Barriers in the Sky

Ting Chen* Ziyang Chen† Qiyao Zhou‡§

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Abstract

This paper investigates the economic impacts of inefficient transport network design, using China's restrictive airspace as a case study. Commercial airlines in China are confined to 20% of the nation's airspace, leading to an average route curvature of 17%, compared to 5% in the US and Europe. Using route curvature as a direct measure of inefficiency, we find that greater route curvature increases airfares while reducing flight frequency, competition, and aeroconnectivity. These aviation market distortions cascade into broader economic costs, reducing intercity trade flows, corporate investment, personal travel, and migration.

Keywords: Transportation network design, Airline, Airspace regulation, Economic connectivity

JEL classification: O18, R11, R12, R42

*Department of Economics, Hong Kong Baptist University. Email: tingchen@hkbu.edu.hk

†Department of Economics, School of Business, Nanjing University. Email: zychenfr@nju.edu.cn

‡Department of Economics, Oklahoma State University. Email: qzhou@okstate.edu

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1 Introduction

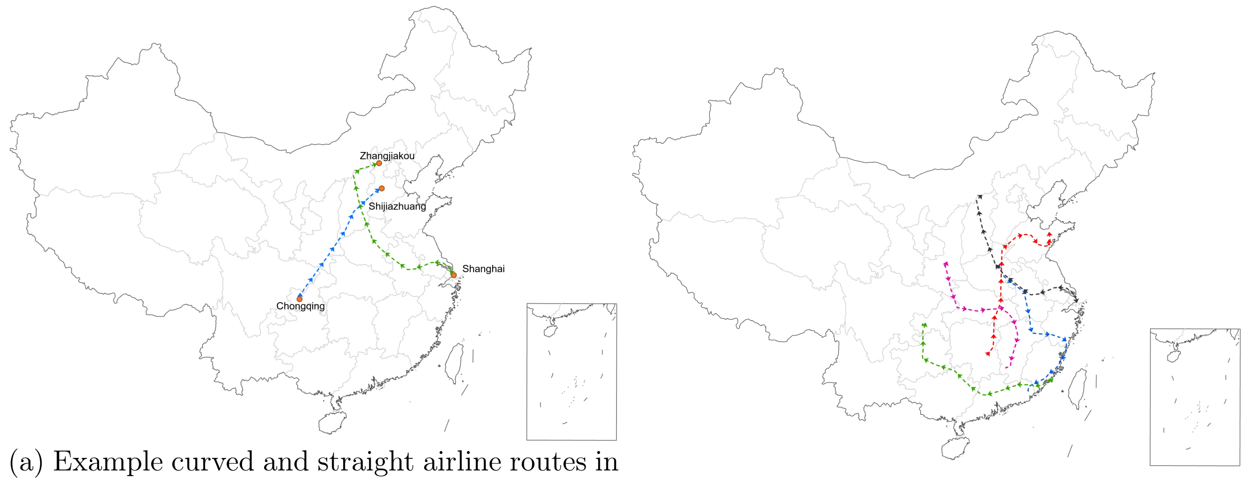
Few inventions better represent the age of globalization than the airline network. Today, people and cargo are transported across the globe at unprecedented speeds and historically low costs. A key advantage of air travel is that airspace is free of physical barriers, allowing aircraft to follow the most efficient direct routes. However, flight paths are often not straight—an often overlooked fact.

Consider two airline routes in China, shown in Figure 1 Panel (a): Shanghai–Zhangjiakou (1,205.1 km direct distance) and Chongqing–Shijiazhuang (1,205.4 km direct distance). Despite their near-identical direct distances, the routes' curvatures—measuring deviations from the straight-line path—differ significantly: 49.9% for Shanghai–Zhangjiakou but 4.8% for Chongqing–Shijiazhuang. This means the Shanghai–Zhangjiakou flight route is on average 543 kilometers longer.

This stark difference is not attributable to common factors such as weather conditions, bird strikes, or air traffic management. Instead, it highlights a critical yet often overlooked source of inefficiency in transportation networks: politics. Geopolitical conflicts, bureaucratic red tape, national security concerns, and other political factors frequently lead to suboptimal design of transportation networks, affecting transportation industry dynamics and generating economic and welfare losses. While extensive research, particularly that of Campante and Yanagizawa-Drott (2018), has documented the welfare gains from transportation connectivity and networks on the extensive margin (Faber, 2014; Bahar et al., 2023), less attention has been given to the economic impact of inefficient route design or network "quality." A key empirical challenge in addressing this gap lies in measurement: How can we quantify route inefficiency? Specifically, how do we identify optimal counterfactual routes?

The airline network provides a unique setting to study inefficient design of transportation networks for two main reasons. First, route curvature provides a direct and intuitive measure of inefficiency. In contrast to land transportation, where the optimal routes are shaped by physical barriers such as mountains and rivers, air travel can be benchmarked against the great circle distance—the shortest path between two points on a sphere. While individual flights may deviate from this benchmark because of "random" factors such as weather, persistent route curvature typically reflects regulatory constraints. Second, the airline industry is one of the most heavily regulated sectors globally. Governments exert significant control

Figure 1: Airline routes in China



(a) Example curved and straight airline routes in China

(b) Five most curved airline routes in China

Notes: Panel (a) shows a typical straight airline route (Chongqing–Shijiazhuang, curvature 4.8%), alongside a typical curved airline route (Shanghai–Zhangjiakou, curvature 49.9%). Panel (b) displays China's five most curved airline routes of over 1000 km: Shanghai–Zhangjiakou (curvature 49.9%, black), Hengyang–Qingdao (curvature 44.5%, red), Zhengzhou–Jieyang (curvature 43.1%, blue), Xi'an–Ganzhou (curvature 43.1%, purple), and Chongqing–Quanzhou (curvature 42.3%, green).

over route establishment, airline formation, and market access through strict licensing and operational requirements. The impact of such regulations on route efficiency is evident from several recent examples: Argentina's pre-2016 mandate that almost all domestic flights pass through Buenos Aires caused substantial detours. The Russia–Ukraine war has forced EU and US carriers to avoid Russian airspace, resulting in longer trans-Pacific and trans-Atlantic routes (e.g., Appendix Figure A1 shows a 15% increase in flight distance between Shanghai and Frankfurt after the war). Similarly, during the 2017 Qatar diplomatic crisis, several Middle Eastern nations prohibited Qatari aircraft from accessing their airspace, disrupting regional flights.

Beyond illustrating the global scope of airspace restrictions, these cases highlight a deeper puzzle: despite their well-recognized inefficiencies, countries rarely reform these regulations.[1] This inertia reflects deep-seated institutional barriers—military priorities, bureaucratic entrenchment, and geopolitical constraints often outweigh economic efficiency considerations, even when the welfare costs are substantial. Given this regulatory stickiness, a critical question emerges: how do economies adapt to such persistent inefficiencies?

[1] For instance, the CEO of Xiamen Airlines, one of the major carriers in the Chinese domestic market, has for years called for easing airspace regulations to allow straighter flight routes. However, airspace regulations and route curvature have barely changed over time. https://news.ifeng.com/c/8XiGOocPjPX

China provides an ideal setting to explore this question. Despite maintaining the world's most restrictive airspace regime (with commercial aviation limited to 20% of airspace versus 80% in the US),[2] China has simultaneously developed the world's largest high-speed rail (HSR) network. This juxtaposition allows us to examine not only the costs of inefficient route design but also whether alternative infrastructure can mitigate these distortions—a question of growing relevance as geopolitical tensions fragment global airspace.

In this paper, we exploit China's unique regulatory environment to empirically investigate how route design inefficiency arose from airspace regulations shape both the airline industry and broader economic connectivity. Our analysis reveals stark inefficiencies: the average curvature of Chinese airline routes is 17%—more than triple the 5% observed in the US and Europe—translating to an additional 164 km of flight distance for an average domestic trip. We first document how this regulatory-induced curvature affects the airline industry itself, examining impacts on airfares, flight frequency, seat capacity, and market competition. We then trace how these distortions cascade through the economy, affecting intercity corporate investment, domestic trade flows, personal travel patterns, and migration flows. Crucially, we leverage variation in HSR availability across city pairs to test whether alternative infrastructure can mitigate the costs of inefficient airspace design—providing insights relevant not only for China but for any economy facing politically-constrained transportation networks.

To study the impact of airspace regulation, we draw on detailed flight path data from Flightradar24, the most "authoritative" provider of real-time aircraft tracking information according to The Guardian. The dataset records coordinates every minute, allowing us to reconstruct airline routes between cities in mainland China and calculate each route's actual distance and curvature. We complement these data with flight prices and carrier information from September 2019 obtained from Ctrip.com, China's leading online travel agency. To capture intercity economic activity, we use four proxies: (i) intercity trade flows based on firms' value-added tax records, (ii) intercity ownership investments from corporate headquarters to subsidiaries, (iii) an index of annual online searches of one city's name by users in another, and (iv) the Weibo mobility index, which tracks the frequency of social media users' annual travel between cities.

One key identification challenge arises from the potential endogeneity of the main independent variable—route curvature. Politically and economically significant cities (e.g.,

[2] Source: Sina Finance.

Beijing) may face more restrictive airspace regulations due to their proximity to military bases, while airlines may have stronger incentives to lobby for straighter routes to major hubs. We first show that neither cities' political hierarchy nor their observed economic characteristics (GDP and population) significantly affect route curvature. To further address concerns about unobserved characteristics, we include departure and arrival city fixed effects, which absorb city-level political and economic factors. This approach is particularly well suited to our setting, as route curvature remains unchanged over time, and our analysis relies on a cross-sectional snapshot of outcomes from 2019. In addition, we control for a comprehensive set of bilateral factors: (i) Geography: Shortest airport-to-airport distance, distance-quintile dummies, and the share of the direct flight path crossing mountains above 2,000 meters; (ii) Economic structure: A dummy for direct HSR connection, the complementarity of local industries based on input–output linkages, and a gravity term for population; (iii) Political status: An indicator for whether both cities are vice-provincial-level or above.

We further implement a placebo test to address endogeneity concerns. Exploiting variation from airline route expansions, we re-estimate the model using city pairs that lacked direct flights in 2011 but became connected by 2019, matched with their 2011 outcomes. Because these city pairs were not directly connected in 2011, subsequent variation in curvature could not have affected their earlier economic connectivity if the conditional exogeneity assumption holds. The placebo results yield small and statistically insignificant effects, lending support to our identification strategy.

Our results show that greater route curvature is associated with (i) higher average economy airfares, (ii) fewer weekly flights, (iii) fewer available seats, and (iv) lower competition, as measured by the Herfindahl–Hirschman Index (HHI). We then examine the broader economic consequences of airspace regulation and find that intercity trade flows, corporate investment, online search intensity, and social media–based travel frequency all decline significantly with increasing curvature between city pairs. Finally, heterogeneity tests reveal that the presence of HSR can substantially offset these negative economic effects, suggesting that alternative infrastructure can mitigate distortions caused by restrictive airspace regulation.

Beyond the intensive margin—how existing curvature affects already connected city pairs—it is also important to consider the extensive margin: how potential curvature shapes the likelihood of new aero-connections. Using the existing airline network, we predict routes for city pairs without direct flights in 2019 and estimate their expected curvature. Since airlines typically expand by building on existing routes to minimize the regulatory costs of securing new airspace, we construct hypothetical routes based on the airline network in 1995. The results indicate that restrictive airspace regulations substantially limit intercity connectivity. A counterfactual analysis shows that if China relaxed its regulations to U.S. levels, approximately 9.1% more city pairs would likely be connected by direct flights.

Our study contributes to the growing literature on the economic impact of transportation infrastructure, which has focused primarily on the economic impacts of connectivity on the extensive margin while paying less attention to the quality of transportation network design (i.e., the intensive margin). Recent research has examined the effects of road or railway connections on market access (Banerjee et al., 2020; Herzog, 2021; Donaldson, 2025), immigration (Sequeira et al., 2020), economic growth (Faber, 2014; Banerjee et al., 2020; Asturias et al., 2019; Dong et al., 2021; Asher and Novosad, 2020), suburbanization (Baum-Snow, 2007; Baum-Snow et al., 2017), urban form (Duranton and Turner, 2012), poverty (Aggarwal, 2018), and knowledge diffusion (Dong et al., 2020; Bahar et al., 2023). Our paper is most closely related to Giroud (2013); Campante and Yanagizawa-Drott (2018), who examine airline networks. Some works also examine how road quality shapes local economic development (Allen and Arkolakis, 2022; Currier et al., 2023; Gertler et al., 2024). We use China's airspace regulation as a case study to show that the quality of transportation network design significantly impacts not only the airline industry itself but also broader economic outcomes. City pairs with a low-quality connection (i.e., with higher airline route curvature) have weaker economic connections, as reflected by intercity travel, corporate investment, patent collaborations, and migration intentions.

Our research is closely related to the growing literature examining political influence on infrastructure development. Studies have documented how electoral incentives shape infrastructure decisions(Akbulut-Yuksel et al., 2024; Fajgelbaum et al., 2024). Prior literature has also revealed regional favoritism as an alternative motive for politicians' infrastructure allocation decisions (Burgess et al., 2015; Alder et al., 2019). Our paper extends the literature by focusing not on the political causes but on the sectoral and broader economic consequences of such decisions—particularly, how politically driven inefficiencies in transportation route design affect interregional economic connectivity. Moreover, we show that when alternative infrastructure exists—HSR in our setting—the economic costs of regulation can be partially alleviated. This finding is in line with the classical findings in Lipsey and Lancaster (1956), and more recent empirical findings in Glaeser and Ward (2009); Kline and Walters (2016); Cravino and Levchenko (2017).

Given our focus on airline regulations, this paper also contributes to the literature on regulation and deregulation in this sector. Following the Airline Deregulation Act of 1978 in the US, economists have studied the policy's impacts on fares (Moore, 1986), economies of scale (Brueckner and Spiller, 1994), and local population, income, and employment growth (Blonigen and Cristea, 2015). For international flights, Winston and Yan (2015) analyze the welfare effects of open skies agreements on US international routes. Although airspace regulation is prevalent because of geopolitical conflicts, military regulations, and other political factors, it has received limited attention in the literature.[3] We extend the literature by providing empirical evidence on how airspace regulations shape the airline industry and how these impacts cascade into broader economic outcomes.

The rest of the paper is organized as follows: Section 2 provides background on airspace regulation and the airline industry in mainland China. Section 3 describes the data utilized in our empirical analysis. Section 4 outlines our empirical strategies, followed by the empirical results presented in Section 5. Finally, Section 6 concludes the paper.

2 Background

2.1 Airspace regulation

Regulation of airspace has historically been shaped by a combination of military, geopolitical, and technological considerations. Following the emergence of powered flight in the early 20th century, the Paris Convention of 1919 laid the legal foundations for air sovereignty, affirming that "every state has complete and exclusive sovereignty over the airspace above its territory." While the 1944 Chicago Convention established the International Civil Aviation Organization (ICAO) to promote international cooperation and technical standards for civil aviation, airspace control remained a sovereign matter, allowing countries to determine their own access and usage rules, with significant implications for airline route design and economic connectivity.

During the Cold War, many nations—especially those with significant military concerns—implemented highly restrictive airspace regimes. The Soviet Union famously denied overflight access to Western carriers, compelling Asia–Europe or Asia–North America flights to make

[3] One exception is Besedeš et al. (2024), who use Russia's airspace closure as a natural experiment to study the impact of distance on trade costs.

major detours and turning cities such as Anchorage into critical refueling hubs. Although Russia eased these Cold War–era restrictions in the 1990s, it introduced a fee of approximately $10,000 for commercial flights to use its airspace.

In contrast, airspace liberalization advanced considerably in the US and Europe after the 1970s. The US Airline Deregulation Act of 1978 not only liberalized pricing and entry but coincided with increased civilian access to previously restricted airspace. Similarly, Eurocontrol has played a key role in facilitating more flexible and integrated airspace use across European countries, although national militaries still retain some control over specific zones.

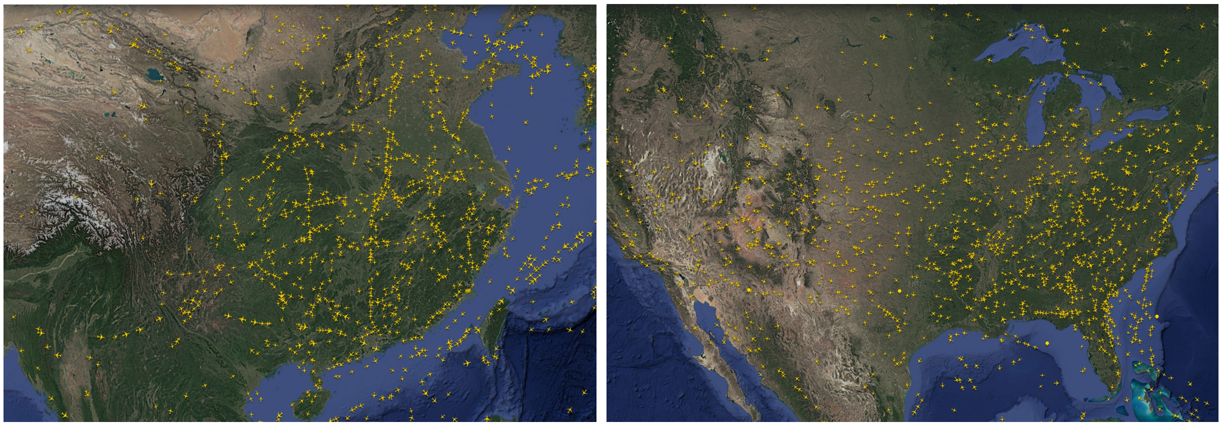
China, which after 2005 quickly rose to become the second largest civil aviation market, has maintained a highly centralized and security-oriented airspace regime. Approximately 80% of Chinese airspace is controlled by the People's Liberation Army Air Force, with civilian commercial flights limited to the remaining 20%. In the US, in stark contrast, commercial aviation can access over 80% of national airspace. This restrictive allocation contributes to significant inefficiencies: Average route curvature in China is approximately 17%,[4] compared to 5% in the US and Europe. This restrictive allocation reflects China's institutionally rigid approach to airspace management. New civilian routes, particularly those that cross multiple jurisdictions, require approval from both the Civil Aviation Administration of China (CAAC), the aviation authority under the Ministry of Transport, and regional military theater commands. These institutional barriers have prevented more efficient route designs despite the dramatic growth in China's aviation market.

The spatial implications of China's airspace regulation vis-à-vis the laissez-faire approach in the US are obvious in Figure 2 Panels (a) and (b). Panel (a) presents a real-time flight map of mainland China, which we obtained around noon (local time) on January 9, 2025, from Flightradar24. It shows dense clustering of flights along narrow corridors and large swaths of "empty" airspace, particularly in central and southern regions. These visible gaps strongly suggest the existence of extensive no-fly zones where commercial aviation is prohibited, consistent with the institutional constraints described above. Panel (b) displays the contemporaneous flight map over the United States, where commercial flights appear evenly distributed across the country, with minimal clustering and no apparent restricted zones.

China's approach, while extreme, reflects broader patterns of politically motivated airspace

[4] Source: https://finance.sina.cn/china/gncj/2014-07-23/detail-iavxeafr5439198.d.html?from=wap, retrieved on January 15, 2025.

Figure 2: Real-time flight map in China and the US



(a) Real-time flight map for China

(b) Real-time flight map for the US

Notes: Panels (a) and (b) show real-time flight maps from www.flightradar24.com for mainland China and the continental US at 12:00 PM Beijing time and 12:00 PM EST on June 1, 2025.

restrictions worldwide. Contemporary examples underscore the ongoing relevance of such controls: The 2022 Russia–Ukraine conflict forced Western carriers to avoid Russian airspace, adding thousands of kilometers to transcontinental flights, while Middle Eastern geopolitical tensions continue to oblige carriers from various nations to make detours. Israeli aircraft remain barred from many Arab countries' airspace, and Taiwanese carriers face significant route restrictions because of limited access to airspace in mainland China.[5] Such restrictions demonstrate that airspace regulation, though largely invisible to passengers, fundamentally shapes airline network efficiency and, as this paper shows, broader economic connectivity between regions.

2.2 Airline industry in China

China's airline industry has experienced rapid expansion since the 1990s, alongside the country's market reforms and privatization. Prior to this period, all commercial air operations were centrally managed by the CAAC. Starting in the mid-1980s and accelerating in the early 1990s, the CAAC allowed entry by regionally backed, private carriers such as Xiamen Airlines, marking the first wave of market liberalization in the sector (Wang et al., 2016). By 2019, the industry had grown to include 49 commercial airlines. However, market concentration remains high: Three major state-owned carriers—Air China, China Eastern Airlines,

[5]Panel (b) of Appendix Figure A presents the curved airline route from Taipei to Frankfurt.

and China Southern Airlines—and their subsidiaries account for approximately two-thirds of the domestic market.

Airfare regulation has also undergone gradual liberalization. The CAAC historically set price ceilings on economy-class fares based on route distance.[6] Since 2013, 200 high-demand routes have been exempt from these ceilings, such that airlines have greater pricing flexibility. In practice, especially outside peak holiday periods, most price caps are nonbinding. In our 2019 sample, 98.2% of flights faced no effective price ceiling.

Despite the limited liberalization on market entry and pricing, the Chinese airline industry remains highly regulated in terms of route authorization and airspace usage. To operate a new route, airlines must submit a detailed application to the CAAC, specifying the aircraft type, flight schedule, and operational plan. If the proposed route uses airspace not currently open to civilian traffic, approval must be obtained from the relevant military theater command. For routes that span multiple military zones, airlines must secure clearance from each involved command. In addition, they must demonstrate local government support and operational readiness.

These bureaucratic hurdles are compounded by the rigidity of existing route infrastructure. Approximately 95% of scheduled airline routes in China have remained unchanged since 1995, reflecting the high institutional costs associated with modifying existing routes or opening new airspace. This persistence entrenches inefficiencies in the domestic aviation network and limits adaptation to evolving economic and mobility patterns.

3 Data and Measures

This section describes the construction of key variables used in this study. Summary statistics of the relevant variables are presented in Appendix Table A1.

Airline routes We construct airline routes using the real-time airflight tracking information from Flightradar24, a global flight tracking service provider. This dataset covers all commercial flights within mainland China, with each flight's latitude and longitude coordinates reported at intervals of 30 to 60 seconds (see details in Appendix Figure A2). These

[6] For most nonmountainous routes, the cap is calculated as $Log(150, 0.6 \cdot Distance) \cdot Distance \cdot 1.1 \cdot 1.25$. This gives a cap of 1,080 CNY (154 USD) for a 1,000 km one-way route and 2,300 CNY (329 USD) for a 3,000 km route.

high-frequency positioning data allow us to map the precise flight path for each route and calculate the actual distance traveled.

The curvature of each route is defined as $Curvature_{i,j} = (\frac{\text{Actual Distance}_{i,j}}{\text{Shortest distance}_{i,j}} - 1) \times 100\%$, where the shortest distance is the great-circle distance between the departure and arrival airports. Route curvature, our preferred measure of route efficiency, can be interpreted as the percentage of additional distance a plane must fly in deviation from the shortest distance. Unlike measures such as extra flight distance or flying time, it is normalized and not directly affected by the shortest possible distance between two cities.[7]

Airfare data We obtained the airfare data from Ctrip (www.ctrip.com), mainland China's largest online travel agency. This dataset contains the average economy-class price for almost all commercial flights scheduled between September 16 and September 22, 2019.[8,9] We also calculate the weekly flight frequency for each airline route based on this dataset. Notably, China's flight scheduling operates on a weekly cycle, with flight schedules remaining virtually identical across weeks within a given flight season, making our one-week sample representative of broader patterns.

Intercity trade flow Intercity trade volume data are sourced from value-added tax (VAT) invoices issued by firms in mainland China in 2018, as recorded by the State Taxation Administration.[10] Each invoice provides transaction details, including the buyer's and seller's locations and the transaction value. Since VAT filing in China is mandatory for all transactions, except for direct sales to consumers and transactions involving firms with small-scale operations (average monthly sales below RMB 3,000), the data captures the vast majority of intercity trade flows (Chen et al., 2025; Egger et al., 2025). The trade flow is aggregated at the city pair level.

[7]We also control for the shortest possible distance between two cities in all specifications.

[8]We use the data for this period since we want to avoid the impact of the COVID-19 shock or any major national holidays.

[9]We exclude flights that depart from or arrive at airports in the 30 ethnic minorities autonomous prefectures in our analysis because of missing information on both the airfares and other outcome variables. These prefectures are typically located in remote area with combined GDP accounts for approximately 1% of the national total.

[10]The 2018 data is the latest available data to us.

Intercity investment flow Firms' intercity investment data are constructed from the universal firm registration database from the State Administration for Industry and Commerce.[11] For each registered firm, we have information related to the geocoded addresses of its headquarter and subsidiaries. From this information, we construct intercity firm investment at the origin-–destination city pair level.

Population mobility To measure intercity population mobility, we compiled two sources of data. The first is the 2019 Weibo mobility index, sourced from the Spatial Data Lab at Harvard University.[12] This index is constructed from aggregated records of individuals' travel patterns based on the geographical information from users' posts on Weibo, the largest social media platform in China.[13] These data are at the origin–destination city pair level. Each observation in the dataset represents the travel intensity from the origin city i to the destination city j.

Second, we use an online search index, the Baidu Index, for 2019 to measure intercity migration intentions.[14] Baidu's market share in China was 73% in June 2019.[15] Baidu tags each query with the user's geographic location at the time of the search.[16] We extract search queries that clearly relate to migration intention, such as "moving to city j" or "employment in city j." We construct the online search index by aggregating these search queries to the origin–destination city pair level. Each observation in this dataset represents the intensity of search among city i's population in terms of migrating to or working in destination city j.

[11] Data source: https://www.gsxt.gov.cn/index.html.

[12] Data source: https://dataverse.harvard.edu/dataverse/weibomobilityindex.

[13] At the end of 2019, Weibo had 516 million active users (36.6% of China's population).

[14] Data source: https://index.baidu.com.

[15] Source: https://marketmechina.com/wp/wp-content/uploads/2019/07/baidu-market-share-search-engines-china-jun-2019.pdf.

[16] This index has been used in previous works to study divorce decisions (Alm et al., 2022) and sentiment in the stock market (Fang et al., 2020).

4 Empirical Strategies

4.1 Empirical specification

To explore the impact of airline route curvature on key outcomes, we estimate the following equation:

$$Y_{i,j} = \beta_1 Curvature_{i,j} + \alpha_i + \theta_j + \gamma X_{i,j} + \epsilon_{i,j} \quad (1)$$

where i denotes the departure city and j denotes the arrival city. $Y_{i,j}$ represents the key outcome variables, including (1) the logarithm of economy-class airfares, (2) the number of flights per week on a given route i, j, (3) the number of seats per week on a route i, j, (4) the Herfindahl-Hirschman Index (HHI) in route i, j to measure competition, (5) trade flows between city i and city j measured based on firms' tax records; (6) the number of subsidiaries in city j whose parent firms come from city i, (7) the indices for Weibo mobility and online search intensity from city i to city j.[17]

$Curvature_{i,j}$ is the key independent variable. It measures the curvature of the airline route from city i to city j. α_i and θ_j represent departure and arrival city fixed effects, respectively. $X_{i,j}$ comprises a set of bilateral control variables including (i) Geography: the logarithm of the shortest (great circle) distance from city i to city j, dummies for distance quintiles to flexibly capture distance effects, the percentage of the direct flight path that passes over mountains with an altitude of at least 2,000 meters; (ii) Economic structure: A dummy for direct HSR connection between city i and city j in 2019, the complementarity of local industries in city i and city j based on input-output linkages,[18] and a gravity term for population; (iii) Political status: An indicator for whether both city i and city j are

[17]Note that, for the ticket price regressions, the observations are at the flight level. All other regressions are estimated at the airline route (i, j) level.

[18]We construct the inter-city industrial complementarity index following Ellison and Glaeser (1997), Ellison et al. (2010), and Baldwin et al. (2023). Specifically, we combine data on each city's industry composition from the 2008 Economic Census with inter-industry linkages from the 2007 national input–output table, both published by the National Bureau of Statistics of China. The industrial complementarity between cities c_1 and c_2 is defined as:

$$\tilde{L}_{c_1,c_2} = \frac{\sum_{i,j} A_{c_1,i} B_{i,j} A_{c_2,j}}{D_{c_1 c_2}},$$

where $A_{c,i}$ denotes the employment share of industry i in city c, and $B_{i,j}$ is the input coefficient from the input-output table. It measures the production linkage between industries i and j. $D_{c_1 c_2}$ is the great-circle distance between cities. Intuitively, $\tilde{L}_{c_1,c_2}$ is larger when city c_1 specializes in industries that are strongly linked to those in which city c_2 specializes.

vice-provincial-level or above.

4.2 Identification

One potential concern regarding Equation (1) is the possibility of omitted variable bias. More politically and economically significant cities (e.g., Beijing) may face more restrictive airspace regulation because they are likelier to have nearby military bases, which could make their connected airline routes more curved. Conversely, airlines may lobby for straighter routes between major cities to maximize profit.[19]

We take several steps to address this concern. We first conduct a balance test by examining whether the route curvature is correlated with cities' observed characteristics. In Table A2, we provide evidence that neither the cities' political hierarchy nor their observed economic characteristics significantly affect route curvature. We also control for departure and arrival fixed effects in all specifications, which are critical in our setting because they absorb both observed and unobserved city-level political and economic characteristics. This argument holds particularly well in this setting, as route curvature does not vary over time and our analysis relies on a snapshot of the outcome variables (in 2019).

There may also be concerns that bilateral economic or political characteristics of city pairs could bias our estimates. Cities with greater complementarities in their economic structures may have straighter airline routes. To address this concern, we control for cities' economic complementarities. We also control for both cities' political hierarchies (whether both are vice-provincial level cities or higher), and a gravity term of population.

Other factors, such as arrival and departure traffic volume, flight takeoff angle, and runway orientation, can also affect the actual flying distance during takeoff and landing. However, they typically change the actual flying distance by less than 10 kilometers, much less than the curvature caused by deviations from the most efficient route to conform to airspace regulations, as shown in Figure 2 Panel (a). Moreover, the arrival and departure city fixed effects can control for factors such as departure traffic volume and runway orientation. Conditional on these fixed effects, these factors are unlikely to directly bias the model estimation. In addition, we exclude flight trajectories in which the aircraft exhibits a prolonged circling pattern before landing when we calculate the actual flying distance. We

[19] Most airline routes have remained unchanged over time, so we cannot estimate the baseline equation and address endogeneity through a difference-in-differences approach.

also incorporate geographic controls, such as the percentage of the direct flight path that passes over mountains with an altitude of 2,000 meters or higher, and dummy variables for the 20 percentiles of bilateral distance to allow for a more flexible control of distance in additional to shortest distance.

Finally, we conduct a placebo test to assess the conditional exogeneity of our key independent variable, $Curvature_{i,j}$. The test exploits variation in the expansion of airline networks across years. Specifically, we re-estimate Equation (1) using city pairs that lacked direct flights in 2011 but were connected by 2019 (allowing us to observe their curvature), together with the 2011 economic outcome variables. The year 2011 is the earliest for which data on intercity investment flows and the online search index are available. If conditional exogeneity holds, $Curvature_{i,j}$ should have no explanatory power in 2011, since direct connections did not yet exist and ex post curvature could not have influenced economic ties. By contrast, if reverse causality or omitted factors jointly determine $Curvature_{i,j}$ and economic connections, then curvature would appear significant even in this placebo setting. Consistent with our identification strategy, we find small and statistically insignificant effects of $Curvature_{i,j}$ on economic outcomes in 2011.

5 Empirical Results

This section presents the estimation results of Equation (1) for various outcomes. We first focus on the impact of airspace regulations on airfares, flight frequency, the total number of seats operated in a given route, and competition. We then analyze how these regulatory impacts cascade into broader economic outcomes. Finally, we investigate the impact of airspace regulation on aeroconnectivity.

To enhance the interpretability of the results, we normalize the main independent variable, $Curvature_{i,j}$, to have a mean of 0 and a standard deviation of 1. A 1.2-standard-deviation decrease in airline route curvature would bring mainland China's airline route curvature to the US level.

5.1 Impact of airspace regulations on airfares, flight frequency, and competition

Table 1 summarizes how route curvature affects airfares, flight frequency, and competition within a given route. Column (1) presents the OLS results, with departure and arrival city fixed effects and a control for the logarithm of the shortest distance between the airport in city i and the airport in city j. Column (2) adds controls for geographic variables, including dummies for distance quintiles to flexibly capture distance effects, and the percentage of the direct flight path that passes over mountains with an altitude of at least 2,000 meters. Column (3) controls for a set of economic and political variables, including an HSR direct connection dummy, an indicator for whether both cities are vice-provincial-level or above, a gravity term based on population, and the complementarity of economic structures between the arrival and departure cities. Finally, Column (4) includes the full set of control variables, which is our most preferred specification.

Panel A of Table 1 reports the impact of airline route curvature on the logarithm of airfares. The observations are at the *flight* level. We find that the results are robust across specifications. The point estimate in Column (4) indicates that if China were to relax airspace regulations by one standard deviation (about 10% in absolute values of curvature), the average airline ticket price would decrease by approximately 1.9%.

If we assume that variable costs (e.g., fuel, depreciation, maintenance, and crew costs) linearly correlate with mileage and account for 50% of the total cost (Koopmans and Lieshout, 2016), a back-of-the-envelope calculation based on the estimates from Column (4) suggests that approximately 38% of the cost increase due to the curved airline route is passed through to consumers.[20]

We next turn our attention to the impact of airspace regulation on flight frequency. The results are reported in Table 1, Panel B. The observations for this regression are at the *airline route* level. We find that a one-standard-deviation increase in route curvature significantly reduces the number of flights on $Route_{i,j}$ by 5.9%, corresponding to about 1.2 fewer flights for the average city pair. The reduction in flight frequency can be attributed to lower demand due to higher prices and reduced supply from increased costs. Panel C reports the impact of route curvature on the number of seats operated per week on a given route.

[20] $\frac{0.019}{0.5 \cdot 0.1} = 0.38$, where 0.1 represents a one-standard-deviation change in route curvature.

Table 1: Impact of route curvature on airfares, flight frequency, and competition

	(1)	(2)	(3)	(4)
Panel A: Dep. Variable: Log airfares				
$Curvature_{i,j}$	0.0242***	0.0214***	0.0191***	0.0191***
	(0.00760)	(0.00736)	(0.00730)	(0.00732)
Sample Mean	4.555	4.555	4.555	4.555
Observations	69694	69693	69693	69693
Adjusted R^2	0.603	0.622	0.624	0.625
Panel B: Dep. Variable: Number of flights per week (Poisson regression)				
$Curvature_{i,j}$	-0.0756***	-0.0742***	-0.0547***	-0.0587***
	(0.0212)	(0.0209)	(0.0206)	(0.0204)
Sample Mean	24.77	24.77	24.77	24.77
Observations	2807	2807	2807	2807
Pseudo R^2	0.656	0.670	0.675	0.684
Panel C: Dep. Variable: Number of seats per week (Poisson regression)				
$Curvature_{i,j}$	-0.0839***	-0.0822***	-0.0601***	-0.0645***
	(0.0226)	(0.0227)	(0.0220)	(0.0220)
Sample Mean	4.433	4.433	4.433	4.433
Observations	2807	2807	2807	2807
Pseudo R^2	0.521	0.531	0.538	0.543
Panel D: Dep. Variable: Herfindahl-Hirschman Index (HHI)				
$Curvature_{i,j}$	0.0204***	0.0196***	0.0155**	0.0159***
	(0.00632)	(0.00630)	(0.00611)	(0.00607)
Sample Mean	0.656	0.656	0.656	0.656
Observations	2807	2807	2807	2807
Adjusted R^2	0.566	0.579	0.579	0.589
log(shortest distance)	✓	✓	✓	✓
Distance bin FE (every 20 percentile)		✓		✓
% >2000m moutains		✓		✓
HSR connection dummy			✓	✓
Political hierarchy			✓	✓
Gravity term of population			✓	✓
Industry complementarity			✓	✓
Departure city FE	✓	✓	✓	✓
Arrival city FE	✓	✓	✓	✓

Notes: (1) This table reports estimates of β_1 from variants of Equation (1). The key independent variable $Curvature_{i,j}$ is standardized to mean 0 and SD 1. A one standard deviation increase in $Curvature_{i,j}$ is around 0.1 increase in absolute values (i.e., fly additional 10% more distance). (2) Column 1 includes the basic control (log great-circle distance). Column 2 adds controls for geographic variables, including dummies for 20 percentiles of bilateral distance to allow for a more flexible treatment of distance, and the percentage of the direct flight path that passes over mountains with an altitude of 2,000 meters or higher. Column 3 controls for a set of economic and political variables, including an HSR connection dummy, an indicator for whether both cities are vice-provincial-level or above, a gravity term based on population, and the complementarity of economic structures between the arrival and departure cities, computed using the input–output table and the 2008 Economic Census. Finally, Column 4 adds the full set of control variables. (3) All regressions include departure and arrival city fixed effects. (4) Robust SEs clustered at the city-pair level in parentheses. * significant at 10%; ** significant at 5%; *** significant at 1%.

Consistent with the results in Panel B, greater route curvature is associated with a lower total weekly seat count.

In Table 1, Panel D, we examine how route curvature affects the competitive structure of the airline industry. The outcome variable is the Herfindahl-Hirschman Index (HHI) within a given route $Route_{i,j}$ (Gil and Kim, 2021; Yuan and Barwick, 2024). We find that greater route curvature is associated with a significant decrease in competition (i.e., an increase in the HHI). Greater route curvature raises firms' operating costs, making airlines less likely to enter a given market. The resulting lack of new entrants increases the HHI, reduces competition, and may also partially explain the price effects observed in Panel A.

Overall, the results in Table 1 indicate that curved airline routes in China adversely affect the domestic airline industry. These routes significantly increase carrier operational costs, raise airfares, compress profit margins, and reduces competition. A back-of-the-envelope calculation suggests that if mainland China were to reduce airline route curvature to the US level (a decrease of 1.2 standard deviations), average airfares would fall by 2.3%, weekly flights per route would rise by 7.1%, and competition would increase, with the HHI falling by 0.019.

5.2 Broader economic activities

In this section, we explore how airline route curvature affects economic connections between cities. The specification in each column remains the same as in Table 1. Observations in all regressions are at the *city pair* level.

Table 2 Panel A reports the impact of airline route curvature on inter-city trade volumes. The results indicate that a one-standard-deviation increase in route curvature between city i and city j reduces inter-city trade volume by approximately 5%. Panel B of Table 2 examines how route curvature influences firms' intercity investment. Consistent with our findings for trade volume, we find that a one-standard-deviation increase in route curvature between city i and city j reduces the number of subsidiaries established in city j by firms headquartered in city i by approximately 4.2%.

One interpretation of the results in Panels A and B is that curved airline routes raise the cost of personal communication and interaction between cities, thereby increasing information acquisition costs and reducing actual information exchange. Limited information about other cities' industrial policies, business environments, and investment opportunities makes firms less inclined to trade or invest across locations. In addition, parent companies place strong emphasis on maintaining effective oversight of subsidiaries. By reducing flight frequency and raising travel costs, curved routes make monitoring and coordination more difficult, further discouraging the establishment of new subsidiaries (Giroud, 2013).

Table 2: Broader economic impact of route curvature

	(1)	(2)	(3)	(4)
Panel A: Dep. Variable: Log trade volume				
$Curvature_{i,j}$	-0.0404**	-0.0463**	-0.0501***	-0.0492***
	(0.0186)	(0.0189)	(0.0184)	(0.0181)
Sample Mean	21.07	21.07	21.07	21.07
Observations	2807	2807	2807	2807
Adjusted R^2	0.888	0.890	0.891	0.891
Panel B: Dep. Variable: # of subsidiaries (Poisson Regression)				
$Curvature_{i,j}$	-0.0493***	-0.0590***	-0.0450***	-0.0421**
	(0.0190)	(0.0197)	(0.0170)	(0.0166)
Sample Mean	16.15	16.15	16.15	16.15
Observations	2805	2805	2805	2805
Pseudo R^2	0.663	0.665	0.675	0.676
Panel C: Dep. Variable: Online search index				
$Curvature_{i,j}$	-0.0933**	-0.103**	-0.0851**	-0.0838**
	(0.0443)	(0.0429)	(0.0392)	(0.0389)
Sample Mean	7.216	7.216	7.216	7.216
Observations	2807	2807	2807	2807
Adjusted R^2	0.877	0.878	0.900	0.900
Panel D: Dep. Variable: Geotagged social media posts (Poisson regression)				
$Curvature_{i,j}$	-0.0316***	-0.0477***	-0.0400***	-0.0417***
	(0.0111)	(0.0122)	(0.0120)	(0.0119)
Sample Mean	26.91	26.91	26.91	26.91
Observations	2807	2807	2807	2807
Pseudo R^2	0.903	0.904	0.905	0.906
log(shortest distance)	✓	✓	✓	✓
Distance bin FE (every 20 percentile)		✓		✓
% >2000m moutains		✓		✓
HSR connection dummy			✓	✓
Political hierarchy			✓	✓
Gravity term of population			✓	✓
Industry complementarity			✓	✓
Departure city FE	✓	✓	✓	✓
Arrival city FE	✓	✓	✓	✓

Notes: (1) This table reports estimates of β_1 from variants of Equation (1). The key independent variable $Curvature_{i,j}$ is standardized to mean 0 and SD 1. A one standard deviation increase in $Curvature_{i,j}$ is around 0.1 increase in absolute values (i.e., fly additional 10% more distance). (2) Column (1) includes the basic control (log great-circle distance). Column (2) adds controls for geographic variables, including dummies for 20 percentiles of bilateral distance to allow for a more flexible treatment of distance, and the percentage of the direct flight path that passes over mountains with an altitude of 2,000 meters or higher. Column (3) controls for a set of economic and political variables, including an HSR connection dummy, an indicator for whether both cities are vice-provincial-level or above, a gravity term based on population, and the complementarity of economic structures between the arrival and departure cities, computed using the input–output table and the 2008 Economic Census. Finally, Column (4) adds the full set of control variables.(3) All regressions include departure and arrival city fixed effects. (4) Robust SEs clustered at the city-pair level in parentheses. * significant at 10%; ** significant at 5%; *** significant at 1%.

In Panel C and D of Table 2, we use two outcome variables: (i) online search intensity related to employment or migration from city i to city j (measured by the Baidu Index), and (ii) intercity mobility inferred from the geolocation of social media posts (the Weibo Mobility Index) to examine the impact of airline route curvature on interpersonal connections and intercity mobility. Both panels confirm that airspace regulations significantly reduce individual mobility and information exchange between cities.

5.3 A placebo test

In this section, we conduct a placebo test to further address the endogeneity concerns. The test exploits variation in airline expansion across years in mainland China. If $curvature_{i,j}$ is exogenous conditional on fixed effects and controls, it should *not* affect outcomes *before* a direct flight connects city i and city j. Any significant association prior to the connection would likely reflect omitted variables or reverse causality rather than a causal effect, as the variable $curvature_{i,j}$ does not start to have any impact before the establishment of the direct flight.

Table 3: A placebo test

Dep. Variable:	# of subsidiaries in 2011 (Poisson)	Online search index in 2011
	(1)	(2)
$Curvature_{i,j}$	-0.0130	-0.00959
	(0.0486)	(0.0136)
Sample Mean	0.913	2.303
Observations	1418	1418
Pseudo/Adjusted R^2	0.550	0.875
log(shortest distance)	✓	✓
Distance bin FE (every 20 percentile)	✓	✓
% > 2000m mountains	✓	✓
HSR connection dummy	✓	✓
Political hierarchy	✓	✓
Gravity term of population	✓	✓
Industry complementarity	✓	✓
Departure city FE	✓	✓
Arrival city FE	✓	✓

Notes: This table reports the results of the placebo tests. We focus on city pairs connected by a direct flight in 2019 but *not* in 2011. All outcome variables are measured in 2011. Robust SEs clustered at the city-pair level in parentheses. * significant at 10%; ** significant at 5%; *** significant at 1%.

Our analysis focuses on airline routes that were established in 2019 but *not* in 2011.[21] We collect the online search index and firm intercity investment data from 2011, the earliest year available for this exercise. We do not incorporate inter-city trade flows and geotagged

[21] It is worthwhile to note that this test relies on the assumption that flight routes remain stable over time. This assumption is plausible, as approximately 95% of routes have remained unchanged since 1995.

social media posts, as these data are not available in earlier years. The results reported in Table 3 show that ex-post route curvature in 2019 has no significant impact on the economic connections between city pairs that were not connected by direct flight in 2011. Moreover, the point estimates are much smaller in magnitude than those in Table 2. Both the statistical and economic insignificance supports our empirical assumption.

5.4 Heterogeneity in high-speed rail

The preceding sections have shown that airspace regulations, by shaping airline route curvature, affect not only the airline industry but also broader economic outcomes. While easing airspace restrictions would be the optimal solution, entrenched bureaucratic and institutional barriers make such reforms difficult to achieve in the short run. This raises a natural question: under what circumstances might economic activity between city pairs be less constrained by airspace regulations?

China's rapid expansion of high-speed rail (HSR) offers a compelling alternative to air travel. By 2019, the HSR network extended more than 30,000 kilometers nationwide. In this section, we examine whether direct HSR connections mitigate the negative impact of curved airline routes on intercity economic exchange. Our expectation is straightforward: city pairs with HSR links should experience smaller economic losses from airline-route curvature, as the availability of a close substitute alleviates market distortions.

Estimation results are reported in Table 4. Panel A presents results for city pairs *with* direct HSR connections in 2019, while Panel B focuses on those *without* such connections. The findings confirm substantial heterogeneity: airline-route curvature has a significantly larger negative effect on intercity economic activity among city pairs lacking HSR links. For trade flows, not only are the effects much smaller among city pairs with HSR, but the coefficients in Columns (1) and (2) are statistically insignificant. For investment flows and intercity mobility, the coefficients remain significant, yet their magnitudes are sharply reduced: the effects for city pairs with HSR are only about 56% and 40% of those without HSR in Columns (3) and (4), and 53% and 69% in Columns (7) and (8). For the online search index, the point estimates in Columns (5) and (6) are similar across groups, but differences in sample means and statistical significance remain. Specifically, a one-standard-deviation increase in curvature reduces online search intensity from city i to city j by about 1.1% of the sample mean for pairs with HSR connections, compared with 1.8% for pairs without.

Overall, the results highlight an unintended benefit of China's HSR network: by providing an effective substitute for air travel, it mitigates the distortions caused by restrictive airspace regulations.

Table 4: Heterogeneity in high-speed rail (HSR)

Dep. Variable:	Log trade volume		# of subsidiaries		Online search index		Geotagged posts	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Panel A: Sample: City pairs *with* direct HSR connection								
$Curvature_{i,j}$	-0.0204	-0.0282	-0.0377**	-0.0340**	-0.0930	-0.102*	-0.0279***	-0.0410***
	(0.0208)	(0.0216)	(0.0165)	(0.0159)	(0.0575)	(0.0572)	(0.0105)	(0.0116)
Sample Mean	21.99	21.99	24.21	24.21	9.071	9.071	47.45	47.45
Observations	1275	1275	1275	1275	1275	1275	1275	1275
Adjusted/Pseudo R^2	0.922	0.924	0.662	0.673	0.901	0.913	0.926	0.928
Panel B: Sample: City pairs *without* direct HSR connection								
$Curvature_{i,j}$	-0.0662**	-0.0768***	-0.0672*	-0.0858**	-0.0959***	-0.103***	-0.0529**	-0.0596***
	(0.0302)	(0.0296)	(0.0366)	(0.0348)	(0.0369)	(0.0340)	(0.0246)	(0.0224)
Sample Mean	20.28	20.28	9.212	9.212	5.647	5.647	9.539	9.539
Observations	1499	1499	1502	1502	1502	1502	1502	1502
Adjusted/Pseudo R^2	0.820	0.824	0.876	0.888	0.693	0.698	0.693	0.698
log(shortest distance)	✓	✓	✓	✓	✓	✓	✓	✓
Distance bin FE (every 20 percentile)		✓		✓		✓		✓
% > 2000m mountains		✓		✓		✓		✓
Political hierarchy		✓		✓		✓		✓
Gravity term of population		✓		✓		✓		✓
Industry complementarity		✓		✓		✓		✓
Departure city FE	✓	✓	✓	✓	✓	✓	✓	✓
Arrival city FE	✓	✓	✓	✓	✓	✓	✓	✓

Notes: (1) This table reports the heterogeneity effects of airline route curvature. (2) The definition of the control variables is the same as in Table 2. (3) Since we use count variables in Columns 1–4, we employ Poisson regressions. (4) Robust SEs clustered at the city-pair level in parentheses. * significant at 10%; ** significant at 5%; *** significant at 1%.

5.5 Aeroconnectivity

The results in Sections 5.1 and 5.2 focus on established flight routes by 2019. Another critical effect of airspace regulations is that they can deter the establishment of new airline routes if the costs of operation is too high for airlines, which may further affect cities' economic connections. This is particularly critical in China's context, as more than 90% of air travel is on direct flights.[22] In this section, we investigate how potential route curvature influences aeroconnectivity between cities, specifically nonstop flight connections.

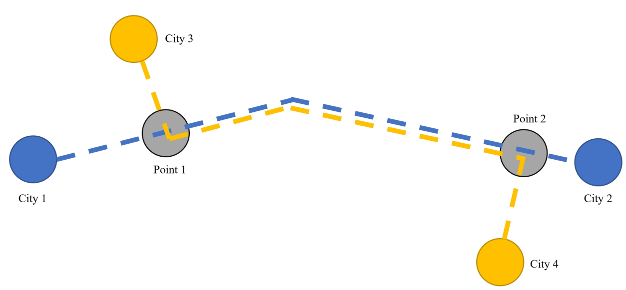
One obstacle for this exercise is that we do not know the actual curvature of airline routes for city pairs without direct flight connections. To address this, we construct hypothetical

[22] According to the 2024 Civil Aviation Industry Development Statistical Bulletin, only about 10% of travelers in China take a connecting flight. Source: https://www.mot.gov.cn/fenxigongbao/hangyegongbao/202505/P020250825409204940412.pdf

airline routes based on existing airline networks. The intuition behind this hypothetical route is as follows: when designing new connections, airlines typically build on existing routes because obtaining authorization to use new airspace is costly. For example, if Cities 1 and 2 already share an established route, and City 3 is close to City 1 while City 4 is close to City 2, then the new route between Cities 3 and 4 will likely resemble the route between Cities 1 and 2. This "free-riding" strategy allows airlines to minimize the cost of applying for new routes.

Figure 3 illustrates the route prediction process. In this figure, Cities 1 and 2 are connected by a nonstop flight (blue dotted line). The predicted route between Cities 3 and 4 is represented by the yellow dotted line. This route minimizes the use of new airspace and maximizes reliance on the existing route, thereby reducing costly applications for new airspace. Based on the predicted flight route between Cities 3 and 4 (yellow dotted line), we calculate the predicted route curvature, $PredictedCurvature_{i,j}$, using the following formula: $PredictedCurvature_{i,j} = \frac{\text{Predicted Flight Route Distance}_{i,j}}{\text{Shortest Flight Route Distance}_{i,j}} - 1$. Where Predicted Flight Route Distance$_{i,j}$ is the distance of the yellow dotted line, and Shortest Flight Route Distance$_{i,j}$ is the shortest distance between Cities 3 and 4.

Figure 3: Illustration of the construction of hypothetical flight route



Notes: This figure illustrates the route prediction process. (1) We use the existing airline routes (blue dashed line) to predict the potential airline route for unconnected city pairs (orange dashed line), and (2) we calculate the predicted curvature by dividing the length of the predicted route (orange dashed line) by the shortest distance between two cities unconnected.

To verify that the hypothetical flight route curvature constructed in Figure 3 correlates with the actual route curvature, we use the airline network in 1995 to compute the predicted curvature for the routes that were established in 2019 but *not* in 1995.[23] We then regress the actual route curvature for these routes on the predicted curvature. The results reported in Table A3 suggest that the predicted route curvature based on the 1995 network is highly

[23]The earliest year for which airline route data are available is 1995. Existing airline routes rarely change over time.

correlated with the actual route curvature.

After establishing a strong correlation between the predicted and the actual route curvature, we examine the impact of potential airline route curvature on aeroconnectivity by estimating Equation (2):

$$Y_{i,j} = \beta_1 PredictedCurvature_{i,j} + \alpha_i + \theta_j + \gamma X_{i,j} + \epsilon_{i,j} \tag{2}$$

Where the dependent variable, $Y_{i,j}$, is a dummy equals to 1 if cities i and j were connected by a nonstop flight in 2019. The terms α_i and θ_j represent the departure and arrival city fixed effects, respectively. $X_{i,j}$ is a set of city pair characteristics, as previously defined.

Table 5: Impact of predicted route curvature on connectivity

Dep. Variable:	Dummy of aeroconnectivity in 2019			
	(1)	(2)	(3)	(4)
Predicted Route Curvature$_{i,j}$	-0.0215***	-0.0184***	-0.0150***	-0.0144***
	(0.00516)	(0.00507)	(0.00520)	(0.00508)
Sample Mean	0.190	0.190	0.190	0.190
Observations	13370	13370	13126	13126
Adjusted R^2	0.305	0.328	0.313	0.333
log(shortest distance)	✓	✓	✓	✓
Distance bin FE (every 20 percentile)		✓		✓
% >2000m moutains		✓		✓
HSR connection dummy			✓	✓
Political hierarchy			✓	✓
Gravity term of population			✓	✓
Industry complementarity			✓	✓
Departure city FE	✓	✓	✓	✓
Arrival city FE	✓	✓	✓	✓

Notes: (1) This table reports the impact of predicted route curvature on the city pairs' aeroconnectivity. (2) To make the results comparable, we normalize the predicted route curvature to a variable with mean 0 and standard deviation 1. (3) We exclude city pairs whose shortest distance is less than 200 km, as these cities are unlikely to have direct flight connections. (4) The definitions of the control variables are the same as those in Table 1. (5) Robust standard errors clustered at the city pair level are reported in parentheses. * significant at 10%; ** significant at 5%; *** significant at 1%.

The results in Table 5 suggest that the underlying curvature of airline routes significantly negatively impacts aeroconnectivity. A one-standard-deviation increase in curvature between cities i and j reduces the probability of a direct flight connection between them by 1.4 percentage points, equivalent to 7.6% of the sample mean. If China were to relax airspace regulations to the U.S. level (around a 1.2 standard deviation reduction in route curvature), there would be 9.1% more city pairs connected by a direct flight.

6 Conclusion

This paper uses China's restrictive commercial airspace as a case study to investigate the economic impacts of inefficient design in transportation networks. In contrast to the literature that focuses primarily on the economic impacts of transportation connectivity at the extensive margin, this paper studies the effects of connection "quality." The airline industry provides an ideal setting for our study. Unlike land transportation connections, where the optimal routes are shaped by multiple physical barriers such as mountains and rivers, airline connections can be evaluated against an obvious quality benchmark, namely, the great circle distance—the shortest path between two points on a sphere.

We collected a novel dataset on flight trajectories to measure actual flight distances and airline route curvatures. Our analysis reveals that, because of the restrictions on commercial use of airspace, the average route curvature in China is 17%, significantly higher than the 5% average in the US and Europe. Empirical estimates indicate that substantial route curvature increases airfares, reduces flight frequency, competition, and decreases the number of aeroconnected city pairs. These inefficiencies impose considerable economic costs, hindering intercity activities such as personal travel, population migration, inter-city trade flows, and intercity corporate investment. Our heterogeneity analysis suggests that the existence of alternatives—HSR in this case—can reduce the welfare loss from curved airline routes when airspace regulations cannot be easily relaxed and routes cannot be straightened in the short run.

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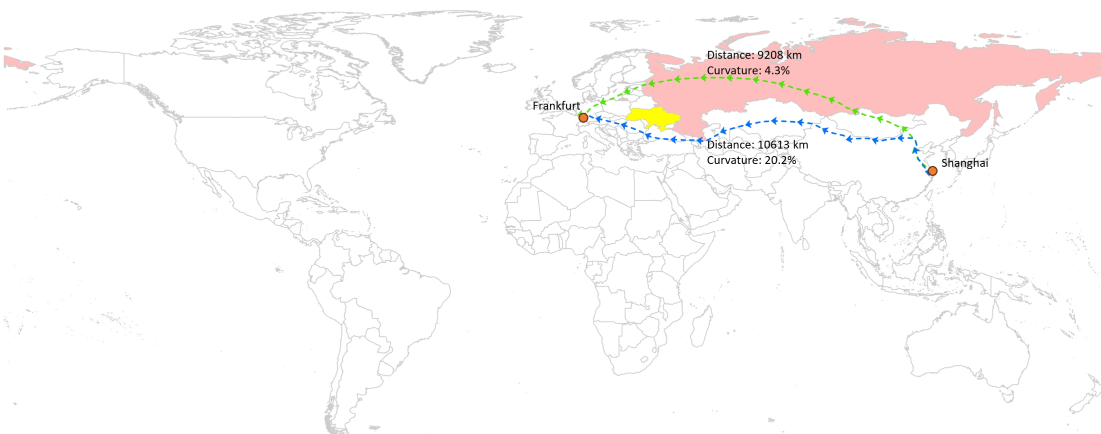
Barriers in the Sky
(Not Intended for Publication)

Online Appendix

A Curved routes on international flights

Figure A1: Curved routes on international flights



(a) Shanghai–Frankfurt flight routes before and after the Russia–Ukraine war

(b) Taipei–Frankfurt flight route in 2025

Notes: The green (blue) line in Panel (a) represents the Shanghai–Frankfurt flight route before (after) Russia's invasion of Ukraine in February 2022. Panel (b) presents the Taipei–Frankfurt flight route in 2025.

B Further data description

Figure A2: Example of airline route data: Shanghai–Beijing

Notes: This figure illustrates the raw data obtained from Flightradar24, using the Shanghai–Beijing airline route as an example. For each airline route, the real-time coordinates of each flight are recorded at an average frequency of once per minute, with the maximum interval between consecutive coordinates not exceeding ten minutes. With these coordinates, we can reconstruct the actual flight path in a GIS environment by connecting the points with a straight line.

Table A1: Descriptive statistics

Variable	Obs	Mean	SD	10^{th} pct	Median	90^{th} pct
Panel A. Airline routes						
Curvature (%)	2807	17.2	9.6	7.2	15.2	28.9
Shortest (great circle) distance (km)	2807	1186.3	498.1	620.7	1127.9	1814.4
Panel B. Flight data						
Average price of flights (USD 2019)	69694	104.7	48.1	54.8	94.1	170.6
# of weekly flights	2807	24.8	32.2	4	14	60
# of weekly seats	2807	4.4	6.7	.6	2.3	10.5
Panel C. City pair data						
Weibo Mobility Index	2807	25	49	1	8	57
Baidu Search Index	2807	7.3	4.7	3.3	5.9	13.2
# of branch firms	2807	16	16.3	1	8	47
Dummy HSR connection	2807	.46	0.5	0	0	1
City pair political hierarchy	2807	.1	.3	0	0	1
Herfindahl-Hirschman Index (HHI)	2807	.7	.3	.3	.6	1
Industry complementarity	2807	0.012	0.007	0.006	0.010	0.019
% route altitude $> 2000m$	2807	0.055	0.158	0	0	0.16
Dummy air connection	14626	.3	.4	0	0	1

Notes: This table summarizes the descriptive statistics of relevant variables used in our empirical analyses.

C Airline route curvature and city characteristics

Table A2: Relationship between airline route curvature and city characteristics

Dep. variable	Curvature (%)	
	(1)	(2)
Population (departure city)	0.00109	0.00182
	(0.00607)	(0.00607)
GDP (departure city)	0.0242	-0.00772
	(0.0585)	(0.0638)
Population (arrival city)	0.000761	0.00147
	(0.00606)	(0.00606)
GDP (arrival city)	0.0274	-0.00316
	(0.0587)	(0.0640)
Political hierarchy (departure city)		0.0586
		(0.0506)
Political hierarchy (arrival city)		0.0564
		(0.0506)
Log shortest distance	-0.914***	-0.918***
	(0.0766)	(0.0765)
Observations	2822	2822
Adjusted R^2	0.149	0.150

Notes: This table reports the relationship between airline route curvature and city characteristics. The populations of the departure and arrival cities are measured in millions. The GDP statistics of the departure and arrival cities are measured in trillions of CNY. The political hierarchy variable is a dummy that equals 1 if the departature/arrival city is a vice-provincial-level city or above. Robust standard errors clustered at the city pair level are reported in parentheses. * significant at 10%; ** significant at 5%; *** significant at 1%.

D Predicted route curvature and actual route curvature

Table A3: Predicted route curvature and actual route curvature

Dep. Variable:	Actual route curvature (%)			
	(1)	(2)	(3)	(4)
Predicted route curvature$_{i,j}$	0.532***	0.525***	0.511***	0.514***
	(0.0774)	(0.0767)	(0.0775)	(0.0785)
Sample Mean	0.175	0.175	0.175	0.175
Observations	1452	1452	1420	1420
Adjusted R^2	0.276	0.285	0.271	0.280
log(shortest distance)	✓	✓	✓	✓
Distance bin FE (every 20 percentile)		✓		✓
% >2000m moutains		✓		✓
HSR connection dummy			✓	✓
Political hierarchy			✓	✓
Gravity term of population			✓	✓
Industry complementarity			✓	✓
Departure city FE	✓	✓	✓	✓
Arrival city FE	✓	✓	✓	✓

Notes: (1) This table uses flight routes that were established in 2019 but not in 1995. (2) It reports the impact of the predicted route curvature described in Figure 3 on the actual route curvature. (3) The definitions of the control variables are the same as those in Table 1. (4) Robust standard errors clustered at the city-pair level are reported in parentheses. * significant at 10%; ** significant at 5%; *** significant at 1%.