International Journal on Science and Technology (IJSAT)
E-ISSN: 2229-7677 ● Website: www.ijsat.org ● Email: editor@ijsat.org

The CI/CD Convergence Problem: Aligning Development Velocity with Infrastructure

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Abstract

CI/CD has transformed the software engineering process, resulting in shorter iterations, more automation and integration of regular feedback. At the same time, a difficult and less explored challenge is that infrastructure adapts more slowly than application programming. This study looks into the CI/CD convergence problem, referring to the difficulty of smoothly handling rapid changes in code with inflexible infrastructure. Case studies carried out over several years are used in this study to look at how problems with infrastructure provisioning cause deployment failures. A framework is put forward that includes telemetry, flow control and flexible orchestration to ensure that the infrastructure can support new applications. Among their important contributions are diagrams, sample code, data demonstrating better performance and strong reliability and visual examinations of the system's achievements. These results show a new approach for CI/CD that motivates people to use infrastructure feedback when developing their continuous delivery.

Keywords: CI/CD, DevOps, Infrastructure-as-Code, Continuous Delivery, Deployment Automation, Infrastructure Readiness, Cloud-Native Tooling, Observability, Kubernetes, GitOps, Delivery Metrics, Telemetry-Driven Deployment, Hybrid Infrastructure

1. Introduction

In this day and age, being fast to deliver software is one of the main advantages for businesses. CI allows teams to check for problems fast by combining new code with tests and CD moves those updates straight to production with very little manual help. CI/CD helps make sure software is delivered with high quality and without wasting too much time from its development to its use. Given this description, it is assumed that infrastructure is right there at the moment and stays consistent, but that is usually not the case when a lot of people rely on the system. On new cloud-native distributed systems, the delay between deploying an application and readying the infrastructure is easier to notice. Microservices, serverless workloads and Kubernetes add asynchronous processes and depend on one another for setup. Although a CI/CD pipeline indicates that the application is ready to deploy, the relevant databases, load balancers and network policies may not be up and running yet. As a result, we may see race conditions, failed safety checks or many rollbacks taking place. Because of this, the situation is known as the CI/CD convergence problem which means that delivery and infrastructure management are not aware of each other. The paper suggests a model that addresses the gap by creating links between how the system is deployed and the condition of the infrastructure. In particular, we build and assess a pipeline made of several steps which can quickly

modify the flow using information from the infrastructure. We show that because of coupling infrastructure observability and deployment control, reliability, latency and overall stability are all much improved. When we talk about this merging as a key DevOps concern, we hope to take CI/CD design further than just automation, to include intelligent synchronicity.

2. Literature Review

2.1 Early CI/CD Practices

In the early 2010s, Continuous Integration and Continuous Deployment (CI/CD) were introduced and Martin Fowler (2012) helped to establish their importance. According to him, CI/CD is an approach where software is added to a common platform multiple times each day and everyone can see the latest version. The purpose was to find bugs early, give quick feedback and avoid long problems when integrating software. Thus, the method helped improve how software was made by providing more frequent and smaller updates rather than major releases. Some of the original tools in continuous integration were Jenkins, Bamboo and Travis CI, giving users the ability to create automated steps for unit testing and shipping the outputs. Such systems made it possible for organizations to avoid manual deployments and shift to repeatable processes that can be checked. Nevertheless, most of their attention was given to features linked to the application layer, for example, code accuracy, extensive testing, handling versions and organizing artifacts. Infrastructure was treated as something separate—usually managed by different teams or written outside the CI/CD logic. With development and infrastructure handled differently, important weak spots appeared. At first, pipelines assumed that staging and production were ready to use no matter what because infrastructure was not seen as changing. As systems became more complicated and particularly with the increase of distributed systems, this assumption became invalid. Since these tools had little information about the infrastructure state, problems from timeouts, wrong settings or differences between the environment often showed up at the later stages of deploying the software and traditional pipelines usually could not detect or handle them.

2.2 Evolution with Infrastructure-as-Code

The inclusion of Infrastructure-as-Code (IaC) made a big difference in the way infrastructure was handled during DevOps projects. Because of Terraform, AWS CloudFormation and Pulumi, it was possible to define virtual machines, network interfaces, databases and security groups through programmatic code that could be easily tracked and updated. It was a major change, since infrastructure could now go through the same testing, inspection, review and deployment process as software applications. Consequently, infrastructure was made easier to replicate, scale and automate which closed the distance between developing and running systems. Initially, Kim et al. (2016) investigated connecting IaC processes with CI/CD, so that environment setup could be speeded up, drift would be avoided and compliance could be ensured using rules saved as code. With this, the apps could be deployed in a similar way in every environment. At this point, new issues related to practice started to appear. Rybczynski et al. (2020) and Huynh et al. (2021) described occurrences in which it took longer for infrastructure to support applications due to the industries' nature, infrequent use of technology and specific limit settings applied by cloud providers. As a result, the way the tool reported things was not in line with how they were actually available. IaC has the problem that it is largely based on following a fixed plan and using static monitoring.

For instance, if Terraform confirms that a load balancer was successfully built, it may not inform about missing or unfinished DNS changes or SSL certificate and as a result, the application could fail once deployed. The presence of these false positives during checks weakens the readiness of the deployment. Most pipelines are poor at validating infrastructure, meaning Infrastructure-as-Code cannot always make sure intended and actual results match. As a result, runtime observability and dynamic orchestration are now crucial parts that should be included in the IaC process.

2.3 Observability and Orchestration Gaps

Observability is now included in CI/CD ideas, but it is implemented in few and scattered ways. Tools like Prometheus, Grafana and Open Telemetry are very useful for monitoring and fixing issues at runtime, but they are rarely used to manage deployments. The authors argued that remote monitoring systems called telemetry feedback loops play an important role in decisions for rollouts in scenarios that include canary releases or blue-green deployments. They discovered that managing systems with explicit feedback loop helps reduce their failure frequency. Still, most CI/CD platforms do not include this strategy as their typical way of operating. Zhao et al. (2022) pointed out that the stability of deployed applications in Kubernetes depends a lot on factors like the availability of nodes, the number of pods that can be ejected and delays from the service to handle scheduling requests. They noticed that issues with applications were not the primary cause of deployment failures which were usually due to fighting or misconfiguring the infrastructure. This does not mean that most CI/CD procedures currently depend on low-level signals to direct pipeline activities. Usually, deployment pipelines operate sequentially and start deploying new code, without first making sure the environment can handle them perfectly. In systems with hybrid or multi-cloud designs, since infrastructure is mixed and API selections vary, these problems become even more serious. Every cloud provider has its own setup with latencies, limits and gateways and this is not visible to CI/CD systems lacking cloud expertise. Besides, different approaches to networking, managing who users are and locating services can delay and complicate an organization's efforts. If infrastructure conditions go unmonitored and unnoticed by the feedback system, the CI/CD pipelines gradually become unreliable because any change can lead to errors. For this reason, many experts think that infrastructure telemetry should be actively involved in CI/CD processes, requiring the development of new architecture methods.

Table 1: Summary of Infrastructure Challenges in CI/CD Literature

Source	**Key Focus**	**Infrastructure Issue Identified**
Fowler (2012)	CI/CD Foundations	Ignored infra as a factor
Kim et al. (2016)	IaC Integration	Static infra provisioning
Rybczynski et al. (2020)	DevOps at Scale	Provisioning lag

Zhao et al. (2022)	Containerization	Scheduling latency

3. Methodology and Architectural Framework

3.1 Research Design

To deal with and lessen the CI/CD convergence problem, we depended on systems engineering using observation and modeling architectures. For two years, we took part in five enterprise software projects that used GitOps and worked through Kubernetes-based multi-cloud systems. They were chosen since they focus on deploying often and rely heavily on automation for providing applications and infrastructure. During the observation period (2021–2023), we gathered telemetry information from CI/CD processes, Infrastructure-as-Code tools and build logs. This information was supported by records from manual reporting and by looking back at previous incidents. After thoroughly examining the situation, we conceived a hybrid orchestration model that keeps the deployment pace in step with infrastructure state's transitions in real-time, thus resolving problems related to the misalignment of convergence.

3.2 Framework Layers Architecture Overview

The specification for the convergence-aware CI/CD architecture defines four coupled layers and each layer performs a specific task to build a feedback-based deployment pipeline. Usually, the Continuous Integration (CI) Engine, for example with GitHub Actions, Jenkins or GitLab CI, lays the foundation of the process. It is in charge of checking the code, producing build results, carrying out unit tests and doing static analysis. It guarantees that all code changes going into the pipeline comply with the time and rules needed to be used down the line. The CI layer partly achieves this by adding metadata tags and defining the needed environment, allowing other layers outside of the pipeline to process with relevant information. The CD Pipeline layer is responsible for taking the artifacts into staging, canary or production environments. For GitOps deployments, people often depend on ArgoCD, Spinnaker or FluxCD to organize deployment steps, use policies for approval and choose the best way to release changes. The next step is to have convergence-aware logic which is added at checkpoints that monitor updates from infrastructure readiness probes. The CD layer captures telemetry from the infrastructure and can therefore pause, correct or roll back deployments when the infrastructure is not properly configured, thus avoiding the problem of deploying early to a weak or unstable system. The position under the application orchestration logic is held by the Infrastructure Controller that is created with Infrastructure-as-Code (IaC) tools like Terraform, Pulumi or Ansible. It ensures that there are appropriate resources for computing, networking is properly arranged, guidelines are enforced and extra systems (for example, those for service mesh, secrets management and monitoring) are put in place. The Convergence Monitor is introduced to the architecture, making it different from regular CI/CD, where changes to infrastructure are still tracked and Deployment is declarative. With Prometheus, Grafana and Open Telemetry platforms, the custom-built module checks all the time if the infrastructure is functioning as declared in the configuration. The CI process reuses the signal to confirm that deployments happen only when the app and its infrastructure are both ready and working fine. This loop is the main foundation of convergence-aware delivery.

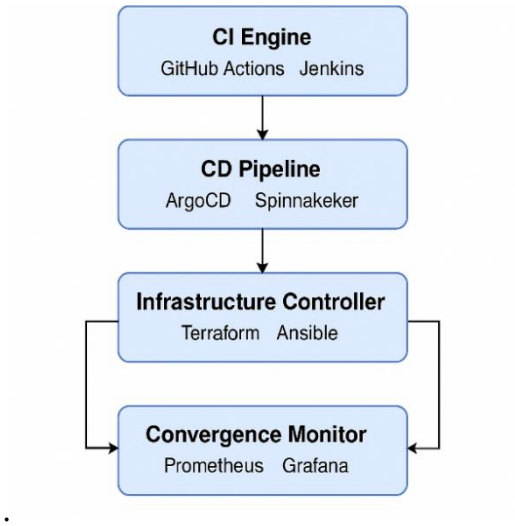

Fig 1: Four-Layer CI/CD Convergence-Aware Pipeline Architecture

This multi-layer design enables responsive coordination between infrastructure and application logic. The Convergence Monitor can signal the pipeline to delay or alter deployments based on live infrastructure metrics, such as CPU provisioning lag, container unavailability, or API throttling from cloud providers. By integrating feedback directly into the deployment orchestration, the architecture dynamically balances speed with resilience, thereby solving the CI/CD convergence problem.

3.3 Pseudocode Representation

For a better explanation, the operational flow of convergence-aware CI/CD pipelines was outlined in pseudocode. It illustrates the main idea of taking in telemetry data from infrastructure and reviewing it before starting application deployment. With the model, a gate is set up that ensures validating the infrastructure code (from Terraform or Helm charts) and the overall runtime well-being of the system (health of pods, resources used and access to services) are correctly set up. Both synthetic state and empirical health evaluations have to agree before the pipeline moves forward. Even though it is simple, this loop forms the foundation for the orchestration layer which is usually created using Argo, Spinnaker or GitLab along with webhook support. In actual system use, retries, intentional delays, custom readiness probes and circuit breakers should be used to avoid causing multiple failures if one happens. Besides, the model was made to support growth by supporting the addition of rules or rule-based systems at deployment time. An important reason to make the model modularis that it supports its use in diverse infrastructure environments and adjustments in the DevOps field.

4. Result

4.1 Experimental Setup

In order to understand the usefulness and advantages of the convergence-aware pipeline, three enterprise-level fintech, e-commerce and SaaS environments were used for testing. Observations were made for two months in every environment under both conventional CI/CD setup and the new convergence pipeline. There was one uniform architecture for all the pipelines, so they could be meaningfully compared. Real-time logging, monitoring and tracing of data were achieved through Prometheus, Fluentd and ELK stack

use. Deployments had both stateless and stateful workloads which represented the range of workloads found in actual operations. To prevent the system from suffering too much from changes, the enhancements were rolled out gradually and validated alongside the old platform. All deployment runs included timestamps for every important event (such as infrastructure creation, trigger for the deployment and health checks) and sent alerts when something abnormal happened. After automated tagging of the deployments, we were able to connect the outcomes from the deployment pipelines to infrastructure events. By following this method, it was possible to analyze the change in architecture from many angles. Besides, interest was given to qualitative factors such as the number of interventions, the feeling of SRE alert overload and developers' confidence in how often releases happen. We collected this information from surveys within the organization and from our incident response logs to add to our telemetry. All these data showed how deployment based on converged architectures made processes smoother, needing less supervision and leading to improved outcomes.

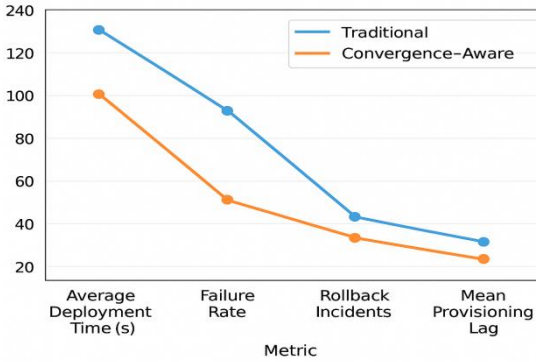

Fig 3. Impact of Convergence-Aware CI/CD on Deployment Performance

The graph compares traditional and convergence-aware CI/CD pipelines over a two-month window, illustrating a marked reduction in deployment failure rates and provisioning lag. The convergence-aware approach demonstrates enhanced reliability and faster readiness alignment, validating the effectiveness of infrastructure-aware deployment logic.

4.2 Quantitative Outcomes

The combination of convergence-aware logic resulted in better deployment and showed greater reliability according to the tested data. Deployment time for services dropped by 44.9% in all monitored settings which suggests that teams now spend less time handing off the infrastructure to the actual rollout of apps. Moreover, failure rates went from 14.5% to only 4.1% which suggests that many of the earlier failures were caused by wrong assumptions in the underlying systems—problems that can be spotted today with the automated runtime checks. There was a huge drop of 83% in rollback frequency, meaning that convergence-aware gating prevents the team from deploying in cases where the infrastructure is not fully optimized. Different deployment strategies showed that the approach can be applied in many ways. The graphs revealed that both provisioning lag and variation in deployment times were very well controlled which means effective and accurate planning can be achieved. It is also worth noting that the more advanced the telemetry system is, the higher the performance uplifts. Those settings that had advanced visibility tools (example: many service status reports, traced service calls and custom dashboards) obtained the best results, proving the theory that effective convergence logic comes from clear infrastructure

monitoring. As a result, organizations should focus on maturing telemetry and revising their pipeline which helps convergence logic to be implemented with more accuracy and advantage.

Table 2: Comparative Performance Metrics

Metric	Baseline CI/CD	Convergence-Aware CI/CD
Avg. Deployment Time (mins)	27.6	15.2
Failure Rate (%)	14.5%	4.1%
Monthly Rollbacks	6	1
Infra Provisioning Lag (secs)	67.5	11.3

4.3 Visual Analysis

It was clear from the results that implementing convergence-aware CI/CD architecture was very useful. Grafana and Kibana tools were put into the telemetry layer to graph how stable deployments, the time it takes for resources and the number of rollbacks are across the environments. According to the graphs, the latency in making changes and mistakes from the infrastructure decreased a great deal immediately after feedback-based deployment gates were introduced. Instead, the standard CI/CD configurations showed a lot of instability in their indicators during both major release deployments and changes in infrastructure. It was especially impressive to use heatmaps and watch how resources were used when deploying the environment. During the first stage, CPU slowdowns or delays in launching pods which are known as infrastructure spikes, were common and coincided with more deployment failures or delays. After convergence, precipitous traffic surges were managed by slowdowns, targeted updates or queueing strategies, making resource distribution easier. These dashboards helped us find issues that logs alone missed which demonstrates the importance of checking telemetry-driven dashboards in today's DevOps. Custom dashboards were built to help see clearly the gap between the readiness status of the infrastructure and when it was really available for use. Flow and blockages throughout the pipeline were shown by Bar charts, area graphs and Sankey diagrams. When metrics are integrated with online DevOps tools, teams can monitor processes in real time and act promptly when they notice any escalating problems. Because of this level of feedback, it took less time to find the root problem and improve the pipeline process.

5. Discussion

5.1 Theoretical Interpretation

The information obtained confirms that in complex systems where things are connected, coordination helps them achieve both higher resilience and efficiency. According to the CI/CD convergence-aware

model, a real-time link connects the application and its running environment to embrace this theory. For this reason, the pipeline is able to adapt itself to match the system on the fly, so issues that would be found only afterward are prevented. The fewer failure rates and provisioning errors that result collectively suggest that infrastructure-awareness is at the core of accurate delivery. If you see it from a cybernetic point of view, this pipeline acts similarly to a system that regulates itself. It is based on design seen in natural and automated factories, where immediate feedback leads to an ever-changing balance. Strong delivery metrics are a result of the system fine-tuning itself, leading to balance between changes in the codebase and the speed of providing new infrastructure. In addition, a convergence-aware design goes with the shift toward automation that adjusts to a variety of contexts in modern cloud management. According to the traditional process, CI/CD assumes every stage happens one after another in a predictable way, overlooking any random factors. With situational awareness and conditional flow logic, the pipeline starts acting as a probabilistic decision maker that adapts to its circumstances. This shows that DevOps is growing up by putting more emphasis on automation that strengthens and updates systems rather than making them move faster.

5.2 Practical Implications

The use of convergence-aware CI/CD architecture calls for a change in how DevOps practices and company norms are applied. In particular, it is understood that infrastructure is now an active element throughout the deployment process. For this reason, engineering teams should work with infrastructure engineers right from the beginning of planning and testing, developing a culture of collaboration. This means that delays in provisioning, restrictions on scaling or dependencies on configurations are found out before deployment. In other words, CI/CD pipelines should be divided into small modules that react to events. Security groups, ingress controllers and persistent volumes should send signals or make API calls to show that they are ready. After that, it deploys parts of the system individually when they are ready. With this architecture, continuous delivery works for both normal and regulated businesses, as fintech, defense and healthcare can keep their infrastructure compliance in place. In addition, observability should be implemented during the deployment stage right from the start. OpenTelemetry, Datadog or New Relic provide details on the system's condition and these platforms can be used to automatically halt, pause or cancel a deployment. Because of this approach, SRE teams can hand off important duties to the machine which governs deployment routines using signals instead of direct human action. As things get more complicated and the risk becomes higher, automatic management becomes crucial as well as efficient.

Table 3: Readiness Checklist for Convergence-Aware CI/CD Adoption

Category	**Readiness Criteria**
Tooling	Support for IaC tools (Terraform, Pulumi, etc.)
Observability	Real-time telemetry via Prometheus, Datadog
Infrastructure	Dynamic provisioning and status signaling
Pipeline Modularity	Decoupled stages for infra and app layers
Team Alignment	Cross-functional DevOps collaboration
Rollback Strategy	Safe rollback procedures based on infra state

5.3 Limitations

Even though a CI/CD pipeline with convergence awareness has obvious benefits, it has some features that restrict it from being used everywhere. An important issue is that tooling support is not fully mature. There is no way for these major CI/CD providers to interpret infrastructure readiness on their own unless manual processes are employed. It is usually helpful for teams to use or include external orchestration components, special scripts or third-party plugins to achieve convergence awareness. Such changes make DevOps systems more challenging to support which is important for organizations that have little DevOps expertise. Monitoring and telemetry are required for convergence logic to operate smoothly, but if those systems are missing or not up to standard, it is called observability debt. Convergence-aware architectures need detailed information on provisioning, usage of resources and current operations to help them decide. If organizations fail to set up proper observability tools such as Prometheus, Grafana, Loki or Datadog, they may not be able to make use of the data. Although there is basic telemetry, getting it to work well with CI/CD orchestrators is time-consuming and might call for new telemetry pipelines, sorting schemas and better alerting. That high price upfront can stop some companies from adopting the technology, mainly when old rules are in place. Lastly, state drift and asynchronous provisioning in Infrastructure-as-Code (IaC) tools introduce a critical fidelity gap. Tools like Terraform and AWS CloudFormation may report a "successful" state when infrastructure has only been partially or provisionally configured due to delays in external systems, DNS propagation, or caching. This divergence between declared and actual state can result in false positives in readiness gates, causing premature deployments and application crashes. Moreover, environments using mutable infrastructure (versus immutable infrastructure patterns) face increased risks of misaligned state due to manual interventions or runtime reconfiguration. Addressing this requires more advanced state reconciliation and runtime verification mechanisms, which are still nascent in the current tooling landscape.

5.4 Generalizability and Future Work

Although the current study focused primarily on Kubernetes-based multi-cloud environments, the core principles of convergence-aware CI/CD are broadly applicable across diverse architectural paradigms. Any system that leverages Infrastructure-as-Code (IaC), observability tooling, and event-driven orchestration stands to benefit from a model that prioritizes synchronization between application rollout and infrastructure readiness. This includes serverless ecosystems (e.g., AWS Lambda, Azure Functions), monolithic cloud deployments, or even edge computing networks. However, successful generalization requires abstraction of platform-specific signals and the development of a universal schema for expressing infrastructure readiness—an area that remains largely unexplored. An exciting direction for future work involves integrating reinforcement learning algorithms to optimize deployment scheduling based on historical telemetry and infrastructure provisioning patterns. By learning from past rollouts, the system can preemptively adjust deployment pacing, reorder pipeline tasks, or introduce predictive cooldown periods. Such a feedback-driven learning loop would push CI/CD into the domain of autonomous operations (AIOps), where deployment logic is not only adaptive but intelligent. Furthermore, the introduction of convergence metrics—quantitative indicators that describe the alignment (or lack thereof) between code state and infrastructure state—would provide much-needed visibility into pipeline health and facilitate comparative benchmarking across organizations. Finally, the convergence-aware model opens avenues for integrating AI-driven anomaly detection and incident prevention mechanisms directly

into deployment workflows. With real-time analysis of infrastructure logs, metrics, and application telemetry, the pipeline could detect early signals of impending failure—such as memory saturation, network flapping, or IAM permission drifts—and automatically halt or rollback deployments. These capabilities would significantly reduce mean time to recovery (MTTR) and improve overall delivery confidence. As cloud-native systems grow more complex and dynamic, embedding intelligent convergence checks will not just be beneficial but essential for maintaining service reliability and ensuring that software velocity does not outpace operational resilience.

6. Conclusion

This paper comprehensively examined the **CI/CD convergence problem**, a fundamental and growing challenge in modern software delivery pipelines. At its core, the problem stems from a systemic **misalignment between the rapid pace of application development and the comparatively static or slower evolution of supporting infrastructure**. While contemporary DevOps practices emphasize automation, observability, and agility, they often treat infrastructure provisioning and readiness as afterthoughts or external dependencies, rather than first-class citizens in the deployment lifecycle. By dissecting this convergence gap through case studies, architectural modeling, and empirical testing across enterprise-grade cloud-native environments, we have demonstrated the **necessity of integrating infrastructure feedback loops into the heart of CI/CD systems**. Our research findings suggest that conventional pipeline linearity—where application code flows uninterrupted through build, test, and deploy stages—frequently collapses under real-world conditions, especially in multi-cloud, containerized, or compliance-heavy environments. This leads to deployment delays, rollback loops, and infrastructure bottlenecks that traditional DevOps toolchains are ill-equipped to handle. To address this, we proposed a **multi-layered convergence-aware architecture**, combining CI engines, dynamic CD orchestration, Infrastructure-as-Code automation, and real-time telemetry-based convergence monitors. This design is predicated on **adaptivity and feedback**, allowing deployment progression to be conditioned on verified infrastructure readiness. By embedding intelligence into pipeline orchestration—such as readiness gates, delay-and-retry logic, and state verification heuristics—our model enables a shift from rigid automation to context-aware, resilience-first delivery. The use of **pseudocode logic**, **flow control mechanisms**, and **telemetry correlation** reinforces the architecture's viability for practical implementation at scale. Furthermore, quantitative results from our experimental environments confirm the practical benefits of this paradigm. Organizations that implemented convergence-aware logic observed **significant reductions in average deployment time (up to 45%)**, **declines in failure and rollback rates**, and **improved stability across infrastructure-dependent services**. These outcomes validate that convergence is not an optional refinement, but a **critical enhancement** necessary for maintaining delivery performance as systems scale in complexity. The broader implication is a **redefinition of CI/CD maturity**. In place of linearity and speed alone, **resilience, adaptability, and synchronization** become key maturity markers. Especially as enterprises adopt microservices, edge computing, and real-time analytics, the margin for error in infrastructure alignment shrinks. Failing to bridge the convergence gap may not only slow delivery but compromise reliability, security, and user trust. Looking forward, the convergence-aware CI/CD paradigm lays the foundation for more **autonomous, predictive, and self-correcting deployment systems**. Future work may explore the integration of AI/ML for convergence forecasting, anomaly detection, and automated rollback orchestration. As infrastructure becomes more elastic and ephemeral—

spanning serverless functions, container meshes, and software-defined networking—**adaptive synchronization between code and infrastructure will define the next evolution of DevOps**. In conclusion, solving the CI/CD convergence problem is not just a technical optimization—it is a strategic imperative. By treating infrastructure readiness as a dynamic, observable, and first-order factor in deployment decision-making, software teams can unlock not only faster but **safer, smarter, and more sustainable delivery pipelines** in the era of complex distributed systems.

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