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Temperature Excursion Risk Window in Pharmaceutical Air Cargo

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Research Article

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Abstract

Purpose

This paper challenges the prevailing flight-phase bias in pharmaceutical air cargo cold chain research by identifying the ground transfer dwell period — between aircraft offload and temperature-controlled facility re-entry — as the primary and systemically undermonitored thermal risk window in international pharmaceutical shipments.

Design/Methodology/Approach:

A practitioner observation methodology is applied across three professional lenses spanning 19 years of multi-carrier air cargo experience: airfreight operations at DHL, commercial pricing at DB Schenker, and route-level data analytics at Turkish Airlines Cargo. Secondary analysis incorporates IATA, FDA, and carrier performance datasets.

Findings:

Ground transfer events — unscheduled apron dwell, non-conditioned pre-departure staging, and customs clearance dwell at U.S. ports of entry — account for a disproportionate share of temperature excursion events in multi-leg pharmaceutical shipments. A commercial pricing mechanism, documented from DB Schenker pricing executive experience, incentivises multi-stop routing that systematically multiplies ground transfer exposure. The South Asia pharmaceutical corridor, characterised by FDA import alert risk and Gulf hub routing, presents the most thermally vulnerable supply chain profile in the global air cargo network.

Practical Implications:

Carrier-agnostic, integrated monitoring platforms that connect predictive delay intelligence with container thermal tolerance calculations represent the necessary evolution beyond flight-phase-centric cold chain management.

Originality/Value:

This paper provides the first practitioner-grounded identification of ground transfer dwell time as the dominant pharmaceutical cold chain failure window, combining operational observation, commercial pricing intelligence, and data analytics in a methodology not replicable from secondary sources.

INTRODUCTION

The Scale of the Problem

Air cargo is indispensable to the global pharmaceutical supply chain. Medicines, vaccines, biologics, and cell and gene therapies share physical requirements — time-sensitivity, temperature control, and regulatory documentation integrity — that make air the only viable mode for the highest-value and most clinically critical segment of pharmaceutical logistics. The International Air Transport Association documented that pharmaceutical product losses during air transport attributable to temperature excursions exceeded $35 billion globally between 2020 and 2024. In the United States, the Food and Drug Administration has issued repeated guidance emphasising the fragility of cold-chain logistics, noting that a single temperature excursion during a transoceanic journey can render an entire consignment of biologics clinically unusable.

The commercial stakes are intensifying. DHL Group announced in February 2026 a €2 billion strategic investment in its airfreight cold chain network, including a dedicated Boeing 777 freighter service between Brussels and Cincinnati — an investment explicitly justified by the need to reduce reliance on third-party commercial airlines and to exert direct control over the handling chain to minimise temperature excursion risk (DHL Group 2026). This investment, one of the largest single commitments in the history of pharmaceutical logistics infrastructure, acknowledges the severity of the current failure rate and the insufficiency of existing monitoring architectures.

Yet despite the scale of the problem, a fundamental analytical gap persists in both academic literature and industry practice: where, specifically, in the pharmaceutical air cargo handling chain do temperature excursions predominantly occur? The answer to this question determines the optimal architecture of any monitoring or intervention system — and it can only be answered fully from the perspective of someone who has been physically present in the handling chain at the acceptance counter, on the apron, in the cargo facility, and in the data analytics function simultaneously.

The Literature Gap: Flight Phase Bias

The academic literature on pharmaceutical air cargo cold chain management exhibits a consistent and documentable bias toward the in-flight phase as the primary thermal risk window. Wang and Chen (2023) in their landmark study on multivariate delay prediction focused on departure and transit delays as the primary driver of thermal exposure. Nguyen et al. (2021) defined delay in terms of flight departure and arrival timing in their Long Short-Term Memory (LSTM) model for cargo delay prediction. Even IATA's CEIV Pharma certification framework — the most widely adopted pharmaceutical cold chain quality standard in the air cargo industry — directs the majority of its infrastructure and process requirements toward in-flight container management and facility temperature control during flight preparation.

This flight-phase bias is understandable in historical context: early pharmaceutical cold chain failures involved inadequate in-flight temperature control on converted passenger aircraft. But the operating environment of 2026 is fundamentally different. Modern wide-body freighters and dedicated pharmaceutical carriers — including Turkish Airlines Cargo's SMARTIST-based operations and DHL's

expanded dedicated freighter network — have largely solved the in-flight temperature management problem for carriers that have made the requisite infrastructure investment. The remaining temperature excursion risk has migrated to the ground. Specifically, it has migrated to the dwell time that pharmaceutical cargo experiences during the transfer between aircraft and temperature-controlled ground facility — a window that existing monitoring architectures, regulatory frameworks, and academic research have systematically underaddressed.

Research Objectives and Contribution

This paper pursues four objectives grounded in 19 years of multi-carrier air cargo industry experience: (1) to identify and document the ground transfer dwell period as the primary pharmaceutical cold chain failure point, drawing on direct operational observation from DHL airfreight operations and data analytics evidence from Turkish Airlines Cargo; (2) to analyse the commercial pricing dynamics — observed through DB Schenker pricing executive experience — that incentivise multi-stop pharmaceutical routing and systematically extend cumulative ground transfer dwell time exposure; (3) to examine the South Asia pharmaceutical air cargo corridor as a case study for the interaction between route complexity, ground transfer risk, and data-measurable performance patterns; and (4) to propose a practitioner-informed monitoring architecture that addresses the ground transfer gap through integrated predictive delay intelligence and carrier-agnostic sensor continuity across the airside-to-landside transition.

The paper's primary contribution to the literature is the identification of ground transfer dwell time as the dominant pharmaceutical cold chain failure window — a finding grounded in operational observation that no simulation-based or secondary-data study can produce, and that has direct implications for the design of next-generation pharmaceutical cold chain management systems.

LITERATURE REVIEW

Pharmaceutical Cold Chain Economics

The economic dimensions of pharmaceutical temperature excursion events are well established. McKinsey & Company (2023) documented that supply chain disruptions cost the average Fortune 500 company 45 percent of one year's profits over a decade — a figure with acute relevance to pharmaceutical manufacturers whose air cargo dependence makes them among the most exposed to logistics disruption costs. IATA's documentation of $35 billion in pharmaceutical losses between 2020 and 2024 attributable to temperature excursions during air transport provides the industry-level financial context within which individual carrier and forwarder cold chain failures must be assessed.

The clinical consequences extend beyond direct financial loss. A temperature excursion that renders a consignment of oncology biologics unusable does not merely destroy product value — it delays treatment for patients whose clinical outcome is time-dependent. The FDA's Drug Shortage Prevention Plan (2023) identified logistics disruptions, including cold chain failures, as contributing factors in 38

percent of the 295 active drug shortage events documented in 2022 and 2023. This clinical consequence dimension elevates pharmaceutical cold chain management from a commercial logistics problem to a public health infrastructure challenge with genuine national importance implications.

The Reactive-to-Predictive Transition

Academic literature on pharmaceutical cold chain monitoring has evolved through three successive paradigms. The first paradigm — passive monitoring — was characterised by paper-based temperature logs reviewed after delivery. The second paradigm — active IoT monitoring — is now industry standard, with platforms including Sensitech, Tive, Emerson, and Berlinger providing real-time temperature and humidity logging throughout the pharmaceutical supply chain. The third paradigm — predictive monitoring — represents the current frontier, with academic work by Nguyen et al. (2021) and Wang and Chen (2023) demonstrating that machine learning models can predict temperature excursion risk from delay probability scores, weather forecasting data, and route characteristics with 78 to 84 percent accuracy at the 48-hour horizon.

The transition from reactive to predictive is significant — but the literature's focus on flight departure delay as the primary predictor reflects the flight-phase bias noted in Section 1.2. Ground transfer dwell time — the variable that this paper argues is the dominant thermal risk factor — does not appear as an independent predictor variable in any of the leading published delay prediction models. It is subsumed within total transit time calculations rather than isolated as a discrete and disproportionately high-risk phase.

Ground Handling Infrastructure and Cold Chain Continuity

The literature on ground handling infrastructure and cold chain continuity is smaller but growing. Merkert and Ploix (2022) examined the relationship between airport ground handling quality and pharmaceutical cargo temperature integrity across 12 major European hubs, finding significant variance in excursion rates that correlated with facility infrastructure investment levels rather than flight duration. Wang et al. (2021) documented that pharmaceutical cargo on routes with more than two connections experienced excursion rates 2.3 times higher than equivalent direct routing — a finding consistent with cumulative ground transfer dwell time exposure as the primary risk variable.

However, no published study has examined ground transfer dwell time as an independent, measurable variable using data from the carrier operations perspective. The studies that exist draw on pharmaceutical manufacturer supply chain audit data or customs clearance records — neither of which captures the precise transfer timing between aircraft offload and cold room re-entry that a ground operations professional observes directly. This is the methodological gap this paper addresses.

South Asia Pharmaceutical Air Cargo Corridor

South Asia — and specifically India — occupies a structurally important position in the global pharmaceutical air cargo network that the literature has not adequately captured. India is the world's third largest pharmaceutical producer by volume and the supplier of approximately 20 percent of global generic medicine exports (IPA 2024). The South Asia to United States air cargo corridor is characterised by multi-stop routing through Gulf carrier hubs, extended customs clearance dwell times at U.S. designated pharmaceutical ports of entry, and significant yield pressure from the dominance of Gulf carrier capacity on South Asia lanes. These structural characteristics create a specific and documentable cold chain risk profile that has not been analysed from the perspective of a data analyst working within the carrier network serving this corridor.

METHODOLOGY

Research Approach

This paper employs a practitioner observation methodology — a research approach that draws systematically on the structured professional experience of the lead author across four air cargo organisations over 19 years, supplemented by secondary analysis of published industry datasets, regulatory documents, and academic literature. This methodology is appropriate for research questions that require operational knowledge unavailable from secondary sources, consistent with established precedents in logistics and supply chain management research for knowledge residing in tacit operational experience (Mangan and Lalwani 2008; Flick 2018).

The practitioner observation framework structures the lead author's professional experience across three distinct analytical lenses:

DHL Airfreight Operations Lens: Direct operational observation of pharmaceutical cargo handling protocols, temperature monitoring device deployment and recovery, excursion event identification and response procedures, and ground transfer workflows across DHL's airfreight network. This lens provides the operational ground-truth evidence for the ground transfer dwell time hypothesis.

DB Schenker Pricing Executive Lens: Commercial intelligence on pharmaceutical cargo rate structures, client routing decisions under cost pressure, and the pricing dynamics that create incentives for multi-stop pharmaceutical routing. This lens provides the commercial mechanism explanation for why ground transfer risk accumulates in practice.

Turkish Airlines Cargo Data Analytics Lens: Quantitative analysis of route-level pharmaceutical yield data, South Asia trade corridor performance metrics, and the correlation between route characteristics and cargo quality outcomes. This lens provides the empirical data analytics evidence that contextualises and validates the operational observations.

Secondary Data Sources

The practitioner observation framework is supported by secondary analysis of the following published data sources: IATA World Air Transport Statistics (2024 and 2025 editions); IATA Air Cargo Market Analysis monthly reports (2023–2025); FDA Drug Shortage Prevention Plan (2023); IATA CEIV Pharma certification requirements; DHL Life Sciences and Healthcare Annual Report (2025); Turkish Airlines Cargo operational performance reports and SMARTIST facility documentation; LogiPharma survey data (2025 and 2026); and academic literature as cited throughout.

The Ground Transfer Dwell Time Hypothesis

The central hypothesis of this paper is formally stated as follows: in international pharmaceutical air cargo shipments involving at least one transit connection, the ground transfer period between aircraft offload at the transit hub and re-entry into the temperature-controlled cargo facility constitutes the primary thermal risk window — exceeding in-flight thermal risk across the full journey population of pharmaceutical shipments currently moving through the global air cargo network.

This hypothesis emerges directly from operational observation at DHL. In practice, the pharmaceutical air cargo handling chain is constructed as follows: origin cold room → pre-flight staging → aircraft loading → in-flight storage → aircraft offload → apron transfer → transit hub warehouse → customs processing → onward flight staging → repeat for each leg → destination offload → apron transfer → destination cold room → final delivery preparation. Each transition in this chain represents a potential thermal exposure event. The in-flight segments — which receive the primary focus of academic and regulatory attention — are in modern wide-body cargo aircraft the most thermally stable segments of this chain. The apron transfer and transit hub warehouse segments — which receive the least monitoring attention — are consistently the least thermally controlled.

FINDINGS: THE GROUND TRANSFER GAP

Where Temperature Excursions Actually Occur: Operational Evidence

The lead author's experience in DHL airfreight operations provides direct observational evidence for the ground transfer dwell time hypothesis. Three categories of ground transfer event present disproportionate thermal risk in the pharmaceutical handling chain as it operates in practice.

Category 1 — Unscheduled Aircraft-to-Facility Transfer Delay: When a pharmaceutical shipment is offloaded from an aircraft at a transit hub, its transfer to the temperature-controlled cargo facility is dependent on ground handling resource availability. During peak hub congestion periods — which at major cargo hubs including Cincinnati, Memphis, and Louisville can extend across multiple daily operating windows — pharmaceutical cargo may remain on the apron or in an untempered staging area for periods ranging from 30 minutes to several hours before facility re-entry. During this period, the pharmaceutical container's passive insulation — designed for the predictable thermal environment of a pressurised cargo hold, not for summer ground temperatures that can exceed 35°C or winter conditions below − 15°C — may be inadequate to maintain the product's specified temperature range.

Category 2 — Pre-Departure Staging in Non-Conditioned Areas: At many regional and secondary cargo airports, pharmaceutical cargo awaiting onward connection flights is staged in general cargo warehouses rather than dedicated temperature-controlled pharmaceutical zones. The Good Distribution Practice (GDP) framework specifies temperature control requirements at pharmaceutical handling facilities, but the definition of 'handling' is applied inconsistently to short-duration pre-departure staging. A pharmaceutical shipment staged for two to four hours in a 28°C general warehouse while awaiting its onward connection is experiencing a thermal exposure event not captured as an excursion by IoT sensor logs only if the container's passive insulation holds internal temperature within specification — an assumption that becomes increasingly unreliable as staging duration extends.

Category 3 — Customs Clearance Dwell Time at U.S. Ports of Entry: The South Asia pharmaceutical corridor — India to United States — routinely involves customs clearance dwell times at U.S. designated ports of entry that represent one of the highest thermal risk segments in the entire journey. CBP's Automated Commercial Environment (ACE) system documents average customs clearance dwell times for pharmaceutical commodity codes at major U.S. import airports. From operational experience at DHL, customs dwell times for Indian pharmaceutical exports at certain U.S. entry points can range from 4 to 18 hours depending on documentation completeness, random examination selection, and FDA import alert status. During this dwell period, the pharmaceutical shipment is in CBP custody — outside the carrier's operational control and often in a customs examination area with no guaranteed temperature control infrastructure.

The Commercial Pricing Driver: DB Schenker Perspective

The ground transfer dwell time hypothesis is reinforced by a commercial pricing dynamic observed directly as a DB Schenker pricing executive. In the pharmaceutical air cargo market, forwarder pricing for international shipments is structured around carrier rate levels that vary significantly between direct routing and multi-stop connections through transit hubs. For a typical Indian pharmaceutical manufacturer exporting biologics to the U.S. East Coast, a direct routing through a Gulf carrier hub with a single transit stop may be priced 15 to 25 percent higher than a multi-stop routing that connects through two or three intermediate points.

Under cost pressure — universal in pharmaceutical logistics procurement, where competitive tender processes drive continued rate reduction — pharmaceutical clients regularly select the lower-cost multi-stop routing. Each additional connection adds one additional ground transfer dwell event to the thermal risk profile of the shipment. To the authors' knowledge, this commercial pressure mechanism has not been previously documented in the academic literature on pharmaceutical cold chain management. It requires simultaneous visibility into the pricing negotiation room and the cargo facility floor — a combination of perspectives that the lead author's career provides uniquely.

The South Asia Corridor: Analytics Evidence

The lead author's data analytics role at Turkish Airlines Cargo provided quantitative context for the ground transfer dwell time hypothesis within one of the most commercially significant pharmaceutical trade corridors globally. India's pharmaceutical export growth to the United States accelerated significantly post-COVID-19, driven by the U.S. government's pharmaceutical supply chain diversification priorities under Executive Order 14017 (Biden 2021). Route-level analytics for the South Asia to U.S. pharmaceutical corridor reveal structural characteristics that amplify the ground transfer risk factors identified above.

The corridor is dominated by Gulf carrier capacity — Emirates SkyCargo, Qatar Airways Cargo, and Turkish Airlines Cargo — all routing through major Middle East hub airports. Istanbul Airport's SMARTIST facility handles South Asia pharmaceutical transshipments through its 9,000 square metre Temperature Controlled Centre (Turkish Airlines Cargo 2025). However, smaller volumes routing through Doha and Dubai transit through facilities with variable pharmaceutical handling infrastructure quality.

For U.S. regulatory purposes, Indian pharmaceutical exports face an additional customs clearance risk factor that amplifies ground transfer dwell time: FDA Import Alert status. Indian pharmaceutical manufacturers with active FDA compliance issues are subject to detention without physical examination on import — a process that can extend U.S. customs dwell time from the standard 4 to 8 hours to 24 to 72 hours. The intersection of FDA detention risk with the multi-stop routing commercial incentive creates the highest-risk pharmaceutical cold chain profile in the global air cargo network — and it is concentrated in a trade corridor that is a primary market for South Asian carriers including Turkish Airlines Cargo.

DISCUSSION

Redesigning the Monitoring Paradigm

If the ground transfer dwell period is the primary thermal risk window — as the operational, commercial, and analytical evidence presented in this paper suggests — then the current monitoring paradigm requires fundamental redesign. IoT sensor-based cold chain monitoring platforms that provide continuous temperature logging throughout the journey correctly capture the in-flight data. But the critical question is not whether data is being logged — it is whether the monitoring architecture includes predictive intelligence that anticipates ground transfer exposure risk before it materialises.

The distinction is significant. A monitoring system that logs an excursion at hour 14 of a 16-hour journey provides documentation for post-delivery dispute resolution. A monitoring system that predicts, at hour 8, that the shipment's scheduled routing through a congested hub will expose the container to an estimated six-hour ground transfer dwell period — and that the container's remaining thermal tolerance makes this dwell period likely to produce an excursion — provides actionable foresight that enables rerouting before the excursion occurs. This is the difference between a reactive monitoring paradigm and a predictive one.

The Carrier-Agnostic Integration Requirement

The ground transfer dwell time problem is inherently a multi-carrier problem. A pharmaceutical shipment moving from Mumbai to New York via Istanbul or Dubai involves handling by at least three separate organisations: the origin carrier, the transit hub ground handler, and the destination carrier or ground handler. Each organisation's monitoring system sees only the segment it controls.

This is the fundamental limitation of carrier-specific monitoring solutions. Turkish Airlines Cargo's TK Pharma monitoring infrastructure is comprehensive for the Turkish Airlines-controlled segments of the journey but does not cover third-party ground handling at origin stations, customs dwell time in U.S. customs examination areas, or final-mile delivery conditions. A carrier-agnostic, integrated monitoring platform — one that bridges all handling parties across the entire journey — is the only architecture that can close the ground transfer monitoring gap.

The Predictive Delay Intelligence Connection

The most practically powerful implication of the ground transfer dwell time hypothesis is that the primary predictor of pharmaceutical cold chain failure is not the in-flight environment — it is the delay that extends ground transfer dwell time beyond the container's thermal tolerance. Academic research demonstrating that machine learning models can forecast ground transfer delay probability with 78 to 84 percent accuracy at the 48-hour horizon (Nguyen et al. 2021; Wang and Chen 2023) creates a direct connection between pharmaceutical cold chain management and predictive delay intelligence infrastructure. When delay prediction is integrated with container thermal tolerance calculations, the system can generate proactive rerouting recommendations before pharmaceutical cargo is loaded on the outbound aircraft — transforming the monitoring architecture's value proposition from reactive documentation to preventive intervention.

CONCLUSION

This paper has presented practitioner-grounded evidence for the ground transfer dwell time hypothesis: that temperature excursions in pharmaceutical air cargo shipments occur predominantly during the transfer period between aircraft offload and temperature-controlled facility re-entry, rather than during the in-flight phase that dominates both academic research and regulatory attention.

The evidence base rests on three complementary pillars. From DHL airfreight operations, direct observational evidence identifies three categories of ground transfer event — unscheduled apron dwell, non-conditioned pre-departure staging, and customs clearance dwell time — that represent the primary unmonitored thermal risk windows. From DB Schenker pricing executive experience, a commercial pricing dynamic is documented for the first time in the academic literature: the competitive rate structure that incentivises multi-stop pharmaceutical routing systematically multiplies ground transfer dwell time exposure. From Turkish Airlines Cargo data analytics, the South Asia pharmaceutical corridor emerges as a high-risk case study where FDA import detention risk and Gulf hub routing combine to create the most thermally vulnerable pharmaceutical supply chain profile in the global air cargo network.

The implications for monitoring system design are direct. Carrier-agnostic, integrated monitoring platforms that connect predictive delay intelligence with pharmaceutical container thermal tolerance calculations — and that maintain monitoring continuity across the airside-to-landside transition — represent the necessary evolution of pharmaceutical cold chain management beyond the flight-phase-centric paradigm that currently dominates the field.

Future research should empirically validate the ground transfer dwell time hypothesis using controlled carrier data partnerships, quantifying dwell time durations across transit hubs and correlating these with temperature excursion event frequencies.

Declarations

DECLARATION OF COMPETING INTEREST

The author declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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