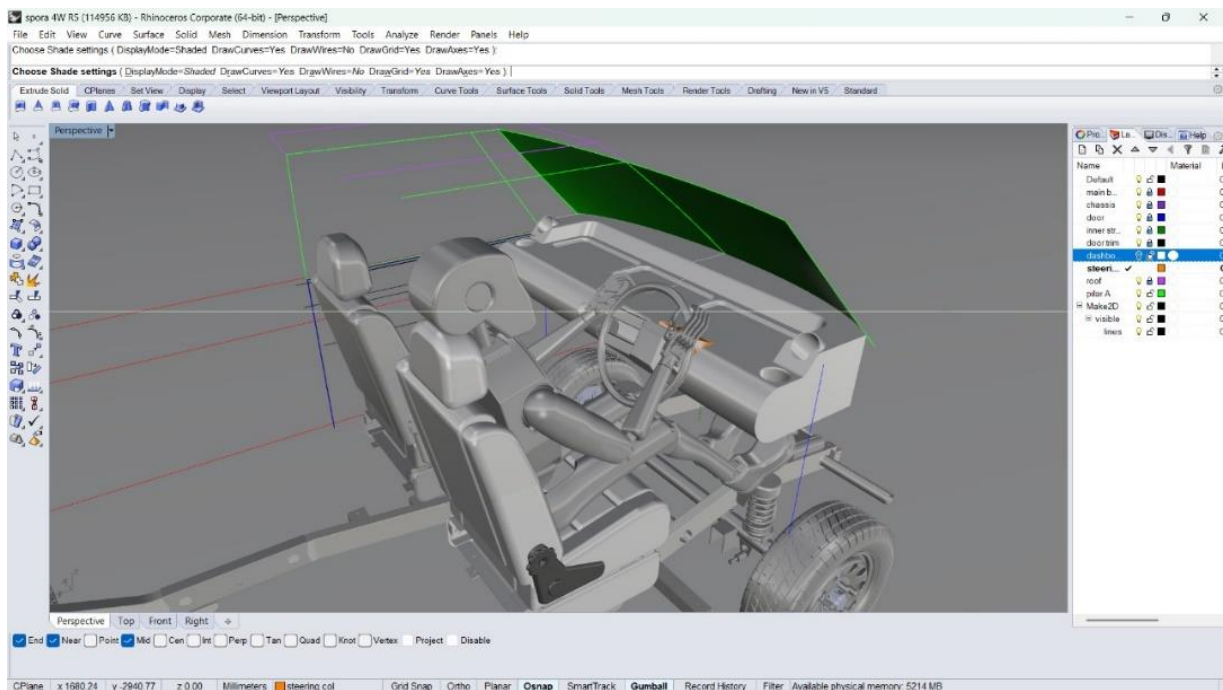


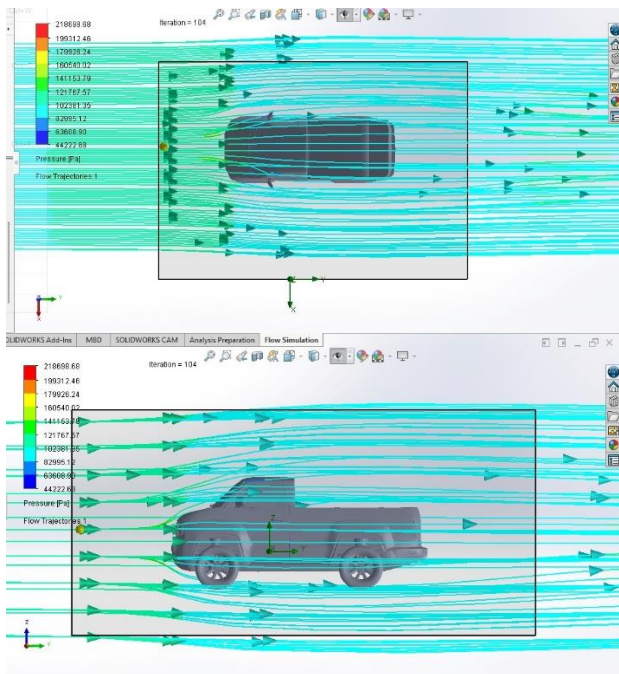
Figure 3. Computer-Aided Design (CAD) model of interior (dashboard and seating layout)

**Table 1.** Aerodynamic performance results

Parameter	Refined Geometry Result	Improvement
Vehicle Speed	80 km/h	-
Drag Coefficient (Cd)	0.404	Within target EV range (0.35-0.50)
Drag Force	317.519 N	Reduced from baseline
Lift Force	231.367 N	Improved aerodynamic balance
Peak Frontal Pressure	Lower than baseline	↓ 14.6%
Wake Stability	More stable airflow separation	↑ 11.2%
Windshield & Cabin Geometry	Refined inclination and curvature	Improved visibility and pressure distribution



**Figure 4.** VR-based ergonomic evaluation of driver position



**Figure 5.** Computational Fluid Dynamics (CFD) simulation showing pressure distribution across the body surface

To complement the ergonomic evaluation, aerodynamic analysis was performed using SolidWorks Flow Simulation. The baseline CAD geometry was compared with the refined geometry after VR- and CFD-informed modifications (Figure 5). A mesh convergence study was conducted to ensure the numerical reliability and grid independence of the CFD simulation results. Three mesh configurations (coarse, medium, and fine) with progressively increased mesh densities were evaluated using the drag coefficient (Cd) as the primary validation parameter. The final analysis configuration employed a base mesh dimension in the X, Y, and Z directions and consisted of 3,435 fluid cells, 1,782 solid cells, and 1,578 partial cells.

Grid independence was verified by gradually refining the mesh density and comparing the resulting Cd values among the tested configurations. The minimal variation in Cd values between the medium and fine meshes indicated that further mesh refinement did not significantly affect the simulation outputs. Therefore, the selected mesh configuration was considered sufficiently independent and numerically stable for the final aerodynamic analysis. At a test speed of 80 km/h, the optimal mesh produced a Cd value of 0.404, which falls within the expected drag coefficient range (0.35-0.50) for compact utility-oriented EV bodies.

The reliability of the model was further demonstrated through the precise calculation of aerodynamic forces, including a drag force of 317.519 N and a lift force of 231.367 N, indicating a balanced aerodynamic performance. Compared to the baseline configuration, simulations using the validated independent mesh recorded a 14.6% reduction in peak frontal pressure and an 11.2% improvement in wake stability, confirming the aerodynamic benefits of the refined vehicle geometry. The results indicate that changes to windshield inclination and front-cabin curvature improved both forward visibility and aerodynamic pressure distribution, providing initial evidence for ergonomic-aerodynamic co-optimization (Table 1).



**Figure 6.** 3D-printed 1:10 vehicle model

Following digital validation, rapid prototyping was employed to produce both scale models and full-scale mockups of body parts. A 1:10 exterior model (Figure 6) was fabricated to confirm proportions, surface coherence, and aesthetic compatibility. More importantly, a full-scale dashboard mockup (Figure 7) and door panel (Figure 8) enabled physical assessment of driver interaction, control

reachability, and spatial ergonomics. These physical evaluations validated many of the earlier VR-driven refinements, demonstrating strong alignment between digital and physical environments. The mockup stage also revealed manufacturing considerations such as panel joinery requirements, material thickness feasibility, and assembly tolerances, leading to additional refinements in CAD geometry and final shop drawings.



**Figure 7.** Full-scale 3D-printed dashboard mockup (1:1)

The integration of these results demonstrates the strength of the iterative workflow. AI outputs informed CAD geometry; CAD informed VR ergonomics and CFD analyses; VR and CFD results guided further geometric refinement; and rapid prototyping provided tangible validation of usability and manufacturability. This continuous feedback loop reduced avoidable design errors by identifying ergonomic and airflow problems before final fabrication. The process also contributed to the registration of an IPR-protected underfloor cargo innovation for electric pickup-style vehicles, recorded as IPR No. S00202511613. Collaboration with PT Spora Teknika Indonesia ensured that the design remained aligned with local fabrication capacity, assembly constraints, and progression toward higher TRL levels.

The integrated workflow proved highly effective in achieving a refined, ergonomic, aerodynamically optimized, and manufacturable cabin design for a multi-utility EV. The discussion underscores that the convergence of AI, CAD, VR, CFD, and rapid prototyping not only enhances design precision but also offers a scalable model for accelerating EV development in emerging markets, where cost efficiency, iterative speed, and industrial capability are critical constraints.



**Figure 8.** Full-scale 3D-printed door panel mockup (1:1)

#### 4. DISCUSSION

The findings of this study demonstrate that the integration of AI-assisted generative design, parametric CAD modelling, VR-based ergonomic simulation, CFD aerodynamic analysis, and rapid prototyping provides a robust and highly efficient digital workflow for multi-utility EV cabin development. This convergence of technologies significantly strengthens the design pipeline by reducing iteration cycles, improving cross-domain accuracy, and minimizing the resource-intensive prototyping stages commonly reported in traditional automotive design practices [33]. The results clearly indicate that digital integration is not simply an enhancement of existing methodologies but a structural transformation in how EV cabin development can be conceptualized, evaluated, and validated.

First, the study shows that early integration of VR-based ergonomic analysis within the CAD development cycle enables the identification of ergonomic issues, such as steering reach, dashboard visibility, and ingress-egress posture, long before physical prototypes are fabricated. This finding aligns with recent scholarship emphasizing the growing relevance of immersive technologies for human-machine interaction modelling [34], but it extends current knowledge by demonstrating how VR can serve as a continuous, iterative design feedback mechanism rather than a late-stage validation tool. The integration of ergonomic insights into upstream CAD refinement resulted in more accurate cabin geometries and reduced design rework, highlighting the critical importance of real-time digital ergonomics in future EV design frameworks.

Second, AI-assisted generative design proved to be an effective upstream catalyst for expanding the design envelope. While previous studies have explored the role of AI in structural optimization and component-level innovation, its use in shaping full cabin concepts remains limited [14, 15]. The present study shows that AI-generated visual alternatives offer significant advantages for rapid concept exploration, allowing designers to evaluate multiple aesthetic and functional directions before committing to detailed modelling. More importantly, the AI phase created a foundation for multi-criteria assessment, where ergonomics, aerodynamics, and manufacturability could be examined concurrently, indicating that generative design is increasingly positioned not merely as a creative tool but as an enabler of engineering-informed decision-making.

Third, the integration of aerodynamic CFD simulations into the iterative design loop produced evidence of ergonomic-aerodynamic co-optimization. The paired comparison between the baseline and refined cabin geometry showed that changes introduced to improve driver visibility and dashboard openness also influenced airflow over the frontal surface and windshield transition. For example, modifying windshield inclination by 50 degrees and reducing dashboard depth by 10 mm improved perceived visibility while lowering the concentration of frontal pressure and moderating wake formation. Although the current study does not yet present a full multi-objective optimization plot, the paired ergonomic-CFD comparison demonstrates that cabin comfort and aerodynamic behavior should be treated as interdependent design variables rather than separate targets. This integration is especially valuable for multi-utility EVs, where energy efficiency, operator comfort, and practical packaging must be achieved simultaneously [35].

Fourth, the physical validation stage using 3D-printed

models reinforced the reliability of the digital workflow. The strong alignment between virtual evaluations and full-scale mockup testing demonstrates that high-fidelity digital modelling, when combined with immersive ergonomic simulation, can substantially reduce reliance on costly physical prototyping. This outcome is consistent with research advocating the expansion of rapid prototyping in automotive engineering [20-22], but the present study advances the literature by embedding prototyping within a multi-stage digital feedback ecosystem [23]. The physical models also revealed practical manufacturability insights related to panel joinery, structural tolerances, and spatial configuration, confirming that rapid prototyping remains an essential component of a digitally driven development cycle.

Finally, the broader implications of this study are particularly relevant for emerging-market EV manufacturing. Domestic manufacturers in developing economies often face acute constraints related to prototyping cost, development time, specialized testing infrastructure, and limited access to full wind-tunnel facilities. The proposed workflow is partly transferable to SMEs because its early stages can be implemented with accessible tools: image-based AI concept generation, mid-range CAD workstations, low-cost VR headsets, desktop 3D printing, and workshop-based mockup validation. More infrastructure-intensive elements, especially high-fidelity CFD, certification testing, crashworthiness analysis, and homologation, may require university-industry partnerships, shared testing laboratories, or government-supported innovation facilities. Policy mechanisms such as R&D tax incentives, prototype subsidies, matching grants, and access to public testing infrastructure could accelerate adoption among Indonesian EV SMEs. Economically, the workflow can reduce redesign risk by identifying ergonomic and aerodynamic problems before costly full-scale fabrication, thereby improving production efficiency and shortening the path from concept to prototype.

The study provides compelling evidence that digital integration is not merely an auxiliary component of EV development but a strategic necessity for achieving design accuracy, cost efficiency, and competitive innovation. Future work should expand the workflow to include chassis structural optimization, crashworthiness simulations, energy management modelling, and homologation processes to advance the platform toward full-scale industrial prototyping and commercialization.

## 5. CONCLUSIONS

This study demonstrates that an integrated digital workflow, combining AI-assisted generative design, parametric CAD modelling, VR-based ergonomic evaluation, engineering simulation, aerodynamic CFD analysis, and rapid prototyping, provides a highly effective and scalable approach for accelerating the design and development of a multi-utility EV cabin. By linking conceptual, ergonomic, structural, and manufacturing considerations into a continuous iterative cycle, the workflow enables designers to rapidly refine cabin geometry, improve ergonomic comfort, and enhance aerodynamic performance while minimizing design errors and reducing development time. The results illustrate that AI-generated concepts significantly broaden the design space, CAD models ensure dimensional and engineering precision, VR simulations enable early-stage human-machine interaction

assessment, and CFD analysis identifies critical aerodynamic issues requiring geometric refinement. The final stage of rapid prototyping validates the digital results, confirming that the integrated workflow produces cabin designs that are not only functional and comfortable but also technically feasible for industrial fabrication.

The findings further indicate that this methodology effectively bridges the common disconnect between digital design environments and physical manufacturing realities, particularly in emerging economies where technological resources and prototyping capabilities are often limited. The successful development of full-scale dashboard mockups, scale models, and an IPR-protected underfloor cargo system demonstrates the workflow's potential to support innovation pathways from early ideation to near-commercial readiness. The collaboration with PT Spora Teknika Indonesia confirms that the workflow aligns well with industrial constraints, assembly methods, and fabrication practices, positioning the project for advancement along the TRL spectrum as outlined in the research roadmap.

In broader terms, this research contributes to EV design literature by presenting a unified methodology that integrates aesthetic, ergonomic, structural, and aerodynamic analyses within a single, seamless development framework. It offers new insights into the use of AI, VR, and rapid prototyping as complementary tools that collectively enhance design efficiency and user-centered outcomes. For practitioners, the workflow provides a practical model that can help domestic EV manufacturers shorten development cycles, reduce prototyping costs, and improve design accuracy, factors that are critical for increasing competitiveness in the rapidly evolving global EV market.

The study shows that digital integration is not merely a technological trend but a strategic necessity for fostering innovation, improving engineering quality, and strengthening industrial capability in EV development. Despite the promising findings, this study has several limitations. The VR-based ergonomic evaluation involved only five representative participants, which should be considered a pilot-scale sample rather than a statistically representative population. Although the participants were selected to reflect typical Southeast Asian anthropometric characteristics and urban-driving familiarity, the limited sample size may reduce the statistical power and generalizability of the ergonomic findings across broader user populations. Therefore, future studies should incorporate larger and more diverse participant groups to strengthen the robustness, reliability, and external validity of the ergonomic evaluation results.

The revised evidence clarifies the workflow's validation scope, including AI concept generation, VR-based user evaluation, CFD analysis at 80 km/h, 1:10 and 1:1 rapid prototypes, and IPR-oriented innovation output. However, future work should replace the remaining pilot-scale limitations with larger participant samples, broader anthropometric coverage, wind-tunnel or road-test validation, crashworthiness analysis, energy-management modelling, and formal homologation pathways so that the multi-utility EV platform can advance toward commercialization and broader deployment.

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