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Critical Path Analysis in New Vehicle Platform Development Projects: A Comparative Study of Passenger Car, SUV, and Electric Vehicle Programs

Poojari Pritish Satish*

Independent Researcher

***Corresponding Author**

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ABSTRACT

Vehicle platform development is among the most complex and capital-intensive undertakings in manufacturing, typically spanning 36 to 48 months from concept to start of production (SOP) and involving engineering expenditure of USD 1 billion to more than USD 6 billion. This paper examines the application of the Critical Path Method (CPM) to new vehicle platform development, using three illustrative but industry-representative case studies: a B-segment passenger car (Project Alpha), a C-segment SUV (Project Beta), and a D-segment battery electric vehicle (Project Gamma). Simulated schedule data, calibrated to published automotive benchmarks and APQP timelines, were analysed using forward/backward pass CPM calculations, float distributions, and Earned Value Analysis (Schedule Performance Index and Schedule Variance). The study finds that powertrain integration, regulatory homologation, and supplier PPAP (Production Part Approval Process) validation are consistently the dominant critical-path drivers across all three platforms, and that electric vehicle development introduces materially greater schedule complexity and variance, driven by battery system integration, battery management system (BMS) software validation, and evolving ADAS certification requirements. Schedule compression through crashing recovered two to four weeks of critical-path time at cost premiums of 12-35% of affected activity budgets, while fast-tracking carried substantially higher rework risk. The paper recommends that automotive OEMs adopt hybrid CPM-Design Structure Matrix (DSM) scheduling frameworks, institutionalise Monte Carlo schedule simulation, and develop dedicated scheduling competencies for electric vehicle and software-defined vehicle programmes. The findings extend the applicability of a decades-old scheduling technique to the contemporary electrification context and offer practical guidance for automotive programme managers and Tier-1 suppliers.

Keywords: Critical Path Method; vehicle platform development; schedule compression; automotive project management; electric vehicle programmes

INTRODUCTION

The global automotive industry faces intensifying competitive and technological pressure. Original Equipment Manufacturers (OEMs) must reconcile shorter development cycles, growing vehicle content and technological sophistication, tightening regulatory requirements, and rising competition from electric vehicle (EV) entrants. Against this backdrop, disciplined project scheduling and critical path management have become central to competitive performance. A full vehicle platform programme, from concept to production, encompasses thousands of engineering tasks, hundreds of supplier development activities, multiple regulatory certification workstreams, and cross-functional integration across chassis, powertrain, body, electronics, and software domains. The engineering expenditure associated with a major vehicle platform can range from USD 1 billion to more than USD 6 billion, and schedule delays translate directly into lost revenue, competitive disadvantage, and, in some cases, regulatory non-compliance exposure.

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The Critical Path Method (CPM), first formalised by Kelley and Walker (1959) for DuPont's chemical plant scheduling, provides a systematic framework for identifying the longest sequence of dependent activities in a project network - the critical path - which sets the minimum feasible project duration. In automotive development, CPM has traditionally been overlaid with Advanced Product Quality Planning (APQP) milestones and Stage-Gate governance. However, the rise of electrification, autonomous driving, and software-defined vehicle (SDV) architectures has introduced critical-path activities - battery integration, BMS software validation, over-the-air update frameworks, and cybersecurity certification - that did not exist in conventional internal combustion engine (ICE) programmes, making a renewed examination of CPM's applicability both timely and relevant.

Industry Context and the Shift Toward Electrification

Historically, vehicle programme scheduling could rely on relatively mature and well-benchmarked ICE powertrain and body engineering timelines, with Stage-Gate and APQP milestones providing predictable checkpoints for programme governance. The accelerating shift toward electrification has disrupted this stability. Battery cell chemistry selection, pack structural and thermal design, and battery management system (BMS) software validation now sit alongside - and frequently dominate - the traditional chassis and body engineering workstreams. At the same time, the proliferation of Advanced Driver Assistance Systems (ADAS) and over-the-air (OTA) software update capability has introduced certification regimes, such as UN Regulation 157, that did not previously exist on the automotive critical path. These developments mean that programme schedules built on ICE-era assumptions risk systematically underestimating both the duration and the variance of contemporary vehicle development, a concern that motivates the comparative, cross-platform design of this study.

Relevance to the Indian Automotive Context

This research is particularly relevant to India's automotive sector. As the world's third-largest car market and a growing hub for global vehicle development activity, Indian OEMs and Tier-1 suppliers are under increasing pressure to align their programme management practices with international standards. Compliance with Bharat Stage VI (BS VI) emission norms, incentives under the FAME-II electric vehicle promotion scheme, and the Production Linked Incentive (PLI) scheme for advanced chemistry cell batteries are together generating new, schedule-critical regulatory compliance workstreams for Indian programme teams. While the case studies in this paper draw on global rather than India-specific benchmark data, the underlying scheduling challenges - regulatory certification complexity, multi-tier supplier dependency, and the emerging demands of electrification - map directly onto the pressures facing the Indian automotive development ecosystem.

Problem Statement and Research Gaps

Despite CPM's broad adoption in general project management, several gaps limit its application to automotive platform development. Network-based CPM struggles to represent the highly iterative, feedback-driven interdependencies typical of vehicle engineering, for which complementary tools such as the Design Structure Matrix (DSM) are needed. Electric powertrain, BMS software, and ADAS integration introduce long-lead, high-uncertainty tasks that existing benchmarks do not adequately capture. Multi-tier supplier delays, particularly at Tier-2 and Tier-3 level, drive critical-path variance that OEM-level schedules frequently fail to model. Empirical frameworks for evaluating the cost-schedule trade-offs of fast-tracking versus crashing remain underdeveloped in the automotive-specific literature, as most compression models originate from general product-development or construction contexts rather than the multi-tier, regulation-intensive automotive setting. Finally, the academic literature has not adequately quantified how regulatory certification regimes - CAFE/AIS and PLI-linked requirements in India, WLTP and the anticipated Euro 7 standard in Europe - propagate through and constrain the critical path of a vehicle programme.

Research Questions

This study is guided by five research questions: (RQ1) Which activities lie consistently on or near the critical path across different vehicle platform types, and what interdependency structures drive critical-path duration?

ISSN 2278-2540 | DOI: 10.51583/IJLTEMAS | Volume XV, Issue VIII, August 2026

(RQ2) How do delays in critical-path activities such as powertrain integration, regulatory homologation, and supplier PPAP (Production Part Approval Process) validation affect project schedule and cost performance? (RQ3) Which schedule compression strategies most effectively recover lost time on critical-path activities in automotive development, and at what cost premium? (RQ4) How do emerging technologies - electrification, ADAS, and software-defined vehicle architectures - affect vehicle development programmes relative to conventional ICE platforms? (RQ5) What organisational and process-level changes can reduce critical-path variance and improve schedule predictability in automotive development?

Objectives and Scope

This paper pursues four objectives, addressed jointly through the five research questions above: (1) to identify the activities that consistently lie on or near the critical path in passenger car, SUV, and EV platform development; (2) to evaluate the schedule and cost impact of critical-path delays using Schedule Performance Index (SPI) and related indicators; (3) to assess the effectiveness and cost premiums of schedule compression strategies (fast-tracking and crashing); and (4) to identify major schedule risks and propose mitigation approaches for OEMs and Tier-1 suppliers.

The study is delimited to automotive OEMs and Tier-1 suppliers engaged in vehicle platform development, and it considers worldwide industry practices and benchmarks with a particular focus on the Indian automotive development setting. It examines three platform types - passenger car, SUV, and electric vehicle - across the full development lifecycle, from concept and feasibility through design and development, prototype validation, regulatory certification, and production readiness (SOP). The analysis draws on illustrative case-study data constructed from published industry benchmarks, academic literature, and APQP/programme-management standards rather than proprietary OEM records, and it does not extend to manufacturing or after-sales operations.

LITERATURE REVIEW

This review synthesises academic and industry literature relevant to critical path analysis in vehicle platform development across five themes: foundational project-scheduling theory, automotive product development management, platform strategy and concurrent engineering, electric and software-defined vehicle development, and risk management in project networks.

Foundations of Critical Path Theory

CPM was formally established between 1957 and 1959 through a collaboration between DuPont and Remington Rand, with Kelley and Walker (1959) providing its key formalisation: a mathematical framework for computing earliest and latest activity start and finish times, thereby identifying zero-float critical activities and the overall minimum project duration. The Program Evaluation and Review Technique (PERT), developed concurrently for the US Navy's Polaris programme, introduced three-point probabilistic time estimation - optimistic, most likely, and pessimistic durations - which is particularly relevant to automotive activities such as prototype testing and regulatory certification that carry significant epistemic uncertainty rather than fixed, deterministic durations. Eisner (2008) extended this foundation to resource-constrained project scheduling (RCPS), demonstrating that resource-levelling heuristics and priority-based allocation rules materially affect both critical-path duration and resource-utilisation efficiency when engineering resources are shared across multiple concurrent vehicle programmes, a condition that is close to universal in multi-platform OEM organisations.

Automotive Product Development Management

Clark and Fujimoto's (1991) landmark empirical study of product development performance at major global automotive OEMs found development lead times ranging from approximately 30 months in best-in-class Japanese manufacturers to more than 60 months in Western counterparts during the 1980s, attributing the difference to organisational design, cross-functional integration, and the 'heavyweight project manager' role - a single individual combining technical authority with organisational influence over the full programme. This concept remains central to automotive critical-path governance, since a heavyweight project manager is typically the escalation point for cross-functional critical-path conflicts. Morgan and Liker (2006) examined Toyota's product development system in depth, documenting disciplined scheduling practices that emphasise front-loading of problem-solving activities, set-based concurrent engineering (SBCE), and rigorous obeya (visual management) room practices. SBCE, in particular, reduces critical-path variability by deliberately deferring final design commitments while exploring multiple design alternatives in parallel, in contrast to the point-based design approach prevalent in many Western OEMs, which commits to a single design solution earlier and subsequently experiences more costly rework cycles on the critical path. Cooper (2017) examined Stage-Gate processes as a governance mechanism for new product development, emphasising the role of phase-gate reviews and go/no-go decision points in preventing resource commitment to programmes carrying unresolved critical-path risk; the integration of Stage-Gate principles with APQP milestone frameworks provides automotive programmes with a structured checkpoint system for critical-path review and escalation.

Platform Strategy and Modularity

Wheelwright and Clark (1992) introduced the concept of platform-based product development strategy, showing that shared platform architectures allow OEMs to amortise critical development investments across multiple vehicle variants, thereby reducing per-model critical-path duration through component reuse and modular design. Their aggregate project plan (APP) framework offers a tool for balancing resource allocation across platform and derivative programmes, directly addressing the resource conflicts that affect critical-path management in multi-programme OEM environments. This literature is directly relevant to the present study's Project Beta case, in which a single platform architecture is designed to underpin three distinct body-style variants, and it underlines why platform modularity is frequently cited as a strategic lever for shortening critical-path duration across an OEM's model range rather than for a single programme in isolation.

Concurrent Engineering and Schedule Compression

Browning and Eppinger (2002) proposed the Design Structure Matrix (DSM) as a complementary analytical tool to CPM for modelling task dependencies and information flows in product development projects. The DSM identifies feedback loops and iterative cycles - for example, between chassis tuning, powertrain calibration, and NVH (noise, vibration, and harshness) optimisation - that a directed acyclic CPM network structurally cannot represent. Their computational experiments demonstrate that such iterative rework loops can extend project schedules by 15-40% relative to CPM predictions that assume purely sequential information flow, a finding with direct bearing on the present study's observation of rework-driven overruns in Project Beta. Smith and Reinertsen (1998) developed an influential framework for product development scheduling built on the premise that time-to-market functions as a competitive weapon, distinguishing fast-tracking (overlapping sequential activities), crashing (adding resources to critical activities), and scope reduction (eliminating or deferring content) as compression techniques with distinct cost-schedule trade-off profiles. Loch and Terwiesch (1998) formalised this trade-off analytically, showing that the optimal degree of overlap between dependent development stages depends on the rate of design-change propagation and the cost of rework, and that excessive fast-tracking can increase total project cost even as it reduces calendar time, because rework triggered by premature downstream activity initiation outweighs the schedule benefit - a dynamic with direct implications for automotive programmes that pursue aggressive simultaneous engineering.

Advanced Product Quality Planning and Supplier Quality Management

The APQP framework, developed by the Automotive Industry Action Group (AIAG, 2008) and formally standardised in IATF 16949 (IATF, 2016), structures vehicle and component development into five phases: Plan and Define Programme; Product Design and Development; Process Design and Development; Product and Process Validation; and Feedback, Assessment, and Corrective Action. Each phase contains specific deliverables and milestones that must be completed before gate progression, offering a natural overlay for CPM-based critical-path analysis, as summarised in Table 1. The Production Part Approval Process (PPAP) - a critical APQP deliverable at the end of Phase 4 - represents one of the most consistently critical-path activities in automotive vehicle development, requiring suppliers to demonstrate through process capability studies, control plans, measurement system analyses, and sample part submissions that their production processes can consistently meet engineering requirements. Because automotive supply chains are multi-tiered, Tier-1 PPAP completion depends on cascaded PPAP approvals from Tier-2 and Tier-3 suppliers, creating complex, densely connected dependency chains on the critical path that are difficult to model using conventional single-tier scheduling assumptions.

Table 1: APQP Phase Structure and Critical-Path Relevance

APQP Phase	Key Activities	Schedule Milestone	Critical-Path Relevance
Phase 1: Plan and Define	Customer requirements, feasibility study, DFMEA initiation	Concept Gate	Network initialisation
Phase 2: Product Design and Development	Design review, prototype builds, DVP&R	Design Freeze	Critical design activities
Phase 3: Process Design and Development	Process flow, control plan, MSA plan	Tooling Release	Supplier PPAP preparation
Phase 4: Product and Process Validation	PPAP, pre-launch control plan, production trial build	SOP Readiness	PPAP critical path
Phase 5: Feedback and Improvement	SPI evaluation, lessons learned	Post-SOP	Programme closeout

Source: Adapted from AIAG (2008) and IATF (2016).

Electric Vehicle and Software-Defined Vehicle Development

The transition to electric vehicle platforms has substantially altered the critical-path profile of automotive development. Berjoza and Jurgis (2017) examined the particular technical challenges of EV development, identifying battery pack design and validation as the most significant critical-path driver in EV programmes; battery cell chemistry selection, pack structural design, thermal management system development, and battery management system (BMS) software validation together constitute a development workstream with no direct equivalent in conventional ICE programmes. Keller et al. (2021) studied the interaction between software development methodologies and hardware development cycles in software-defined vehicle (SDV) architectures, identifying a 'chicken-and-egg' dependency between hardware platform finalisation and software integration testing as a major source of schedule variability. Traditional CPM methodologies, which presume predetermined, fixed activity durations, do not readily capture the iterative, sprint-based nature of software development cycles, which must nonetheless ultimately reconcile with fixed hardware milestones. The integration of ADAS further complicates scheduling due to the regulatory certification requirements of standards such as UN Regulation 157 (lane-keeping systems); validation of ADAS systems typically requires data collection exceeding millions of kilometres of real-world and simulated driving, a requirement that cannot be meaningfully compressed through resource expansion alone and which therefore places ADAS validation activities on or near the critical path in contemporary vehicle programmes.

Risk Management in Project Networks

Hillson (2009) developed a widely used framework for project risk management that distinguishes threat risks (events with a negative influence on project objectives) from opportunity risks, a distinction directly applicable to automotive critical-path risks such as supplier bankruptcy, engineering change order (ECO) cascades, test failure and retesting cycles, regulatory certification delay, and technological readiness shortfalls. Vanhoucke (2012) investigated the relationship between project network topology and schedule risk exposure, finding that projects with dense activity networks and multiple near-critical pathways exhibit greater schedule variation than those with a single dominant critical path - a structural feature that characterises automotive vehicle

ISSN 2278-2540 | DOI: 10.51583/IJLTEMAS | Volume XV, Issue VIII, August 2026

development, with its hundreds of concurrent engineering workstreams, and that makes probabilistic schedule analysis (Monte Carlo simulation) a more appropriate risk-assessment tool than deterministic CPM used in isolation. Krishnan and Ulrich (2001) reviewed the product-development literature from a decision-making perspective, identifying key schedule-critical decisions - including product architecture choices, component standardisation decisions, and supplier involvement strategies - and demonstrating that early resolution of architectural uncertainties, particularly platform-sharing boundaries and module interfaces, is critical to reducing downstream schedule variance on the critical path.

Summary and Research Gaps

The reviewed literature establishes a robust theoretical foundation for CPM application in product-development contexts generally, and in automotive development specifically. However, several gaps relevant to contemporary vehicle platform development remain only partially addressed: empirical research comparing CPM implementation across multiple automotive platform typologies - ICE and EV in particular - is limited; the relationship between agile software-sprint cycles and hardware-milestone CPM networks in SDV platforms lacks a developed theoretical treatment; existing schedule-compression cost models do not account for automotive-specific cost structures and resource profiles; and the literature lacks a systematic treatment of how multi-tier supply-chain PPAP dependencies drive critical-path variance. This paper addresses these gaps through a structured case-study examination of three vehicle platform typologies, thereby contributing fresh comparative evidence and practical scheduling guidance to the automotive project-management literature, following the case-study research principles set out by Yin (2018).

METHODOLOGY

Research Design

This study adopts a sequential mixed-methods design. In the quantitative stage, illustrative project schedule data for three vehicle platform case studies are analysed using CPM-based indicators - critical-path duration, float distribution, and earned-value measures. In the qualitative stage, the resulting schedule performance is interpreted through documented industry practice and platform-typology comparison, following case-study principles set out by Yin (2018).

Data and Sampling

Because genuine OEM schedule data are commercially sensitive, the study uses simulated case-study data calibrated to published benchmarks, principally the empirical lead-time ranges reported by Clark and Fujimoto (1991) and the AIAG APQP Reference Manual (AIAG, 2008). No proprietary OEM data are used. Three platforms were purposively selected to maximise variance across powertrain type, segment, and regulatory regime while holding programme scale broadly comparable, as summarised in Table 2.

Table 2: Case Study Sampling Overview

Case Study	Platform Type	Powertrain	Target Market	Planned Duration
Project Alpha	B-segment passenger car	Petrol / mild hybrid (MHEV)	Global / India	42 months
Project Beta	C-segment SUV (3 variants)	Petrol / diesel / MHEV	Global	46 months
Project Gamma	D-segment electric SUV	BEV, 400V, dual motor	Global / Europe	48 months

Source: Case study analysis (this study), calibrated to Clark and Fujimoto (1991).

ISSN 2278-2540 | DOI: 10.51583/IJLTEMAS | Volume XV, Issue VIII, August 2026

Analytical Tools

Critical-path identification used standard forward-pass (earliest start/finish) and backward-pass (latest start/finish) calculations, with total float TF = LS - ES = LF - EF and critical activities defined as those with TF = 0, following the original CPM formalisation of Kelley and Walker (1959) summarised in Table 3. Schedule performance was assessed using the Schedule Performance Index (SPI = EV / PV) and Schedule Variance (SV = EV - PV), where SPI below 1.0 and negative SV indicate schedule underperformance, following standard Earned Value Management practice (Fleming & Koppelman, 2016). Compression analysis identified the lowest cost-per-week crashable activities and assessed fast-tracking overlap potential and associated rework risk. Qualitative risk was assessed using the probability-by-impact matrix reproduced in Table 4, following Hillson (2009), and supplemented by illustrative Monte Carlo P50/P80 completion estimates, presented for Project Gamma in Table 13.

Table 3: CPM Key Formulae and Definitions

Term	**Symbol / Formula**	**Definition**
Earliest Start	ES	Earliest time an activity can begin
Earliest Finish	EF = ES + Duration	Earliest time an activity can complete
Latest Start	LS = LF - Duration	Latest time an activity can start without delaying the project
Latest Finish	LF	Latest time an activity can finish without delaying the project
Total Float	TF = LS - ES = LF - EF	Maximum time an activity can be delayed without impacting SOP
Free Float	FF = ES(successor) - EF	Delay allowable without affecting the successor's earliest start
Critical Activity	TF = 0	Activity with no schedule flexibility
Schedule Performance Index	SPI = EV / PV	Measure of schedule efficiency (1.0 = on schedule)
Schedule Variance	SV = EV - PV	Negative value indicates behind-schedule performance

Source: Adapted from Kelley and Walker (1959) and Fleming and Koppelman (2016).

Table 4: Qualitative Risk Probability-Impact Scoring Matrix

Probability\ Impact	**Negligible (1)**	**Minor (2)**	**Moderate (3)**	**Major (4)**	**Catastrophic (5)**
Very High (5)	5	10	15	20	25
High (4)	4	8	12	16	20
Medium (3)	3	6	9	12	15
Low (2)	2	4	6	8	10
Very Low (1)	1	2	3	4	5

Source: Adapted from Hillson (2009). Risk score bands: 15-25 Critical (immediate escalation); 8-12 High (active mitigation); 4-6 Medium (monitoring); 1-3 Low (periodic review).

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RESULTS

Case Study 1: Project Alpha (Passenger Car)

Project Alpha's critical path runs through vehicle architecture definition, platform dimensional layout, powertrain package integration, powertrain-chassis interface specification, suspension design, MHEV system integration, emissions calibration, regulatory type approval, Tier-1 PPAP completion, production trial build, and SOP, for a total critical-path length of 108 weeks. Critical activities accounted for 22% of all programme activities and near-critical activities (float of 1-2 weeks) for a further 13%, indicating substantial schedule sensitivity. SPI held at a consistent 0.93 from Month 12 through Month 36, reflecting systemic underperformance driven by MHEV calibration complexity exceeding initial estimates; SOP was achieved at Month 44.4, a 2.4-month slip conservatively estimated at USD 45 million in lost revenue from delayed market entry. Compression analysis, summarised in Table 5, identified Tier-1 PPAP acceleration as offering the most favourable cost-to-recovery ratio.

Conceptually, the chain in Figure 1 illustrates why a single-platform ICE programme carries a distinctive schedule-risk signature: with few parallel branches, each activity is gated almost entirely on its immediate predecessor, so the network behaves more like a series circuit than a distributed one. Architecture and layout decisions taken in the first fourteen weeks propagate forward through powertrain packaging, suspension design, and MHEV calibration before converging on the regulatory and PPAP workstreams at the tail of the chain. This structural feature - a long, thin dependency chain rather than a dense web of parallel paths - means that Project Alpha's overall schedule sensitivity to any single upstream delay is higher than that of the more distributed, multi-variant networks examined in Projects Beta and Gamma below.

Figure 1: Critical Path Activity Chain - Project Alpha (Passenger Car)

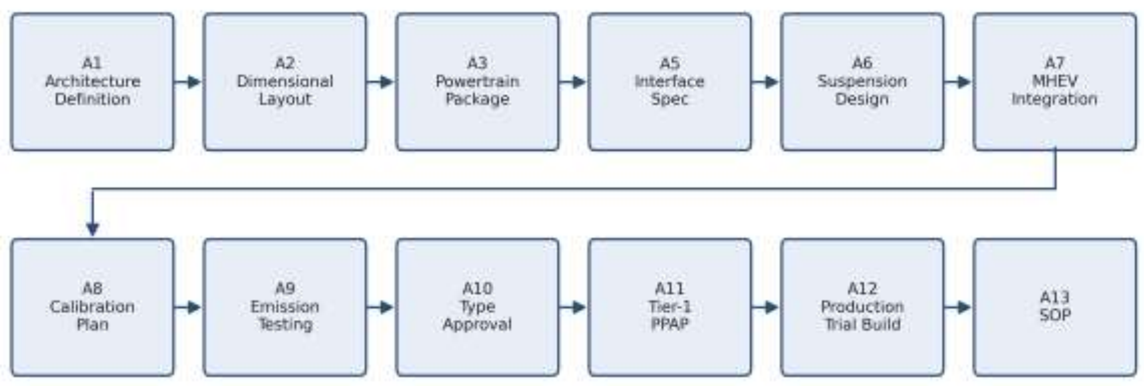


Table 5: Schedule Compression Analysis - Project Alpha

Activity	Normal Duration	Crash Duration	Cost Premium	Feasibility
Engine calibration & emission testing	14 weeks	11 weeks	+USD 1.2M (28%)	High
Regulatory type approval testing	12 weeks	10 weeks	+USD 0.8M (22%)	Medium
Tier-1 supplier PPAP completion	10 weeks	8 weeks	+USD 0.6M (18%)	High
MHEV system integration design	12 weeks	10 weeks	+USD 1.5M (35%)	Low

Source: Case study analysis (this study).

ISSN 2278-2540 | DOI: 10.51583/IJLTEMAS | Volume XV, Issue VIII, August 2026

Case Study 2: Project Beta (SUV)

Project Beta's multi-powertrain, multi-variant strategy widened the critical-path footprint relative to Alpha: 25% of activities were critical and a further 17% near-critical. Diesel NVH optimisation and calibration (16 weeks) was the longest single critical activity, and multi-variant regulatory type approval (14 weeks) represented the most complex certification workstream, requiring separate submissions per powertrain variant across multiple markets. SPI deteriorated progressively from 0.97 at Month 12 to 0.91 at Month 24 and 0.88 at Month 36, driven successively by diesel NVH calibration delay, 4WD driveline integration issues, and a multi-market type-approval backlog. SOP slipped three months, to Month 49, with 4WD driveline rework triggered by NVH validation failures identified as a key contributor. Table 6 compares the float distribution of Alpha and Beta, showing that Beta carries both a higher proportion of critical activities and a higher proportion of near-critical activities, consistent with its greater programme complexity.

Table 6: Float Distribution by Risk Category - Projects Alpha and Beta

Float Category	Alpha: Activities	Alpha: % of Total	Beta: Activities	Beta: % of Total	Risk Classification
Critical (TF = 0)	13	22%	18	25%	Critical
Near-Critical (low float)	8	13%	12	17%	High Risk
Low Float (moderate)	15	25%	20	28%	Medium Risk
Comfortable Float (high)	24	40%	22	30%	Low Risk

Source: Case study analysis (this study). Near-Critical band = 1-2 weeks total float for Alpha and 1-3 weeks for Beta; Low Float band = 3-6 weeks for Alpha and 4-8 weeks for Beta, reflecting each programme's total critical-path duration.

Case Study 3: Project Gamma (Electric Vehicle)

Project Gamma's critical path is dominated by three interdependent streams: battery system development (cell chemistry selection, pack structural design, thermal management, and UN 38.3 safety and abuse testing), the software/ADAS stream (BMS software development, SDV domain-controller integration, and ADAS sensor and software validation), and Euro NCAP/UN Regulation 157 regulatory certification. ADAS software validation, at 22 weeks, was the single longest critical activity in the study, reflecting the data-collection and simulation burden of UN R157 certification. The battery-development workstream alone accounted for 78% of Gamma's total critical-path duration, compared with 45% for ICE powertrain activities in Alpha. Thirty percent of activities were critical and 20% near-critical - the highest proportions among the three platforms. SPI fell from 0.95 (Month 12) to 0.88 (Month 24) and 0.82 (Month 36), and SOP slipped 4.5 months (9.4% of planned duration) to Month 52.5, the largest overrun in the study. The overrun was attributed approximately 40% to battery integration complexity, 35% to software-hardware integration failures, and 25% to regulatory certification delay. Table 7 summarises Gamma's qualitative risk register, scored against the probability-impact framework in Table 4; software integration and regulatory certification risks both reach the Critical band.

Table 7: EV-Specific Schedule Risk Register - Project Gamma

Risk Category	Risk Event	Probability	Schedule Impact	Risk Score
Technology	Battery cell chemistry change post-design freeze	Medium (30%)	8-16 weeks	High

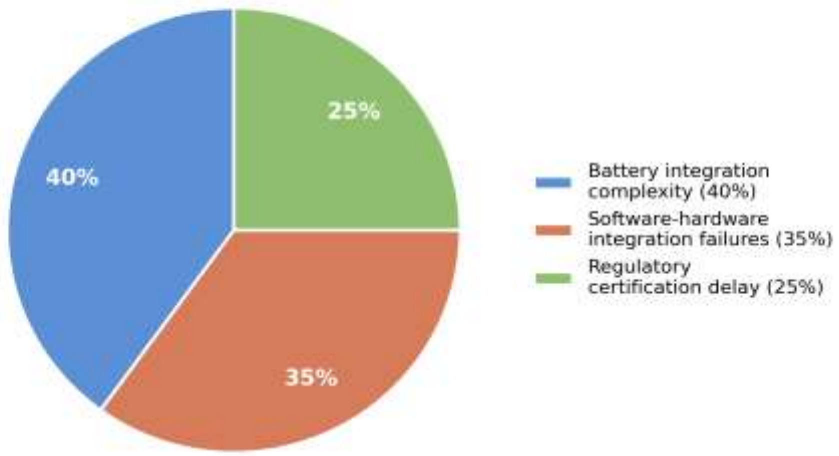
ISSN 2278-2540 | DOI: 10.51583/IJLTEMAS | Volume XV, Issue VIII, August 2026

Software	BMS software integration failure at EV1 build	High (45%)	4-12 weeks	Critical
Regulatory	UN R157 ADAS certification rejection	Medium (35%)	12-24 weeks	Critical
Supply Chain	Battery cell supplier capacity constraint	Medium (30%)	6-16 weeks	High
Integration	SDV architecture OTA update failure at DVP	High (40%)	6-12 weeks	High

Source: Case study analysis (this study); risk categorisation and probability-impact scoring follow the threat-risk framework of Hillson (2009).

Conceptually, the five risk categories in Table 7 are not independent draws but a coupled system: a battery cell chemistry change (Technology) is likely to trigger downstream BMS software rework (Software), and, if it affects the data submitted for type approval, can in turn delay UN R157 certification (Regulatory). This coupling is characteristic of electric vehicle programmes and helps explain why Gamma's realised 4.5-month overrun exceeded what any single risk category, taken in isolation, would have predicted. It also reinforces Vanhoucke's (2012) broader finding that dense, interconnected risk networks generate compounding rather than simply additive schedule variance - a dynamic that deterministic, single-point CPM scheduling is structurally unable to represent.

Figure 2: Drivers of the 4.5-Month Schedule Overrun - Project Gamma (EV)



Comparative Analysis

Table 8 summarises schedule performance across the three platforms. Critical-path density, schedule overrun, and final SPI all move consistently in the same direction from the ICE passenger car through the SUV to the EV platform, indicating that platform electrification is associated with structurally greater schedule risk rather than a one-off effect specific to a single programme.

Table 8: Comparative Schedule Metrics Across Platforms

Metric	Project Alpha	Project Beta	Project Gamma
Planned duration (months)	42	46	48

ISSN 2278-2540 | DOI: 10.51583/IJLTEMAS | Volume XV, Issue VIII, August 2026

Actual SOP (months)	44.4	49.0	52.5
Schedule overrun (months)	2.4	3.0	4.5
Critical activities (%)	22%	25%	30%
Near-critical activities (%)	13%	17%	20%
Final SPI (at planned SOP)	0.95	0.88	0.85

Source: Case study analysis (this study).

Table 9 disaggregates critical-path status by activity category. Powertrain integration, regulatory type approval, and supplier PPAP are critical in all three platforms, while software development rises from near-critical in Alpha and Beta to fully critical in Gamma, and battery system development appears only in the EV platform but immediately dominates it.

Table 9: Critical-Path Driver Categories Across Platforms

Activity Category	**Project Alpha**	**Project Beta**	**Project Gamma**	**Trend**
Powertrain integration	Critical	Critical	Critical (BEV)	Consistently critical
Regulatory type approval	Critical	Critical	Critical (+ADAS)	Increasingly complex
Supplier PPAP	Critical	Critical	Critical (new tech)	Consistently critical
Software development	Near-critical	Near-critical	Critical	Rising criticality
Battery system	N/A	N/A	Critical (dominant)	EV-specific
Body structure	Near-critical	Near-critical	Near-critical	Stable

Source: Case study analysis (this study).

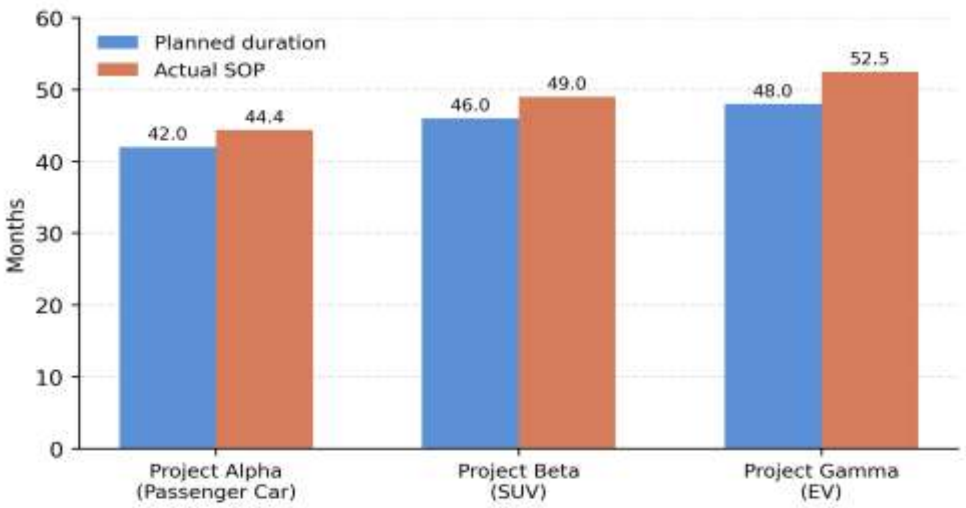
Table 10 reports the underlying Schedule Performance Index and Schedule Variance data at each review point, providing the quantitative basis for the SPI trend shown in Figure 4. The widening SV gap for Gamma relative to Alpha and Beta at Month 36 (-13.0 weeks versus -7.2 and -9.0 weeks respectively) illustrates the accelerating, rather than constant, rate of schedule slippage characteristic of first-generation EV programmes.

Table 10: Schedule Performance (SPI and SV) at Programme Review Points - All Platforms

Review Point	**Alpha SPI**	**Alpha SV (wks)**	**Beta SPI**	**Beta SV (wks)**	**Gamma SPI**	**Gamma SV (wks)**
Month 12	0.93	-2.4	0.97	-1.5	0.95	-2.5
Month 24	0.93	-4.8	0.91	-5.5	0.88	-7.5
Month 36	0.93	-7.2	0.88	-9.0	0.82	-13.0

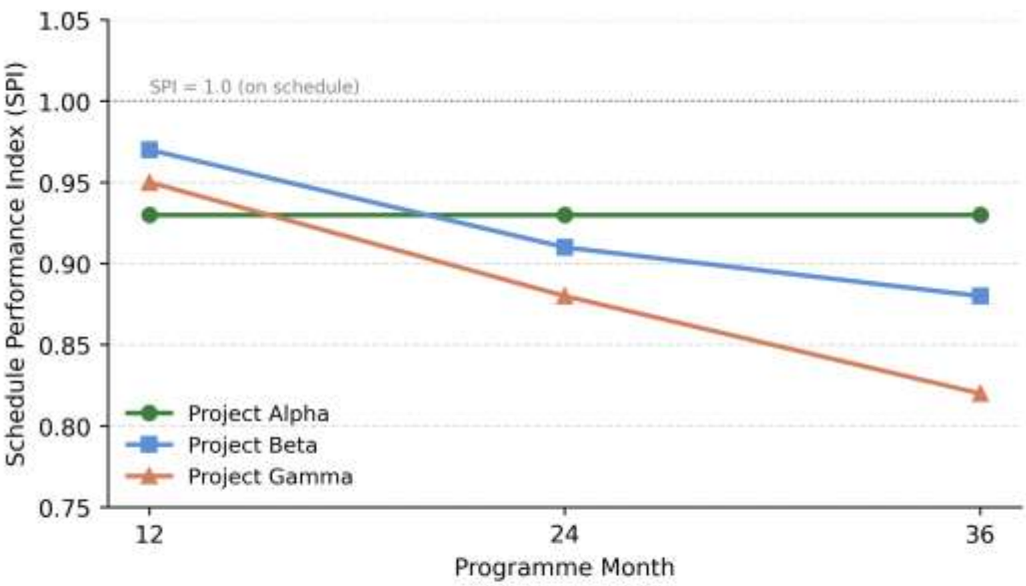
Source: Case study analysis (this study); SPI and SV computed following Earned Value Management practice (Fleming & Koppelman, 2016).

Figure 3: Planned versus Actual SOP Duration Across Platforms



Conceptually, the widening gap visible in Figure 3 is not a constant offset carried through each programme but an accelerating one, as the SPI and SV data in Table 10 make clear. Rather than a fixed delay introduced early and preserved unchanged to SOP, each platform's shortfall against plan compounds over the review window, with the absolute schedule variance roughly doubling between Month 12 and Month 24, and doubling again for Gamma between Month 24 and Month 36. The rate of that compounding, rather than the overrun's final magnitude alone, is what most clearly separates the three platforms, and it is examined directly through the SPI trend in Figure 4.

Figure 4: Schedule Performance Index (SPI) Trend Across Platforms, Months 12-36



DISCUSSION

Powertrain Integration as a Universal Driver

Across all three case studies, powertrain integration activities occupy 25-35% of total critical-path length, consistent with Clark and Fujimoto's (1991) observation that powertrain-chassis integration is the primary schedule driver in automotive development. In the EV context, battery pack integration has effectively replaced ICE powertrain integration as the dominant critical workstream, and its structural position in the project network - generating chassis layout constraints that in turn determine suspension geometry and body attachment points - means that any delay propagates across multiple concurrent development streams.

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Illustrative DSM Application: The Chassis-Powertrain-NVH Feedback Loop

The literature review noted that CPM's directed acyclic structure cannot represent the iterative feedback loops that Browning and Eppinger (2002) identify as a major source of automotive rework, and that this study's own CPM-DSM integration is, at the network level, illustrative rather than empirically demonstrated. To make that limitation concrete rather than abstract, Table 11 constructs a small DSM for the three Project Beta activities implicated in the rework episode reported under Case Study 2 above: 4WD powertrain package integration (B2), suspension geometry validation (B5), and diesel NVH optimisation and calibration (B4). In the underlying CPM network these activities are represented as a simple forward sequence; the DSM instead marks where information must also flow backward.

Table 11: Illustrative Design Structure Matrix - Project Beta Chassis-Powertrain-NVH Loop

From \ To	B2: 4WD Powertrain Integration	B5: Suspension Geometry Validation	B4: Diesel NVH Optimisation
B2: 4WD Powertrain Integration	-	Forward	-
B5: Suspension Geometry Validation	-	-	Forward
B4: Diesel NVH Optimisation	Feedback	Feedback	-

Source: Case study analysis (this study); DSM notation follows Browning and Eppinger (2002). Marks are illustrative and reflect the rework relationship described under Case Study 2 (Project Beta), not a measured information-flow survey.

Read as a CPM network, B2 feeds B5, which feeds B4, and the schedule terminates once B4 completes. Read as a DSM, B4 also feeds back into both B5 and B2: NVH validation is not merely a downstream consumer of suspension and powertrain decisions but a source of iteration into them, which is exactly the mechanism behind the '4WD driveline rework triggered by NVH validation failures' reported earlier. A CPM-only schedule has no notation for this feedback and will therefore treat B4 as complete once its 16-week duration elapses, understating the true critical-path length whenever the feedback marks are live. A DSM constructed at the concept phase, clustering activities by feedback intensity per Browning and Eppinger (2002), would have flagged this specific loop as a priority for either earlier cross-functional resolution or explicit rework contingency, rather than allowing it to surface only once aggressive fast-tracking had already compressed the buffer between B2 and B4.

Regulatory Certification as an Immovable Anchor

Regulatory approval activities appear on the critical path in every case study and exhibit the lowest crashability of any major activity category, because external authorities govern testing protocols and processing times that cannot be accelerated through resource addition alone. UN Regulation 157 ADAS certification in Project Gamma added 22 weeks of critical-path time with an estimated maximum compression of only 15%. This suggests that OEMs developing EV and ADAS-equipped programmes should treat regulatory certification as a fixed schedule anchor around which other activities are sequenced, rather than as a downstream validation deliverable, and should pursue early regulatory engagement and harmonised parallel-market submissions to manage this risk.

Supplier PPAP as the Highest-Risk Convergence Point

Tier-1 PPAP completion consistently emerges as the critical-path node with the highest in-degree (number of predecessor activities), reflecting its dependence on both upstream OEM engineering finalisation and cascaded Tier-2/Tier-3 sub-supplier approvals. Across all three cases, actual PPAP completion occurred two to four weeks later than planned, a systematic underestimation attributable to optimistic assumptions about Tier-2 process capability, inadequate resubmission buffers, and insufficient early supplier involvement. This two-to-

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four-week figure is measured only at the Tier-1 interface, however, because none of the three case studies extends direct schedule visibility into Tier-2 or Tier-3 operations - a scope limitation of this study noted further under Limitations below. Table 12 offers an illustrative decomposition of how that slip is likely to accumulate across tiers, consistent with commonly reported automotive supply-chain lag patterns, to make the mechanism concrete rather than treating the Tier-1 slip as a single undifferentiated event.

Table 12: Illustrative Multi-Tier PPAP Cascade Lag

Supply Tier	**Typical Dependency**	**Illustrative Added Lag**	**Cumulative Lag at Tier-1**
Tier-3 (raw material / sub-component)	Material certification, process capability studies	1 week	1 week
Tier-2 (component / sub-system)	Cascaded PPAP approval from Tier-3, own capability studies	1 week	2 weeks
Tier-1 (system supplier to OEM)	Final PPAP submission pending Tier-2 approval and OEM sign-off	0-2 weeks	2-4 weeks

Source: Illustrative decomposition (this study), constructed to be consistent with the 2-4 week Tier-1 slip reported across the three case studies above; not a measured multi-tier schedule.

The decomposition clarifies why mitigation confined to the Tier-1 relationship is structurally insufficient: schedule risk visible only at the Tier-1 PPAP milestone has, by construction, already absorbed delay accumulated at tiers the OEM's programme office rarely monitors directly, leaving little runway to react once it surfaces. This reinforces the Early Supplier Involvement recommendation offered in the Conclusion, which should extend joint schedule visibility at least one tier deeper than current OEM practice typically reaches. On the cost side, applying the study's own estimate of approximately USD 18.75 million in lost revenue per month of SOP delay for a B-segment programme, a two-week schedule recovery - the reduction Project Alpha achieved by crashing Tier-1 PPAP completion - corresponds to an illustrative avoided-loss value of approximately USD 8.6 million (at 4.33 weeks per month), against a crashing cost of USD 0.6 million. This implies an approximate 14:1 benefit-cost ratio, materially higher than engine calibration's comparable ratio for the same programme (a three-week recovery at a 28% premium, per Table 5), which explains why PPAP-focused crashing consistently emerged as the most favourable compression lever across the cases examined and offers programme managers a concrete decision rule: crash budget should be prioritised toward whichever critical activity clears the highest benefit-cost ratio computed on this basis, not simply the activity with the largest absolute recovery.

Structurally Higher Variance in Electric Vehicle Programmes

Project Gamma's 4.5-month overrun (9.4% of planned duration), against 2.4 months (5.7%) for the passenger car and 3.0 months (6.5%) for the SUV, indicates that first-generation EV platforms carry structurally higher schedule risk than their ICE counterparts. The dominant contributor was software-hardware integration failure, reflecting a fundamental mismatch between iterative, sprint-based software development and the fixed-duration activity assumptions of deterministic CPM. This finding points toward the need for hybrid CPM-Agile scheduling approaches that allow software iterations to be systematically reconciled with hardware milestone structures.

The mismatch can be quantified rather than left qualitative. Project Gamma's SDV architecture and domain-controller integration activity (G7) is scheduled as an 18-week fixed-duration CPM node. At a typical two-week agile sprint cadence, that single node must absorb approximately nine sequential sprints, each capable of independently generating scope changes, defect backlogs, or architecture revisions that a fixed-duration, single-owner CPM activity has no notation for. This is the concrete mechanism behind Keller et al.'s (2021) hardware-software 'chicken-and-egg' dependency: the CPM network commits to G7's 18-week duration before

ISSN 2278-2540 | DOI: 10.51583/IJLTEMAS | Volume XV, Issue VIII, August 2026

the outcome of, in effect, the ninth sprint is known, so any late-sprint architecture change becomes an unplanned schedule variance rather than an anticipated iteration - precisely the dynamic reflected in the 'Software' and 'Integration' rows of Table 7's risk register.

This structural mismatch is also why deterministic point estimates understate EV schedule risk more than they understate ICE risk. Table 13 constructs an illustrative probabilistic schedule estimate for Project Gamma, following the Monte Carlo P50/P80 approach described in the Methodology and motivated by Vanhoucke's (2012) finding that dense, near-critical-path-heavy networks carry more schedule variance than deterministic CPM alone can represent.

Table 13: Illustrative Probabilistic Schedule Estimate - Project Gamma

Estimate Basis	SOP (Month)	Contingency vs. Deterministic Plan
Deterministic CPM (planned, Table 2)	48	-
P50 (illustrative median estimate)	52	+4 months
P80 (illustrative 80th-percentile estimate)	55	+7 months
Realised outcome (this study, Case Study 3)	52.5	+4.5 months

Source: Illustrative estimate (this study), constructed following Vanhoucke (2012); not the output of an executed Monte Carlo simulation. P80 contingency is informed by the two Critical-band risks in Table 7 (BMS software integration failure and UN R157 certification rejection).

The realised outcome of Month 52.5 sits almost exactly at the illustrative P50 estimate, a coincidence that nonetheless illustrates the paper's central methodological point: a probabilistic schedule commitment targeting P70-P80 confidence, as recommended in the Conclusion, would have been a more defensible planning basis for Project Gamma than the deterministic 48-month point estimate against which the programme was originally baselined and against which its 4.5-month overrun was subsequently measured.

Compression Is Effective but Must Be Targeted

Across all three case studies, crashing recovered two to four weeks of critical-path time at cost premiums of 12-35% of affected activity budgets, with the most crashable activities being those involving physical testing capacity - engine calibration, NVH testing, and prototype builds - that can be parallelised through resource addition. Fast-tracking proved considerably riskier: Project Beta's aggressive overlap of 4WD driveline integration and NVH calibration generated rework that consumed the intended schedule benefit, corroborating Browning and Eppinger's (2002) finding that rework loops can extend schedules by 15-40%. This supports a disciplined compression hierarchy in which crashing is preferred for high-resource-elasticity, low-rework-risk activities; fast-tracking is reserved for activity pairs with well-defined interfaces; and scope reduction is evaluated first for discretionary content.

Limitations

This study's principal limitation is its reliance on illustrative, simulated case-study data rather than proprietary OEM schedule archives; while parameters were calibrated to published benchmarks, the findings should not be read as empirically validated representations of specific real-world programmes. A related and distinct limitation is that, although the paper repeatedly contextualises its findings against Indian regulatory frameworks (BS VI, FAME-II, PLI), it does not include empirical India-specific case data - the three case studies are calibrated to global benchmarks, and no Indian OEM or Tier-1 supplier schedule was examined directly. The Table 11 DSM illustration and Table 12 PPAP cascade decomposition are similarly conceptual rather than measured: they demonstrate how CPM-DSM integration and multi-tier delay attribution could be operationalised, not that they have been, and a genuine DSM analysis would require activity-level information-

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flow data this study's scope does not extend to. The analysis further examines schedule status at discrete review points rather than through continuous dynamic simulation, and is based on three case studies, which constrains statistical generalisability. Finally, the study relies on secondary literature rather than primary interviews with programme managers, and its conclusions regarding EV scheduling reflect the state of practice as of early 2026.

CONCLUSION

This study examined the application of the Critical Path Method to new vehicle platform development across three typologies - passenger car, SUV, and electric vehicle - using illustrative but industry-calibrated case studies analysed through forward/backward pass CPM calculations, float distribution, and Earned Value Analysis. The research fulfilled its four stated objectives: identifying the activities that consistently occupy the critical path, evaluating the schedule and cost impact of critical-path delay, assessing the effectiveness and cost premiums of compression strategies, and identifying the principal schedule risks facing OEMs and Tier-1 suppliers. Across all three platforms, powertrain integration, regulatory certification, and supplier PPAP validation emerged as consistent schedule anchors, each characterised by high technical complexity and strong external dependency that limits direct OEM control. Electric vehicle platforms introduce materially greater critical-path complexity than their ICE counterparts, driven by battery system development and software-hardware integration challenges, and recorded the largest schedule overrun of the three programmes studied. Schedule compression through crashing proved feasible but cost-intensive, while fast-tracking carried disproportionate rework risk in an industry characterised by dense information interdependence between engineering activities. Taken together, the findings affirm that CPM remains a foundational scheduling technique for automotive development more than six decades after its introduction, while also demonstrating that its deterministic, sequential assumptions require deliberate augmentation to remain fit for purpose in the electrification era.

The principal contributions and recommendations arising from this research can be summarised as follows:

- Powertrain integration, regulatory certification, and supplier PPAP validation should be treated as fixed schedule anchors in automotive programme planning, warranting the most rigorous resource allocation, risk management, and executive-level schedule oversight from the concept phase onward.
- Electric vehicle programmes require dedicated scheduling competencies, distinct from those used for ICE platforms, that explicitly reconcile battery system development timelines, BMS software validation cycles, and evolving ADAS/SDV certification requirements with hardware milestone structures.
- Deterministic CPM should be augmented rather than replaced: integrating Design Structure Matrix (DSM) analysis exposes iterative rework loops before they reach the critical path, while Monte Carlo simulation at each programme gate provides P50/P80 completion probabilities that deterministic single-point schedules cannot.
- Hybrid CPM-Agile scheduling frameworks are needed to reconcile iterative, sprint-based software development with fixed-duration hardware milestones, addressing the single largest driver of EV schedule overrun identified in this study.
- Schedule compression decisions should follow a disciplined hierarchy: crashing is preferable for high-resource-elasticity, low-rework-risk activities such as physical testing; fast-tracking should be reserved for activity pairs with well-defined interfaces; and scope reduction of discretionary content should be evaluated before either is authorised.
- Proactive float management is essential given that 13-20% of programme activities sit at near-critical status across the platforms studied; explicit schedule reserves and active float monitoring are required to prevent near-critical activities from transitioning to critical status unnoticed.

- Early Supplier Involvement (ESI) programmes should be institutionalised for all critical-path Tier-1 suppliers, and should explicitly extend joint schedule visibility at least one tier deeper than current practice, given that the illustrative decomposition in Table 12 suggests a meaningful share of the two-to-four-week PPAP slip observed in this study originates upstream of the Tier-1 interface most OEM programme offices monitor.

- Structured regulatory engagement roadmaps - including pre-submission meetings and harmonised parallel-market filing strategies - should be established at the concept gate for programmes with complex or novel certification requirements, since regulatory activities proved the least crashable of any critical-path category.

- Future research should prioritise five extensions: validating these findings against actual OEM schedule archives; conducting genuine activity-level DSM analysis of iterative loops such as the chassis-powertrain-NVH example illustrated in Table 11; mapping multi-tier Tier-2/Tier-3 PPAP dependencies empirically rather than illustratively, as in Table 12; empirically testing hybrid CPM-Agile frameworks on live SDV programmes; and conducting longitudinal, multi-OEM comparisons of ICE, EV, and SDV programme durations, including India-specific empirical case studies that this study's global-benchmark design could not provide.

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