Institutional Permeability and Cross-Border Transmission: Evidence from Uzbekistan's 2017 Liberalization

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Abstract

While standard diffusion frameworks predict that liberalizing reforms generate positive spillovers in geographically proximate regions, borders are not frictionless membranes. Even observable connectivity may fail to translate into cross-border economic co-movement when institutional frictions govern whether interaction activates transmission. Using Uzbekistan's 2017 exchange-rate unification as a natural experiment, this paper examines whether reform-driven spillovers were attenuated by the institutional regime of neighboring Turkmenistan. Using annual VIIRS night-time lights across 19 matched border crossing pairs on the Uzbek-Turkmen, Uzbek-Kyrgyz, and Uzbek-Tajik frontiers, I document a large and frontier-specific divergence following the reform – a pattern absent on Kyrgyz and Tajik frontiers sharing identical Uzbek-side conditions. Two main tests rule out observable explanations. First, Turkmen attenuation persists even when restricting to the highest-interface crossings, where market-mediated transmission is most plausible. Second, a benchmark residual test shows Turkmen crossings under-absorbed significantly relative to connectivity-based predictions during the reform period, with partial normalization after 2022 coinciding with bilateral border policy relaxation. The timing of this reversal, which tracks policy rather than any change in geography or trade composition, is difficult to reconcile with non-institutional explanations. The results suggest that geographic proximity and observable infrastructure are necessary but insufficient for cross-border spillovers: institutional permeability, itself partly a bilateral policy parameter rather than a fixed property of the neighboring regime, determines whether transmission mechanisms activate.

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Section 1: Introduction

Economic liberalization in one country is often assumed to generate positive spillovers in geographically proximate regions. Standard diffusion frameworks and gravity-based models predict that reductions in trade costs, exchange-rate distortions, and border frictions should increase bilateral exchange and stimulate economic activity in adjacent settlements (Krugman 1991; Hanson 1996; Head and Mayer 2014). Yet borders are not frictionless membranes. Even when formal tariffs are low, institutional frictions such as currency controls, mobility restrictions, and administrative barriers to private trade can substantially attenuate cross-border economic interaction (McCallum 1995; Anderson and van Wincoop 2003). Whether such frictions operate at the settlement level, and whether their effects can be identified relative to comparable frontiers, is the central question of this paper.

This paper explores this in the context of Central Asia following Uzbekistan's 2017 exchange-rate unification and liberalization, one of the most significant economic reforms in the region in the post-Soviet period (World Bank 2024). In September 2017, Uzbekistan unified its multiple exchange rate tiers, eliminated restrictions on foreign exchange access, and removed administrative barriers to cross-border commerce, ending a system under which parallel rates had artificially segmented domestic and international markets. Associated reforms reduced licensing requirements for private cross-border trade and loosened restrictions on foreign currency holding. Using annual night-time lights (NTL) from the VIIRS Black Marble product for 2012-2024 as a proxy for local economic activity (Henderson, Storeygard, and Weil 2012; Donaldson and Storeygard 2016), I examine 19 matched border crossing pairs across the Uzbek-Turkmen, Uzbek-Kyrgyz, and Uzbek-Tajik frontiers. These three frontiers share Uzbek-side economic conditions but differ sharply in the institutional permeability of the neighboring regime. Kyrgyzstan maintains a relatively open border and market-oriented economy, with freely convertible currency and WTO membership since 1998. Tajikistan occupies an intermediate position as a WTO member with its own currency restrictions and state dominance in key sectors. Turkmenistan, by contrast, operates one of the most closed and centralized economies in the world (Guriev and Treisman 2019).

The central empirical finding is a large and frontier-specific divergence. Uzbek-side settlements pulled significantly ahead of matched Turkmen counterparts following the reform (a gap of 0.49 asinh units,

$p<0.01$), while no comparable divergence emerged on Kyrgyz or Tajik frontiers. This asymmetry persists after conditioning on geography, infrastructure, and observable commercial activity. Even restricting to the highest-interface crossings, where market-mediated transmission is most plausible, Turkmen towns absorb 0.99 fewer units of Uzbek-side change per unit than matched crossings on benchmark borders ($p<0.001$).

An observed divergence alone does not provide a complete explanation. The central question is not simply whether spillovers occur, but how cross-border transmission operates and whether it depends on local interface. In particular, the significantly attenuated Turkmen transmission may reflect either a lack of economically active crossings or a failure of cross-border transmission mechanisms to convert interaction into local economic activity.

To examine this mechanism, I estimate first-difference transmission models that measure how changes in Uzbek-side activity map into changes on the neighboring side. I then construct crossing-level measures of local interface using OpenStreetMap data, including commercial density, road connectivity, and proximity to major cities, and allow transmission elasticities to vary with these features. Finally, I test whether the relationship between interface and transmission differs systematically on the Turkmen frontier relative to benchmark borders.

Three findings emerge:

1. The Uzbek-Turkmen frontier diverges significantly and specifically following the reform, while no comparable divergence is observed on Kyrgyz or Tajik frontiers.
2. Transmission is consistently attenuated on the Turkmen frontier across specifications, including at high-interface crossings where transmission potential is greatest.
3. Turkmen crossings under-absorb relative to connectivity-based predictions during the reform period, with partial normalization after 2022 coinciding with changes in border policy.

Tajikistan, by contrast, exhibits intermediate transmission relative to Kyrgyzstan and Turkmenistan.

The central contribution of this paper is not to simply document a null spillover result, but to show that cross-border transmission is heterogeneous and systematically weaker along the distinct frontiers, even conditional on observable interface. These patterns are difficult to reconcile with explanations based solely on geography, infrastructure, or trade composition, and are consistent with institutional or policy constraints affecting how cross-border interaction translates into local economic activity.

More broadly, this paper enriches existing literature on spatial diffusion, border effects, and political economy in four ways. First, it provides settlement-level evidence on reform spillovers using high-resolution nightlights data in a region where conventional economic statistics are limited. Second, it moves beyond binary spillover tests by estimating country-specific transmission elasticities that reveal a gradient across all three neighboring frontiers: Kyrgyzstan transmitting strongly, Tajikistan weakly, and Turkmenistan negatively. Third, it introduces a connectivity-conditioned benchmark to assess under-absorption relative to comparable frontiers. Fourth, it demonstrates that the benchmark residual design can distinguish between structural under-transmission and reform-activated under-absorption.

The remainder of the paper proceeds as follows. Section 2 reviews the relevant literature and develops the theoretical framework. Section 3 describes the data and sample construction. Section 4 outlines the empirical strategy. Section 5 presents the main results. Section 6 discusses interpretation and alternative explanations. Section 7 concludes.

2. Literature Review

2.1 Cross-Border Spillovers and Border Effects

Economic geography and international trade theory predict that reductions in trade costs increase bilateral exchange and generate localized growth near border regions (Krugman 1991; Hanson 1996; Head and Mayer 2014). Gravity models imply that proximity and market size jointly determine trade flows, while new economic geography emphasizes agglomeration forces and market access. When a country undertakes liberalizing reforms, such as exchange-rate unification or tariff reduction, nearby regions in neighboring countries may benefit through increased trade, arbitrage, labor mobility, and service-sector activity.

Empirical evidence on border effects, however, demonstrates that national borders remain powerful separators of economic activity. McCallum (1995) documents large border effects even between Canada and the United States. Subsequent work shows that borders shape trade, migration, price dispersion, and firm location (Anderson and van Wincoop 2003; Gopinath et al. 2011). Even when formal tariffs are low, institutional frictions – including the arbitrary customs enforcement, capital controls, and mobility restrictions Turkmenistan often employs – can attenuate cross-border economic interaction.

Most empirical studies treat border effects as binary: either spillovers occur or they do not. Less attention has been paid to the elasticity of transmission – how strongly changes on one side of a border translate into changes on the other – and what determines the relationship. This paper reframes cross-border spillovers as a transmission problem, focusing on how shocks propagate across borders and how this propagation depends on conditions at crossing points and the institutional regime governing exchange. While McCallum (1995) and Anderson & van Wincoop (2003) quantify the size of the border effect, this paper identifies a mechanism of this border effect: the elasticity of institutional absorption

2.2 Institutional Regimes and Border Permeability

Political economy research suggests that institutional regimes can shape the permeability of borders and the extent of cross-border economic interaction (Guriev and Treisman 2019; Way 2005). Authoritarian systems may impose administrative barriers, currency restrictions, or mobility controls that reduce effective exchange even when geographic proximity would predict strong integration. These frictions need not eliminate cross-border exchange entirely: they may instead alter the composition, scale, or organization of interaction in ways that reduce its capacity to generate localized economic spillovers.

Figure 1: Institutional Characteristics of Uzbekistan's Neighboring Frontiers

	Uzbek–Kyrgyz (7 crossing pairs)	Uzbek–Tajik (6 crossing pairs)	Uzbek–Turkmen (6 crossing pairs)
Freedom House score (2024)	26 / 100 Not Free	5 / 100 Not Free; 0/40 political rights	1 / 100 Not Free; lowest score globally
Regime type	Electoral authoritarian; two mass uprisings (2005, 2010); competitive if flawed elections; limited civil society space	Consolidated authoritarian; Rahmon family dominance since 1992; political opposition eliminated; zero political rights score for seven consecutive years	Hermit state; presidential dynasty; second most isolated country globally; no independent media; state controls all information flows
GDP per capita (2023, USD)	$1,970 Remittances ≈ 18% of GDP	$1,161 Remittances ≈ 48% of GDP	$8,233 Official; widely considered overstated given black market exchange rate
Principal industries	Gold mining, remittances, agriculture, re-export trade; major informal transit hub for Chinese goods	Aluminum smelting, cotton, hydropower exports, remittances; heavily dependent on labor migration	Natural gas (~84% of exports); 4th-largest proven reserves globally; cotton, petrochemicals; near-total state ownership of productive assets
Currency convertibility	Freely convertible (som); no restrictions; among first CIS states to fully liberalize; no parallel market	Restricted; official rate maintained; capital controls in place; some parallel market spread	Severely restricted; official rate fixed since 2008; black market rate ~4× official (2017–2020); hard currency access controlled by state banks
WTO membership	Member since December 1998; shortest CIS accession (2 years); tariffs bound at low levels	Member since March 2013; 12-year accession process	Non-member; only non-WTO economy in Central Asia; government commission on accession established 2013 but no active negotiations
Private sector and trade administration	Substantial private sector dominant in trade and retail; minimal licensing for small traders; large informal cross-border commerce	Moderate; state dominates aluminum, energy, cotton; private SMEs in services; administrative barriers to cross-border trade	State directs allocation in all major sectors; private cross-border trade requires licensing through state intermediaries; foreign exchange for imports requires state approval
Heritage Foundation Economic Freedom rank (2023)	110th / 184 "Moderately Free"	135th / 184 "Mostly Unfree"	161st / 184 "Repressed"; lowest among post-Soviet states
Implied θ_0 (Table 5, col. 2)	*+0.415*** (strong transmission)	*+0.092* (weak; not significant)	*−0.113* (negative implied transmission)

Central Asia provides a useful setting to examine these dynamics. Uzbekistan's 2017 reforms liberalized foreign exchange markets and reduced administrative barriers to cross-border exchange. Kyrgyzstan has historically maintained relatively open borders and higher levels of regional integration. Turkmenistan, by contrast, remains highly centralized, with extensive currency controls, state-administered trade, and severe restrictions on private cross-border movement. These differences imply that the same Uzbek-side shock may transmit differently across borders on account of the institutional environment governing whether economic interaction generates local activity[1].

These institutional differences are summarized in Figure 1, which documents structural features of each neighboring frontier that are independent of Uzbekistan's 2017 reform. The three frontiers exhibit a clear gradient in institutional permeability: Kyrgyzstan maintains relatively open borders and a convertible currency regime; Tajikistan occupies an intermediate position with administrative and financial frictions; and Turkmenistan exhibits extensive state control over currency, trade, and cross-border mobility. These differences provide a natural setting to examine whether similar cross-border interface conditions translate into different transmission outcomes depending on the institutional environment.

2.3 Local Interface and Heterogeneous Transmission

While standard gravity models emphasize aggregate trade flows, cross-border transmission at the local level depends on the presence of observable interface through which economic interaction occurs. I define local interface as the extent to which cross-border exchange is mediated through decentralized, market-based activity at border nodes.

At the crossing level, interface varies with features such as commercial density, road connectivity, and proximity to urban centers. These characteristics capture the capacity of a crossing to support logistics, trade intermediation, and local economic activity.

Let crossing p connect Uzbek settlement U_p and non-Uzbek settlement N_p. Let ΔY_{pt}^{U} denote the change in Uzbek-side activity. Interface proxies the capacity for transmission – a crossing with dense commercial nodes and good road connectivity is better positioned to support cross-border economic activity. Whether that capacity is realized depends on whether institutional frictions allow market-mediated exchange to operate:

[1] Notably, not all authoritarian regimes suppress cross-border economic integration. Singapore, the UAE, and early-reform China maintained highly open economic borders under such governance. The paper does not claim authoritarianism universally blocks spillovers; it documents that institutional permeability varies and maps onto observable transmission outcomes.

(1) $$\Delta Y_{pt}^{N} = \theta_0 \Delta Y_{pt}^{U} + \theta_1 \left(\Delta Y_{pt}^{U} \times Interface_p\right) + \varepsilon_{pt}$$

A crossing with high interface but binding institutional frictions may exhibit no greater transmission than one with lower interface, because the frictions suppress the conversion of interaction into economic activity regardless of observable connectivity. This distinction motivates the benchmark residual design: by conditioning on interface when predicting transmission from benchmark borders, I isolate attenuation that cannot be accounted for Turkmen crossings by observable local conditions.

2.4 A Simple Transmission Framework

Consider a reduced-form representation of cross-border transmission:

(2) $$\Delta Y_{pt}^{N} = \lambda_p \Delta Y_{pt}^{U} + \varepsilon_{pt}$$

where λ_p is a crossing-specific transmission elasticity.

Let transmission depend on interface and border-specific frictions:

(3) $$\lambda_p = f(Interface_p) - \tau_{border}.$$

Here, $f(Interface_p)$ captures the potential for transmission generated by observable interface, while $\tau_{border} \geq 0$represents effective frictions that inhibit the conversion of interaction into local economic activity.

This framework yields two testable predictions. First, Turkmen crossings should exhibit systematically lower realized transmission than benchmark borders, even conditional on comparable interface levels. Second, if the frictions are policy-contingent rather than structural, they should be sensitive to changes in border access policy, generating a reversal in transmission patterns when policies relax.

The benchmark residual design follows directly. I estimate the baseline transmission rate on Kyrgyz pairs, which serve as the permeable-border benchmark, and test whether Turkmen crossings absorb at rates consistent with that benchmark. A significantly negative residual indicates elevated τ on the Turkmen frontier. A subsequent reversal in the post-2022 period provides evidence that τ is policy-contingent rather than permanent.

2.5 Night-Time Lights as a Proxy for Economic Activity

Night-time lights are widely used as a proxy for subnational economic activity, particularly in contexts where official statistics are limited or unreliable (Henderson, Storeygard, and Weil 2012; Chen and Nordhaus 2011; Donaldson and Storeygard 2016). At the settlement level, luminosity correlates with income, consumption, and electrification. In the Central Asian context, subnational economic data are sparse and subject to reporting concerns, especially in Turkmenistan. VIIRS night-time lights provide consistent, high-frequency, cross-country coverage from 2012 onward.

While nightlights are an imperfect proxy for economic activity, several features of the empirical design mitigate concerns about measurement error. Identification relies on within-settlement changes over time and within-pair co-movement, rather than cross-sectional level comparisons. All countries are processed using identical extraction, masking, and aggregation procedures, ensuring cross-border comparability. Gas flaring is explicitly masked using geolocated flare coordinates with a 5 km exclusion radius, which is particularly important in the Turkmen context where hydrocarbon production could otherwise contaminate measured luminosity near extraction sites.

2.6 Contribution to the Literature

This paper contributes to three strands of literature. First, it provides settlement-level evidence on reform spillovers in Central Asia using high-resolution satellite data in a context where conventional economic statistics are limited or unreliable, contributing to a growing literature using remote sensing to study economic activity in data-sparse environments (Henderson, Storeygard, and Weil 2012; Donaldson and Storeygard 2016).

Second, it shifts the empirical focus from binary spillover detection to the estimation of cross-border transmission elasticities at the crossing level. By estimating first-difference models with crossing-pair and year fixed effects, the design isolates within-pair co-movement over time and directly measures the degree to which economic shocks propagate across borders.

Third, it introduces a benchmark residual approach that allows under-absorption to be evaluated relative to observable local conditions on comparable frontiers, rather than against a theoretical benchmark. This design has two advantages over standard null spillover tests: it explicitly conditions on interface when generating predictions, and it allows for a natural policy test when institutional conditions change. The post-2022 reversal in benchmark residuals, coinciding with bilateral transport normalization, is consistent with policy-contingency of institutional frictions that is rare in this literature.

The paper does not claim that authoritarian regimes universally block spillovers. Rather, it demonstrates that the observed attenuation on the Turkmen frontier is difficult to reconcile with geography, infrastructure, or trade composition, and imply a significant effect of elevated effective frictions that are sensitive to border policy.

3. Data

3.1 Night-Time Lights

The primary outcome variable is annual night-time luminosity from the VIIRS Black Marble product, covering 2012–2024. VIIRS provides daily radiance measurements at approximately 500-meter spatial resolution, corrected for stray light, atmospheric effects, and lunar illumination. For each settlement, I compute annual mean radiance within polygons defined by administrative boundaries and manually verified settlement extents. All countries are processed using identical extraction, masking, and aggregation procedures to ensure cross-border comparability.

To accommodate zero values and maintain comparability with log-based specifications, radiance is transformed using the inverse hyperbolic sine:

(4)
$$Y_{it} = \operatorname{asinh}(NTL_{it}) = \log\left(NTL_{it} + \sqrt{NTL_{it}^2 + 1}\right)$$

For large values, this transformation approximates the natural logarithm; for small values, it remains well-defined at zero.

Because gas flaring may artificially inflate luminosity in energy-producing regions, I mask flare sites using geolocated flare coordinates with a 5 km exclusion radius. Robustness checks using 3 km and 10 km buffers yield similar results. This is particularly important in the Turkmen context, where hydrocarbon production could otherwise contaminate measured luminosity near extraction sites.

3.2 Settlement Classification

The empirical design distinguishes settlements by proximity to the Uzbek border. For each country, settlements are classified into three mutually exclusive categories:

- Border settlements: within 20 km of the Uzbek border.
- Middle settlements: among the top 30 cities by population (population > 10,000), located in the middle tercile of the national distance-to-border distribution.
- Far settlements: among the top 30 cities by population (population > 10,000), located in the far tercile of the national distance-to-border distribution.

Distance is computed using standard geodesic centroid-to-border measures. Middle and far settlements serve as within-country comparison groups, allowing the design to net out country-level shocks and isolate border-specific dynamics.

3.3 Border Pair Construction

To analyze cross-border spillovers at a finer spatial level, I construct matched settlement pairs at major border crossings. Each pair consists of one Uzbek settlement and one non-Uzbek settlement (Turkmen, Kyrgyz, or Tajik), located at or immediately adjacent to a formal crossing node. Pairs are constructed by matching each non-Uzbek border town to its geographically adjacent Uzbek counterpart at a shared formal crossing node, yielding 6 Uzbek–Turkmen, 7 Uzbek–Kyrgyz, and 6 Uzbek–Tajik pairs.

Pair identifiers are fixed over time, allowing estimation of two-sided specifications of the form:

$$Y_{ipt} = \alpha_p + \delta_t + \gamma(UZBside_i \times Post_t) + \varepsilon_{ipt}, \tag{5}$$

where $p$indexes crossing pairs and $i$indexes settlements within each pair. This specification absorbs time-invariant crossing characteristics and isolates asymmetric responses across the border.

3.4 Reform and Period Indicators

The key treatment period begins in 2017, corresponding to Uzbekistan's exchange-rate unification and associated liberalization measures.

I define three mutually exclusive period indicators: *Post2017* equals one for 2017-2019 (initial reform window, prior to COVID); *COVID* equals one for 2020-2021 (pandemic disruption period); *Reopen2022* equals one for 2022 onward (bilateral normalization period). These indicators partition the post-reform sample; Post2017 does not remain active in COVID or post-2022 years.

These indicators allow the analysis to separate reform effects from pandemic-related disruptions and subsequent normalization.

3.5 Border-Node Interface Measures

To capture heterogeneity in local transmission channels, I construct crossing-level measures of local interface using OpenStreetMap (OSM) data via the Overpass API.

For each crossing polygon (defined as a 10 km buffer around each paired border node), I compute:

- Shop density: number of retail and commercial establishments per square kilometer
- Distance to nearest major city: road-network distance to cities with population greater than 100,000
- Road connectivity indicators: proximity to trunk and primary highways

Shop density proxies the intensity of market-mediated activity at the border, capturing the presence of commercial nodes through which cross-border exchange can generate local spillovers. Road connectivity and proximity to major cities capture the integration of each crossing into broader transport and distribution networks.

These variables jointly proxy the extent to which cross-border interaction is mediated through decentralized, market-based activity, which I refer to as local interface. All measures are constructed symmetrically across countries and are normalized for interpretability. The crossing intensity index is a standardized composite average of shop, intersection, and road z-scores, where each z-score is computed across all 19 non-Uzbek crossing towns. Note that several Turkmen border settlements, including Dashoguz, Turkmenabat, and Konye-Urgench, are regional cities rather than small rural settlements, which explains why Turkmen crossings score comparably to or above benchmark settlements on road infrastructure despite greater institutional closure. Summary statistics by frontier are reported in Table 1.

Table 1: Border-node Interface Characteristics by Frontier

Summary statistics for border settlements within 20 km of the Uzbek border; OpenStreetMap data

	Uzbek–Turkmen				Uzbek–Kyrgyz				Uzbek–Tajik			
	Mean	SD	Min	Max	Mean	SD	Min	Max	Mean	SD	Min	Max
A. Commercial interface												
Shop density (shops/km²)	0.366	0.487	0.024	1.322	0.286	0.423	0.018	1.140	0.088	0.120	0.006	0.322
B. Road infrastructure												
Road capacity density (km/km²)	0.250	0.095	0.108	0.372	0.167	0.063	0.090	0.246	0.129	0.096	0.039	0.314
Intersection density (per km²)	7.246	5.779	1.889	14.592	6.260	5.300	2.309	17.235	4.565	4.623	0.451	12.365
C. Market access												
Distance to nearest city (km)	0.401	0.387	0.106	1.124	27.624	24.101	0.534	64.531	27.022	35.346	0.168	79.601
D. Composite index												
Crossing intensity index	−0.072	0.191	−0.375	0.156	−0.152	0.471	−0.564	0.623	−0.433	0.221	−0.703	−0.055
Settlements (N)	6				7				6			

Notes: Sample consists of non-Uzbek border settlements within 20 km of the Uzbek border at each matched crossing node. All measures are constructed from OpenStreetMap data via the Overpass API and are treated as time-invariant. *Shop density* counts retail and commercial establishments per km² within a 10 km buffer of each crossing node. *Road capacity density* is the total length of trunk and primary roads per km². *Intersection density* counts road intersections per km². *Distance to nearest city* is road-network distance to the nearest city with population >100,000. The *crossing intensity index* is a composite z-score combining shop density, intersection density, and road capacity density, normalized to mean zero and unit standard deviation in the full sample.

Two patterns in Table 1 are worth noting for the empirical analysis that follows. First, Uzbek-Turkmen crossings score comparably to or above benchmark crossings on every interface measure: shop density (0.366 vs. 0.286 on the Kyrgyz frontier), road capacity density (0.250 vs. 0.167), and intersection density (7.246 vs. 6.260). The composite crossing intensity index is highest on Turkmenistan's frontier (-0.072) and lowest on the Tajik frontier (-0.433). Second, Turkmen crossings are closer to major cities than either benchmark frontier (mean 0.401 km vs. 27.6 km for Kyrgyz and 27.0 km for Tajik), reflecting the presence of regional urban centers such as Turkmenabat and Dashoguz at several crossing nodes. This gradient is important context for the transmission results: any attenuation found on the Turkmen frontier in Sections 5.3 and 5.4 cannot be attributed to inferior observable interface.

Importantly, interface measures are treated as time-invariant in the baseline specification. This reflects the relatively slow-moving nature of infrastructure and commercial geography and ensures that estimated effects capture how pre-existing interface conditions shape the transmission of shocks, rather than contemporaneous changes in local activity.

3.6 Final Panel Structure

The final dataset consists of annual observations from 2012–2024 and includes:

- settlement-level luminosity
- border proximity classifications
- crossing-pair identifiers
- interface measures

For transmission analysis, I construct first differences:

$$\Delta Y_{pt} = Y_{p,t} - Y_{p,t-1} \tag{6}$$

The resulting transmission panel contains 228 pair-year observations across 19 border pairs (reduced to 84 observations in high-interface subsamples).

3.7 Measurement Considerations

Night-time lights provide an indirect measure of economic activity and may reflect electrification, infrastructure expansion, or urban development rather than formal output alone. However, several features of the empirical design mitigate these concerns.

1) Identification relies on within-settlement changes over time rather than cross-sectional level comparisons.
2) Cross-border comparisons are conducted using identical measurement technology and processing pipelines, ensuring consistency across countries.
3) Robustness checks across alternative spatial thresholds yield similar results.
4) Gas flare sites are identified using time-invariant coordinate data. While flaring activity varies over time, flare locations are geographically stable, and the fixed-location masking approach is standard in the literature. Results are unchanged using 3 km and 10 km exclusion buffer alternatives.

While OpenStreetMap data may be subject to measurement error or differential coverage across countries, the analysis leverages interface measures primarily as cross-sectional moderators of transmission rather than as outcomes of interest. To the extent that measurement error in interface is classical, it would attenuate estimated interaction effects, making the results conservative.

Finally, given the absence of reliable subnational economic data for Turkmenistan in particular and Central Asia in general, satellite-based measures provide a consistent and comparable proxy for economic activity across borders.

4. Empirical Strategy

The strategy proceeds in three stages: paired-border specifications that establish the frontier-specific divergence and its timing; baseline difference-in-differences, presented as descriptive context and motivation for the transmission framework; and transmission models that estimate cross-border elasticities, condition on local interface, and test for systematic attenuation on the Turkmen frontier.

4.1 Baseline Difference-in-Differences

To document whether border settlements exhibit differential luminosity trends relative to interior settlements within each country, I estimate:

$$Y_{it} = \alpha_i + \delta_t + \beta(Border_i \times Post_t) + \varepsilon_{it} \tag{7}$$

where Y_{it} is asinh-transformed night-time luminosity for settlement $i$in year t, α_i are settlement fixed effects, δ_t are year fixed effects, $Border_i$ indicates settlements within 20 km of the Uzbek border, and $Post_t$ equals one for 2017–2019.

The coefficient β captures differential luminosity changes in border settlements relative to interior settlements. Standard errors are clustered at the settlement level.

To control for period-specific shocks that may differentially affect the sample, I include additive period indicators for COVID (2020–2021) and post-2022 without interacting them with Border:

(8) $$Y_{it} = \alpha_i + \delta_t + \beta_1(Border_i \times Post2017_t) + \beta_2 COVID_t + \beta_3 Reopen2022_t + \varepsilon_{it}$$

These additive indicators absorb common period shocks while the Border × Post term captures differential border effects in the reform window.

The difference-in-differences design relies on the assumption of parallel pre-trends between border and interior settlements. I assess this using event-study specifications:

(9) $$Y_{it} = \alpha_i + \delta_t + \sum_{k \neq -1} \gamma_k \, (Border_i \times 1[t = k]) + \varepsilon_{it}$$

Pre-2017 coefficients provide a test for differential pre-trends (see Appendix). Pre-2017 coefficients indicate significant pre-trends for Uzbekistan, Kyrgyzstan, and Tajikistan in the one-sided border-vs-interior design; these specifications are therefore presented as descriptive. Pre-trends pass for the Turkmenistan one-sided design only (Wald χ^2=1.16, p=0.763; see Appendix Figure A1).

4.2 Paired-Border Specification

To isolate asymmetric responses at specific crossing nodes, I estimate paired-border models of the form:

(10) $$Y_{ipt} = \alpha_p + \delta_t + \gamma(UZBside_i \times Post_t) + \varepsilon_{ipt}$$

where $p$indexes border pairs and $\alpha_p$are pair fixed effects. Y_{ipt} denotes asinh-transformed VIIRS luminosity for settlement i, where i indexes the Uzbek-side and non-Uzbek-side settlements within crossing pair p; α_p are crossing-pair fixed effects absorbing all time-invariant characteristics of each crossing; δ_t are year fixed effects absorbing common annual shocks; and $Post_t$ equals one for 2017 onward in the pooled specification.

This specification compares Uzbek and non-Uzbek settlements within the same crossing, absorbing all time-invariant crossing characteristics. The coefficient γcaptures whether Uzbek-side settlements respond differentially relative to their paired neighbors. Standard errors are clustered at the pair level.

4.3 Transmission Elasticity Model

The baseline specifications test for level differences. To measure cross-border spillovers directly, I estimate first-difference transmission models:

(11)
$$\Delta Y_{pt}^{non} = \theta_0 \Delta Y_{pt}^{uzb} + \alpha_p + \delta_t + \varepsilon_{pt}$$

where $\Delta Y_{pt} = Y_{p,t} - Y_{p,t-1}$.

The coefficient θ_0 captures the extent to which changes in Uzbek-side activity transmit across the border. This specification absorbs time-invariant crossing characteristics and common year shocks, isolating within-pair co-movement over time.

4.4 Interface-Moderated Transmission

To test whether spillover transmission depends on local interface, I estimate:

(12)
$$\Delta Y_{pt}^{non} = \theta_0 \Delta Y_{pt}^{uzb} + \theta_1 (\Delta Y_{pt}^{uzb} \times Interface_p) + \alpha_p + \delta_t + \varepsilon_{pt}$$

Where the coefficient θ_1 captures whether transmission elasticity varies systematically with observable interface on the benchmark (Kyrgyz) frontier.

Interface measures include shop density, road connectivity, and proximity to major cities. These variables proxy the extent to which cross-border interaction is mediated through decentralized, market-based activity at border nodes.

The sign and significance of θ_1 indicates whether transmission elasticity varies systematically with observable interface on benchmark frontiers.

4.5 Turkmen Attenuation and Interface Interaction

To test whether the mapping from interface to transmission differs systematically on the Turkmen frontier, I estimate:

$$
\begin{aligned}
\text{(13)} \qquad \Delta Y_{pt}^{non} = {} & \theta_0 \Delta Y_{pt}^{uzb} + \theta_1 \left(\Delta Y_{pt}^{uzb} \times Interface_p\right) + \theta_2 \left(\Delta Y_{pt}^{uzb} \times TKM_p\right) \\
& + \theta_3 \left(\Delta Y_{pt}^{uzb} \times Interface_p \times TKM_p\right) + \theta_4 (\Delta Y_{pt}^{uzb} \times TJK_p) \\
& + \theta_5 (\Delta Y_{pt}^{uzb} \times Interface_p \times TJK_p) + \alpha_p + \delta_t + \varepsilon_{pt}
\end{aligned}
$$

Here, TKM_p is an indicator for Turkmen border pairs, while TJK_p is an indicator for Tajik border pairs. KYG serves as the omitted baseline frontier while θ_3 captures whether the relationship between interface and transmission differs on that border; θ_2 captures average attenuation on the Turkmen frontier relative to Kyrgyzstan, and θ_4 captures average attenuation on the Tajik frontier relative to Kyrgyzstan. The direct Turkmen interaction term θ_2 is the primary object of interest; θ_3 tests the additional hypothesis that the interface-transmission relationship differs specifically on the Turkmen frontier.

A negative and statistically significant interaction involving TKM_pindicates that transmission is attenuated relative to what would be predicted by interface alone.

4.6 Benchmark Residual Test

As a complementary approach, I estimate the mapping from interface to transmission using Kyrgyz pairs:

$$
\text{(14)} \qquad \Delta Y_{pt}^{non} = f(\Delta Y_{pt}^{uzb}, Interface_p) + \alpha_p + \delta_t + \varepsilon_{pt}
$$

I then apply this mapping to Turkmen pairs to generate predicted values and compute residuals:

$$Residual_{pt} = \Delta Y_{pt}^{non} - \widehat{\Delta Y}_{pt}^{non} \tag{15}$$

Negative residuals indicate under-absorption relative to benchmark borders. This approach provides an out-of-sample test of whether Turkmen transmission is systematically lower than predicted by interface-based relationships observed elsewhere. I test mean residuals separately for the 2017–2021 period – the reform and pandemic window during which all benchmark borders were progressively reopening while Turkmenistan maintained hard closures – and the post-2022 period, corresponding to Turkmenistan's bilateral transport reopening. The benchmark is estimated on 7 Kyrgyz pairs. The design is valid under the assumption that, absent elevated institutional frictions, Uzbek—Turkmen crossings would exhibit transmission rates consistent with the Kyrgyz benchmark. The near-zero pre-reform residuals documented in Panel A of Table 5 provide empirical support: before the 2017 reform, Turkmen pairs absorbed Uzbek-side shocks at rates statistically indistinguishable from the Kyrgyz benchmark, establishing that the post-reform divergence is reform-specific rather than a pre-existing structural feature.

4.7 Inference

Unless otherwise specified:

- Settlement-level models cluster standard errors at the settlement level
- Pair-level models cluster at the border-pair level
- All specifications include year fixed effects
- All reported p-values are two-sided

5. Results

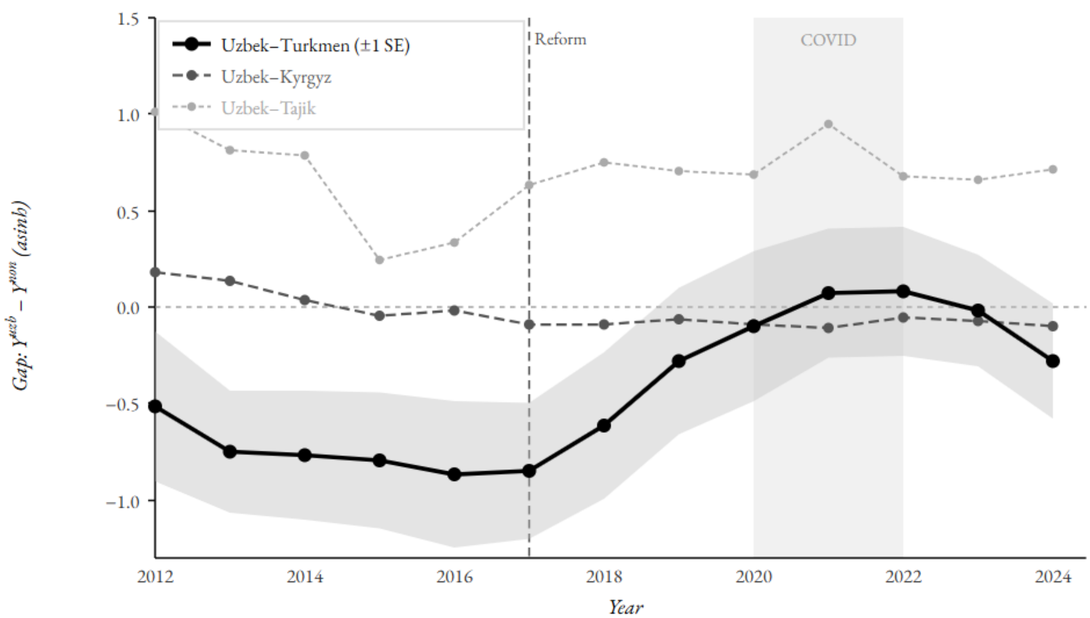
This section presents results in the following order: paired-border estimates establishing frontier-specific divergence (5.1), baseline difference-in-differences as motivating context (5.2), transmission elasticities and Turkmen attenuation (5.3), the high-interface restriction (5.4), and the benchmark residual test (5.5).

5.1 Paired-Border Estimates

The central empirical finding emerges from paired-border specifications that compare Uzbek-side and non-Uzbek-side settlements within the same crossing pair.\The Uzbek-Turkmen frontier exhibits a large and precisely estimated divergence: Uzbek-side settlements pulled ahead of matched Turkmen counterparts by 0.490 asinh units following the reform (SE=0.134, p=0.004). No comparable divergence is observed on Uzbek-Kyrgyz ($\beta=-0.138$, $p=0.137$) or Uzbek-Tajik ($\beta=0.084$, $p=0.785$) frontiers in the full post-2017 window. This frontier-specificity is the central empirical fact of the paper: Uzbek border towns diverged from their matched Turkmen counterparts specifically, not from matched Kyrgyz or Tajik counterparts, despite sharing identical Uzbek-side economic conditions.

Figure 2: Uzbek-Side Luminosity Gap by Frontier, 2012-2024

Mean within-pair gap ($Y^{uzb} - Y^{non}$, asinh scale); shaded band = ±1 SE for Uzbek–Turkmen series only



Notes: Each series plots the mean within-pair luminosity gap ($Y^{uzb} - Y^{non}$, asinh scale) across matched crossing pairs for each frontier, 2012–2024. Positive values indicate Uzbek-side settlements are brighter than matched non-Uzbek counterparts; negative values indicate Uzbek-side settlements are dimmer. The gray band denotes ±1 standard error for the Uzbek–Turkmen series (N=6 pairs); Kyrgyz and Tajik series are shown without bands for clarity given high cross-pair variance in the Tajik sample. The shaded region denotes the COVID period (2020–2021); the vertical dashed line marks the 2017 reform. Before the reform, Uzbek border towns were consistently dimmer than matched Turkmen counterparts (negative gap). Following 2017, the gap closes rapidly and crosses zero around 2021. The Uzbek–Kyrgyz gap fluctuates narrowly around zero throughout. The Uzbek–Tajik gap is positive throughout but stable, reflecting baseline luminosity differences rather than reform-driven divergence.

Figure 2 illustrates the raw gap dynamics underlying this result. Before the 2017 reform, Uzbek border towns were consistently dimmer than their matched Turkmen counterparts – the gap was negative throughout 2012-2016, averaging approximately -0.86 asinh units. Following the reform, the gap closes rapidly and crosses zero around 2021. The Uzbek-Kyrgyz gap, by contrast, fluctuates narrowly around zero throughout the entire sample period. The Uzbek-Tajik series is positive throughout but stable, reflecting baseline luminosity differences rather than reform-driven divergence.

Table 2: Paired-Border Estimates

Dependent variable: asinh night-time luminosity; crossing-pair and year fixed effects; standard errors clustered by pair

	Coefficient	SE	p-value	N	R^2
Panel A: Full post-reform window (Post2017 = 2017 onward)					
Uzbek-side × Post2017					
Uzbek–Turkmen	0.490***	(0.134)	0.004	156	0.246
Uzbek–Kyrgyz	−0.138	(0.087)	0.137	182	0.052
Uzbek–Tajik	0.084	(0.300)	0.785	156	0.004
Panel B: Split-period estimates					
Uzbek–Turkmen frontier (N=156, pairs=6)					
Uzbek-side × Post2017–2019	0.158	(0.138)	0.275		
Uzbek-side × COVID	0.724***	(0.188)	0.003		
Uzbek-side × Post2022	0.666***	(0.119)	<0.001		
Uzbek–Kyrgyz frontier (N=182, pairs=7)					
Uzbek-side × Post2017–2019	−0.136	(0.083)	0.128		
Uzbek-side × COVID	−0.155	(0.113)	0.192		
Uzbek-side × Post2022	−0.130	(0.110)	0.260		
Uzbek–Tajik frontier (N=156, pairs=6)					
Uzbek-side × Post2017–2019	0.057	(0.311)	0.858		
Uzbek-side × COVID	0.181	(0.316)	0.579		
Uzbek-side × Post2022	0.047	(0.307)	0.882		

Notes: Each crossing pair consists of one Uzbek settlement and one geographically matched non-Uzbek settlement at a formal border crossing node (6 Uzbek–Turkmen, 7 Uzbek–Kyrgyz, 6 Uzbek–Tajik pairs). Crossing-pair and year fixed effects included in all specifications. *Uzbek-side* equals one for the Uzbek settlement in each pair. Standard errors clustered at the crossing-pair level. Panel A uses a single post-2017 indicator spanning the full reform period; Panel B disaggregates into Post2017–2019 (initial reform window), COVID (2020–2021), and Post2022 (border reopening period). The Uzbek–Turkmen frontier exhibits large and significant divergence in Panel A and from 2020 onward in Panel B; no comparable divergence is observed on Kyrgyz or Tajik frontiers in any specification.

*** $p<0.01$, ** $p<0.05$, * $p<0.10$.

Table 2 establishes the headline result: the Uzbek-Turkmen frontier diverges significantly following the reform (β=0.490***, p=0.004), while neither the Uzbek-Kyrgyz nor the Uzbek-Tajik frontier shows a comparable effect. The divergence is frontier-specific.

Table 2, Panel B dissects this by period. The gap widens significantly on the Uzbek–Turkmen frontier during both the COVID period (β=0.724***, p=0.003) and the post-2022 period (β=0.666***, $p<0.001$). The initial 2017–2019 window shows a positive coefficient that does not reach statistical significance (β=0.158, p=0.275), consistent with the pre-existing level deficit visible in Figure 1. Uzbek border towns began the reform period substantially dimmer than their matched Turkmen counterparts, interpretable as the gap closing the deficit before turning positive. The benchmark residual test confirms that Turkmen under-absorption is nonetheless present and significant in the pre-COVID years specifically. Across all three periods and both benchmark frontiers, the Uzbek-Kyrgyz and Uzbek-Tajik coefficients are small and statistically insignificant, ruling out a general feature of Uzbekistan's post-reform trajectory.

Taken together, these results establish that the post-2017 divergence is both large and frontier-specific, motivating a closer examination of whether this pattern reflects differences in cross-border transmission rather than differences in underlying economic conditions.

5.2 Baseline Difference-in-Differences

Before turning to transmission estimates, it is worth clarifying what the paired-border divergence in Section 5.1 does and does not reflect. If Uzbek border settlements had simply accelerated relative to the Uzbek interior following the reform, the divergence from matched Turkmen counterparts would not require a cross-border transmission explanation. The within-country specifications in this section rule out that interpretation: Uzbek border towns did not outperform Uzbek interior settlements post-2017, establishing that the divergence reflects a failure of cross-border transmission rather than a domestic Uzbek border-town effect.

Table 3: Baseline Differences-in-Differences

Dependent variable: asinh night-time luminosity; settlement and year fixed effects; standard errors clustered by settlement

	Coefficient	SE	p-value
A. Uzbekistan (N=351, towns=27)			
Border × Post2017–2019	−0.045	(0.125)	0.718
Border × COVID	−0.188	(0.180)	0.297
Border × Post2022	−0.082	(0.143)	0.566
B. Turkmenistan (N=208, towns=16)			
Border × Post2017–2019	0.134	(0.345)	0.698
Border × COVID	0.158	(0.458)	0.730
Border × Post2022	0.256	(0.475)	0.590
C. Kyrgyzstan (N=221, towns=17)			
Border × Post2017–2019	−0.176	(0.111)	0.113
Border × COVID	−0.220	(0.151)	0.143
Border × Post2022	−0.185	(0.140)	0.185
D. Tajikistan (N=156, towns=12)			
Border × Post2017–2019	−0.194	(0.160)	0.225
Border × COVID	−0.012	(0.206)	0.953
Border × Post2022	0.210	(0.213)	0.323

Notes: Each panel reports a separate within-country regression comparing border settlements (within 20 km of the Uzbek border) to far settlements (omitted category). All specifications include settlement and year fixed effects; standard errors clustered at the settlement level. *Post2017–2019* equals one for 2017–2019; *COVID* equals one for 2020–2021; *Post2022* equals one for 2022 onward. These specifications are presented as descriptive; event-study diagnostics indicate significant pre-trends in the one-sided design for all countries and coefficients should not be interpreted as causal. The absence of significant border effects in any country is consistent with reform effects that were diffuse rather than border-concentrated.

*** $p<0.01$, ** $p<0.05$, * $p<0.10$.

This subsection provides descriptive context but does not identify the mechanism driving the divergence. Table 3 reports baseline difference-in-differences estimates comparing border to interior settlements within each country. No significant border effects are found for any country in any period. Uzbek border settlements did not grow significantly faster than Uzbek interior settlements following the reform, and Turkmen border settlements did not decline significantly relative to Turkmen interior settlements.

This pattern is consistent with reform effects that were diffuse across Uzbekistan's economy rather than spatially concentrated at border towns, which is plausible given the country's economy-wide exchange rate unification and trade liberalization initiatives. It also indicates that the divergence documented in Section 5.1 does not reflect Uzbek border towns booming in absolute terms, but rather the Uzbek side maintaining broad-based growth while Turkmen border towns failed to absorb this growth across the border.

Event-study diagnostics indicate significant pre-trends in the border-vs-interior design for Uzbekistan, Kyrgyzstan, and Tajikistan, and these estimates should not be interpreted causally. Pre-trends pass for the Turkmenistan one-sided design (Wald χ^2=1.16, p=0.763; see Appendix Figure A1), but the null result for Turkmenistan is consistent across specifications regardless. The one-sided DiD is therefore presented as descriptive context. The remainder of the analysis focuses on paired-border and transmission designs that do not rely on the parallel-trends assumption.

The absence of border-specific effects within countries, combined with the strong divergence across matched border pairs, suggests that the relevant variation operates through cross-border interactions rather than within-country spatial gradients. This motivates a shift from level-based comparisons to a transmission framework that directly measures how shocks propagate across borders.

5.3 Transmission Elasticities

To distinguish between simple divergence and differences in cross-border transmission, I now estimate first-difference transmission elasticities. Table 4 reports results across six specifications.

Table 4: Cross-border Transmission Elasticities

Dependent variable: ΔY_{non} (first difference, asinh night-time luminosity, non-Uzbek side); crossing-pair and year fixed effects; Uzbek–Kyrgyz frontier as baseline

	(1) KYG Baseline	(2) Country Wedge	(3) Composite Connectivity	(4) Road Only	(5) Shop Only	(6) High-Interface (Top Tercile)
ΔUzbek NTL (= KYG θ_0)	0.458**	0.415***	0.459***	0.334***	0.388**	0.954***
	(0.125)	(0.142)	(0.120)	(0.101)	(0.155)	(0.117)
ΔUzbek × TKM (rel. to KYG)	—	−0.528***	−0.523**	−0.462***	−0.501***	−0.994***
		(0.183)	(0.193)	(0.133)	(0.162)	(0.179)
ΔUzbek × TJK (rel. to KYG)	—	−0.323**	−0.599***	−0.555***	−0.314*	—
		(0.136)	(0.154)	(0.079)	(0.177)	
ΔUzbek × Connectivity	—	—	0.144**	0.359***	−0.076	—
			(0.056)	(0.099)	(0.164)	
ΔUzbek × Connectivity × TKM	—	—	−0.224	−0.356**	−0.094	—
			(0.142)	(0.136)	(0.199)	
ΔUzbek × Connectivity × TJK	—	—	−0.670***	−0.647***	0.051	—
			(0.132)	(0.089)	(0.196)	
Implied country-specific θ_0:						
KYG (baseline)	0.458**	0.415***	0.459***	0.334***	0.388**	0.954***
TJK	—	0.092	−0.140	−0.221	0.074	—
TKM	—	−0.113	−0.064	−0.128	−0.113	−0.040
Pair FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Clustered SE (pair)	Yes	Yes	Yes	Yes	Yes	Yes
Observations	84	228	228	228	228	84
Pairs	7	19	19	19	19	7
R^2	0.316	0.065	0.105	0.102	0.081	0.342

Notes: The dependent variable is the first difference of asinh-transformed VIIRS night-time luminosity for the non-Uzbek settlement in each crossing pair. All specifications include crossing-pair and year fixed effects; standard errors clustered at the pair level. The Uzbek–Kyrgyz frontier serves as the baseline; all country-specific coefficients are estimated relative to this benchmark. Column (1) reports transmission for Kyrgyz pairs only. Columns (2)–(5) use the full 19-pair panel; *TKM* and *TJK* indicate Uzbek–Turkmen and Uzbek–Tajik border pairs respectively. *Connectivity* refers to the composite crossing-intensity index (col. 3), road capacity density (col. 4), or commercial shop density (col. 5), all normalized. Column (6) restricts to the top tercile of crossing-intensity index (84 pair-year observations, 7 pairs: 4 Turkmen, 3 Kyrgyz); no Tajik pairs qualify for this subsample. The implied country-specific θ_0 shows a clear ordering: Kyrgyzstan transmits strongly (0.415–0.459***), Tajikistan weakly (0.074–0.092), and Turkmenistan negatively (−0.064 to −0.128). The connectivity × TJK triple interaction is large and negative in columns (3) and (4), suggesting that the Tajik under-transmission relative to Kyrgyzstan is especially pronounced at higher-interface crossings — consistent with disruptions to Fergana Valley commercial networks following the 2021 Tajik–Kyrgyz border conflict.

*** $p<0.01$, ** $p<0.05$, * $p<0.10$.

Column (1) establishes a baseline: the average transmission coefficient across all 19 pairs is 0.458 (SE=0.125, p<0.05), indicating significant cross-border co-movement on average. This average, however, masks substantial frontier-level heterogeneity.

Column 2 introduces country-specific transmission coefficients with Kyrgyzstan as the omitted baseline, estimated jointly in a single regression. The results reveal a clear gradient across all three frontiers: the implied Kyrgyz transmission elasticity is 0.415 (p<0.001), Tajikistan's is 0.092 (not significant as a standalone), and Turkmenistan's is -0.113, implying negative transmission. The Kyrgyz–Tajik difference of -0.323 (p=0.029) and the Kyrgyz–Turkmen difference of −0.528 (p=0.007) are both statistically significant, establishing that all three frontiers transmit at meaningfully different rates.

Columns 3-5 augment the specification with crossing-level interface measures: the composite crossing-intensity index (column 3), road capacity density (column 4), and commercial shop density (column 5) – interacted with both ΔUzbek and the country indicators. Conditioning on interface reveals three results.

First, the baseline interface interaction (ΔUzbek × Connectivity) is positive and significant in the composite and road specifications (0.144**, 0.359***), indicating that on the Kyrgyz benchmark frontier, higher-connectivity crossings generate stronger transmission. This confirms that observable interface capacity does enable market-mediated spillovers on permeable borders.

Second, the direct Turkmen attenuation terms (ΔUzbek × TKM) remain consistently negative and statistically significant across all three interface specifications (−0.523**, −0.462***, −0.501***), confirming that the Kyrgyz–Turkmen gap documented in column 2 is robust to conditioning on observable interface. The Turkmen triple interaction (ΔUzbek × Connectivity × TKM) is negative across specifications but statistically significant only in the road-only case (−0.356**), indicating that TKM's attenuation does not vary systematically with connectivity level and is relatively uniform whether crossings are well-connected or not. This is a meaningful finding: TKM's suppression of transmission is not concentrated at low-connectivity crossings that might be dismissed as commercially inactive. It extends uniformly across the observable infrastructure range.

Third, the Tajik terms show a distinct pattern. The direct Tajik attenuation (ΔUzbek × TJK) is consistently negative and significant (-0.599***, -0.555***, -0.314*), confirming the structural under-transmission identified in column 2. The Tajik triple interaction (ΔUzbek × Connectivity × TJK) is large, negative, and significant in the composite and road specifications (-0.670***, -0.647***), indicating that higher-connectivity Tajik crossings transmit less relative to comparable Kyrgyz crossings. This likely reflects that the Fergana Valley crossings that dominate the high-interface end of the Tajik sample were disproportionately disrupted by the 2021 Tajik–Kyrgyz border conflict, which severed or degraded the very crossings where overland trade was most concentrated. This pattern reinforces the paper's broader argument: interface capacity is necessary but not sufficient for transmission, and whether it generates economic co-movement depends on the broader environment within which it operates.

These results indicate that while cross-border transmission is present on average, it differs systematically across frontiers, with consistent attenuation on the Turkmen border. The persistence of this pattern across specifications motivates examining whether attenuation remains even where transmission potential is highest.

5.4 High-Interface Restriction

To assess whether the Turkmen attenuation persists at crossings where market-mediated transmission is most plausible, Column (6) of Table 5 restricts the sample to the top tercile of crossing-intensity index values, or 84 pair-year observations across 7 pairs (4 Turkmen, 3 Kyrgyz). The high-interface subsample selects on the crossing-intensity index, meaning Turkmen pairs here are those with the highest observable commercial and infrastructural activity.

Within this high-interface subset, the baseline transmission coefficient is large and precisely estimated (β=0.954, SE=0.116, $p<0.001$), indicating strong cross-border co-movement at well-connected crossings on benchmark borders. Turkmen attenuation in this restricted sample is -0.994 (SE=0.178, $p<0.001$), implying that Uzbek-side changes generate essentially no net transmission into Turkmen towns even at the most commercially active and well-connected crossings. The result demonstrates that even at the most commercially active crossings, the transmission elasticity on the Turkmen frontier is effectively zero. Attenuation is therefore not a function of observable commercial activity or infrastructure; it operates upstream of these features, at the level of whether trade and cross-border interaction can translate into local economic outcomes at all.

5.5 Benchmark Residual Test

This subsection provides the paper’s sharpest test of whether Turkmen crossings under-absorb relative to a benchmark mapping from interface to transmission. I estimate the interface-transmission mapping using Kyrgyz crossing pairs only, then project this mapping onto Turkmen and Tajik pairs out-of-sample and compute residuals.

Table 5: Benchmark Residual Means Applied to Turkmen and Tajik Pairs

Out-of-sample residuals from transmission model estimated on Kyrgyz pairs only; tested against zero

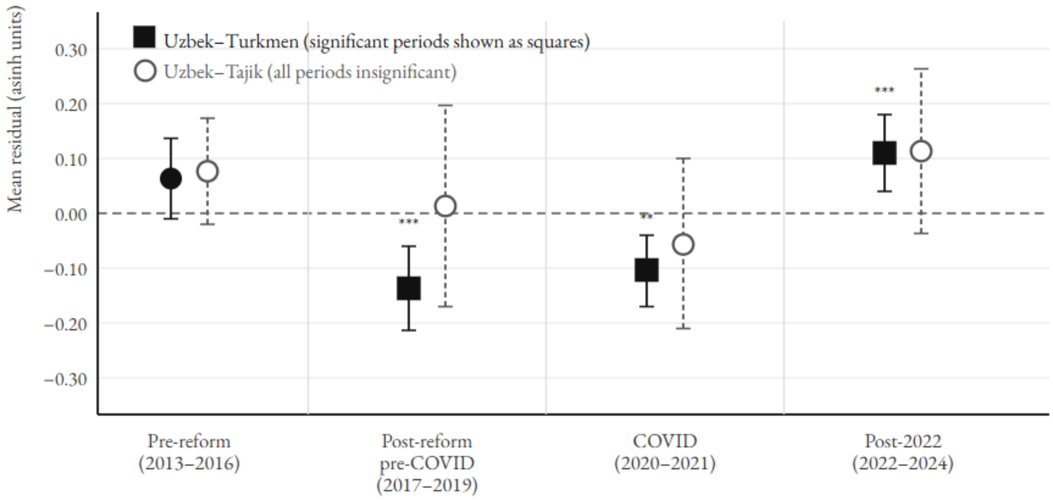
Period / Year	Uzbek–Turkmen			Uzbek–Tajik		
	Mean	SE	p-value	Mean	SE	p-value
A. Pooled period estimates						
Pre-reform (2013–2016)	0.062	0.038	0.116	0.076	0.050	0.139
Post-reform, pre-COVID (2017–2019)	−0.138***	0.039	0.003	0.015	0.052	0.878
COVID (2020–2021)	−0.104***	0.033	0.009	−0.056	0.074	0.496
Post-2022	+0.109***	0.036	0.007	+0.114	0.072	0.155

Table 5 reports pooled period estimates. The pre-reform period (2013-2016) produces mean residuals that are not significantly different from zero (mean=0.062, p=0.116). As shown previously, pre-reform Uzbek-side shocks transmitted into benchmark towns at a significant rate (β=0.180, p<0.001), confirming the benchmark had power to detect deviations during this period. The significant negative Turkmen residuals in both post-reform subperiods: −0.138 (p = 0.003) in 2017–2019 and −0.104 (p = 0.009) in 2020–2021 (corresponding to the post-reform pre-COVID and the post-reform COVID periods, respectively), therefore reflect genuine comparability rather than a failure to detect existing under-absorption. This baseline symmetry is important: it indicates the under-absorption subsequently detected is specifically associated with the reform period rather than being a permanent feature of the bilateral relationship.

The benchmark residual results provide the clearest evidence of systematic attenuation. Turkmen crossings under-absorb relative to connectivity-based predictions during the reform period and converge toward those predictions following partial normalization (mean = +0.109, p = 0.007). The pre-reform baseline near zero combined with the post-reform under-absorption is consistent with the interpretation that the 2017 reform activated transmission potential that Turkmenistan's institutional frictions then suppressed.

Figure 3: Benchmark Residual Means by Period (Uzbek-Turkmen and Uzbek-Tajik Frontiers)

Out-of-sample residuals from transmission model estimated on Kyrgyz pairs only; bars show 95% confidence intervals; tested against zero



Notes: Residuals are out-of-sample predictions from the benchmark transmission model estimated on Kyrgyz crossing pairs only (β_{uzb}=0.493***, β_{comp}=0.171**), applied separately to Turkmen and Tajik crossing pairs. Bars show 95% confidence intervals; significance markers (**, ***) indicate mean residuals significantly different from zero at the 5% and 1% levels respectively (one-sample t-test). Filled squares indicate statistically significant TKM periods; filled circles indicate non-significant TKM periods; open circles indicate TJK periods (all non-significant). The Uzbek–Turkmen frontier shows near-zero pre-reform residuals followed by significant under-absorption in the reform and COVID periods, with partial normalization post-2022. The Uzbek–Tajik frontier shows residuals not significantly different from zero in any period, indicating that Tajikistan's lower transmission elasticity relative to Kyrgyzstan is a structural feature present throughout the sample, not specifically activated by the 2017 reform. This contrast between reform-activated attenuation (Turkmenistan) and structural under-transmission (Tajikistan) provides the sharpest evidence that the Turkmen pattern is reform-specific rather than a permanent bilateral characteristic.

6. Interpretation and Alternative Explanations

The empirical results establish three core facts.

i) Divergence is frontier-specific: Uzbek settlements pull ahead of matched Turkmen settlements, but not Kyrgyz or Tajik counterparts.

ii) Cross-border transmission is systematically attenuated on the Turkmen frontier, even conditioning on observable interface.
iii) This attenuation is concentrated in the post-2017 period and partially reverses after 2022.

This section interprets these findings and evaluates alternative explanations.

6.1 Discussion

The results establish a clear and frontier-specific pattern. Uzbek-side settlements diverge significantly from matched Turkmen counterparts following the reform, while no comparable divergence is observed on Kyrgyz or Tajik frontiers that share the same Uzbek-side economic conditions. This asymmetry is the central empirical fact of the paper.

The transmission framework provides a mechanism for interpreting this pattern. On the Kyrgyz border, changes in Uzbek-side activity transmit positively across space, indicating that cross-border interaction translates into local economic co-movement. Tajikistan also transmits positively, but at a substantially lower elasticity than Kyrgyzstan, indicating weaker conversion of cross-border interaction into local activity. On the Turkmen frontier, by contrast, transmission is consistently attenuated across specifications. This attenuation persists after conditioning on observable interfaces such as road connectivity, commercial density, and proximity to cities, and remains large even when restricting to the highest-interface crossings, where transmission potential is greatest.

The contrast with Tajikistan is particularly informative: Tajik crossings exhibit lower transmission than Kyrgyz crossings while not displaying reform-activated under-absorption, suggesting that transmission varies systematically across frontiers in a manner consistent with differences in institutional permeability.

The benchmark residual results sharpen this interpretation. Relative to the transmission patterns observed on benchmark borders, Turkmen crossings under-absorb significantly during the reform period, including in the pre-COVID years when borders were open. This under-absorption reverses after 2022, coinciding with changes in bilateral border policy. The combination of frontier-specific divergence, attenuation conditional on interface, and time variation aligned with policy changes suggests that the observed pattern is consistent with institutional constraints on how cross-border interaction translates into local economic activity, rather than just differences in geography, trade, or observable connectivity.

6.2 Institutional Frictions as an Interpretation

One interpretation is that institutional features of the Turkmen regime generate elevated effective frictions in cross-border economic interaction. These may include restrictions on currency convertibility, administrative barriers to trade, limits on cross-border mobility, and regulatory constraints on private enterprise.

Such frictions need not eliminate cross-border exchange entirely. Instead, they may alter the composition, scale, or organization of interaction in ways that reduce its capacity to generate localized spillovers. For example, even when goods cross the border, restrictions on market participation, licensing, or informal activity may limit the extent to which trade generates complementary services, retail activity, and local economic dynamism.

Under this interpretation, the observed attenuation reflects not the absence of connectivity or proximity, but a reduced effectiveness of transmission channels. Observable interface, such as roads and commercial nodes, may exist, but institutional constraints limit the extent to which these features translate into economically meaningful interaction.

The empirical design does not identify specific institutional mechanisms. Rather, it shows that the observed attenuation is difficult to reconcile with explanations based solely on conventional macroeconomic or trade explanations, geography, infrastructure, or observable interface, and is consistent with elevated effective frictions plausibly rooted in policy or institutional constraints.

Importantly, the paper does not claim that Turkmenistan's domestic institutional regime changed after 2022. In fact, currency controls, state trade intermediation, and restrictions on private enterprise remain in place. Rather, the post-2022 improvement reflects changes in the bilateral policy framework governing how those institutions interact with Uzbekistan specifically. This distinction suggests that institutional permeability in bilateral relationships is partially separable from a country's absolute institutional quality, and can be influenced by diplomatic engagement and bilateral agreements even without domestic liberalization. More broadly, the temporal pattern supports the claim that institutional permeability is not a fixed parameter but responds dynamically to the bilateral policy environment, with implications for how development economists think about the conditions under which reforms in one country generate spillovers in neighbors.

6.3 Alternative Explanations

6.3.1 Measurement Error in Night-Time Lights

Night-time lights measure luminosity rather than output directly, and differences in electrification or infrastructure investment could affect measured outcomes. However, several features of the empirical design mitigate this concern.

Measurement procedures are identical across countries, gas flaring is explicitly masked, and the analysis relies on within-settlement changes over time rather than level comparisons.

Transmission models use first differences, reducing bias from persistent measurement differences. To explain the observed attenuation, measurement error would need to be systematically correlated with reform timing on the Turkmen side, which is unlikely.

6.3.2 National Economic Shocks

A second possibility is that national economic conditions in Turkmenistan suppressed growth independently of cross-border dynamics. The transmission specifications address this concern directly. By estimating first-difference models with crossing-pair and year fixed effects, the design absorbs time-varying national shocks common to all settlements within a country. A uniform Turkmen economic contraction would affect border and interior settlements symmetrically and would be differenced out.

The crossing-pair fixed effects additionally absorb all time-invariant characteristics of each specific crossing node.

The Turkmen indicator in the transmission model therefore captures residual attenuation conditional on Uzbek-side shocks and common year effects, which is orthogonal to aggregate national trends. Furthermore, the frontier-specificity of the paired-border result provides additional evidence against a pure national shock story: if Turkmenistan were experiencing a uniform national downturn, one would not expect it to manifest specifically at border crossings matched to Uzbek towns rather than uniformly across the country.

6.3.3 Structural Differences in Border Settlements

Turkmen border towns may differ systematically from Kyrgyz or Tajik border towns in ways not captured by observable interface measures. To address this concern, the transmission specifications condition explicitly on crossing-level interface, including commercial density and network connectivity.

Across both road-only ($\beta=-0.462^{***}$, $p<0.01$) and shop-density ($\beta=-0.501^{***}$, $p<0.01$) specifications, the direct Turkmen attenuation term remains negative and statistically significant, indicating the result is robust to the choice of interface measure.

The attenuation effect remains statistically significant after conditioning on these characteristics and persists even in the high-interface subsample. This makes it unlikely that the results are driven solely by differences in observable settlement structure or infrastructure.

6.3.4 Pandemic-Related Disruptions

The large gap widening during 2020-2021 might suggest COVID-era border disruptions explain the divergence. Three pieces of evidence argue against this interpretation as the primary explanation.

i) The benchmark residual test shows significant under-absorption during the post-reform years. Under-absorption was therefore consistently present under a period of expanded trade and activity.

ii) Uzbekistan closed its borders with all three neighbors in March 2020, not only with Turkmenistan. If the COVID closure were driving the divergence, one would expect comparable gap widening on the Kyrgyz or Tajik frontiers. No such widening is observed.

iii) The critical difference is not in border closure but in reopening: Uzbekistan progressively reopened road crossings from October 2020 and lifted all COVID-related entry restrictions by June 2022, while Turkmenistan maintained hard closures through most of 2022, with bilateral transport to Uzbekistan only fully resuming in November 2022. The COVID period therefore captures differential reopening trajectories rather than symmetric closure, and that differential maps directly onto Turkmenistan's institutional response to the pandemic rather than Uzbekistan's policies.

6.3.5 Trade Composition and Pipeline-Based Exchange

A fifth potential concern is that the Uzbek-Turkmen attenuation reflects the composition of bilateral trade rather than institutional frictions. Turkmenistan's exports to Uzbekistan are concentrated in natural gas and electricity, transported via pipelines that generate limited localized crossing-level activity. However, this explanation is incomplete for several reasons. First, the empirical design measures the transmission of Uzbek-side shocks, not Turkmen exports. Uzbekistan's exports to Turkmenistan consist predominantly of manufactured and intermediate goods including fertilizers, plastics, and machinery, transported overland through the specific crossings in the sample. Second, the high-interface restriction shows attenuation persisting even at crossings with substantial observable commercial and infrastructural activity. If trade composition explained the attenuation, one would expect it to be weaker at commercially active crossings where overland trade is most concentrated. Third, the post-2022 normalization in benchmark residuals is inconsistent with a trade composition explanation. Pipeline composition did not change in 2022; what changed was Turkmenistan's border access policy and the bilateral framework governing cross-border exchange. The timing of partial normalization tracks policy rather than trade structure. Taken together, these results suggest that trade composition or volume alone is unlikely to explain the observed pattern.

6.3.6 Measurement of Interface

A further concern is that interface measures derived from OpenStreetMap data may reflect mapping intensity rather than underlying economic activity. If Turkmen settlements were systematically under-mapped, measures such as shop density could understate true interface.

Diagnostic checks do not support this concern. Overall mapping density is not systematically lower in Turkmenistan relative to neighboring countries, and the share of settlements with zero mapped shops is similar across countries. These patterns suggest that commercial points of interest are not systematically missing in Turkmen locations.

To further address this issue, I construct an alternative interface measure based solely on road infrastructure, excluding commercial points of interest. Across both road-only and shop-density specifications, the direct Turkmen attenuation term remains negative and statistically significant, indicating the result is not sensitive to the choice of interface measure.

This pattern suggests that the divergence arises specifically in commercially mediated interface rather than in physical connectivity alone. In other words, infrastructure is present, but the economic interactions typically associated with that infrastructure do not translate into comparable spillovers on the Turkmen frontier.

Because interface predicts transmission on benchmark borders, but Turkmen crossings do not exhibit lower interface, the persistence of attenuation is unlikely to reflect measurement error in interface. If anything, the summary statistics suggest that this attenuation is conservatively estimated, since Turkmen border towns in fact experience heightened proximity to the nearest major city.

6.3.7 Benchmark Validity

The benchmark residual projection’s validity is supported by leave-one-out analysis, covariate balance, and a pre-reform power check.

First, leave-one-out analysis confirms that the post-reform under-absorption result is negative across all variations of the benchmark sample and statistically significant in all but one case at the 5% level, ruling out dependence on any single crossing pair.

Second, a covariate balance comparison shows that Turkmen crossings are not outliers relative to the benchmark sample on the primary interface measure. The composite crossing-intensity index shows no significant difference between Turkmen and benchmark towns ($p=0.232$) and complete covariate overlap.

Third, pre-reform Uzbek-side shocks were non-trivial in magnitude and transmitted into benchmark towns at a significant rate ($\beta=0.180$, $p<0.001$) during 2013–2016, establishing that the pre-reform near-zero Turkmen residuals reflect genuine comparability rather than insufficient statistical power.

Taken together, these alternative explanations fail to jointly account for the three defining features of the result: frontier-specificity, persistence conditional on interface, and post-2022 reversal. Any alternative must explain all three simultaneously.

6.4 External Validity

The analysis focuses on settlement-level night-time lights in Central Asia, a setting characterized by limited data availability and substantial institutional heterogeneity. However, the empirical framework of estimating transmission elasticities and conditioning on local interface applies more broadly to settings where cross-border spillovers are expected but may be constrained by institutional or policy factors.

In particular, the approach provides a general method for testing whether geographic proximity and observable connectivity translate into economic co-movement, and for identifying cases in which this mapping breaks down.

6.5 Summary Interpretation

Taken together, the evidence supports a unified interpretation. The Uzbek-Turkmen frontier diverged significantly following Uzbekistan's 2017 reform, while comparable divergence is absent on Kyrgyz and Tajik frontiers, even when sharing the same Uzbek-side conditions. Section 6.3 established that no single alternative – geography, infrastructure, national shocks, trade composition, or pandemic disruptions – accounts for the pattern individually. More decisively, no combination of these alternatives simultaneously explains the frontier-specificity, the persistence of attenuation conditional on interface, and the post-2022 reversal. Any credible non-institutional account must satisfy all three constraints jointly.

What remains after ruling out these alternatives is a residual wedge consistent with the reform period. The most parsimonious interpretation is that Turkmenistan's institutional regime generates elevated effective frictions in cross-border economic interaction which are present in observable infrastructure but not reducible to it, which is consistent with the contrast between Turkmen and Tajik benchmark residual patterns.

The temporal pattern following 2022 also suggests that institutional permeability is jointly determined by both countries' governance choices. Uzbekistan's reform created transmission demand that Turkmenistan's institutional framework initially could not accommodate. The subsequent bilateral response (transport normalization, a free trade zone agreement, and broader diplomatic engagement) partially bridged this gap without requiring full domestic institutional change in Turkmenistan. The result is a relationship-specific transmission elasticity that evolved in response to external policy shocks, with implications for how spillovers from reform can be partially facilitated through bilateral engagement rather than requiring full institutional convergence.

7 Conclusion

This paper studies how economic shocks transmit across borders and whether that transmission depends on the institutional environment governing exchange. Using Uzbekistan's 2017 exchange-rate unification and liberalization as a source of variation, I examine settlement-level night-time lights across matched border pairs on the Uzbek-Turkmen, Uzbek-Kyrgyz, and Uzbek-Tajik frontiers, with the results establishing a consistent pattern. Uzbek-side settlements diverge significantly from matched Turkmen counterparts following the reform, while no comparable divergence is observed on Kyrgyz or Tajik frontiers. Transmission elasticities are positive on benchmark borders but significantly attenuated on the Turkmen frontier, including at crossings with high levels of observable connectivity. A benchmark residual approach shows that Turkmen crossings under-absorb relative to connectivity-based predictions during the reform period, with this pattern reversing after 2022 as bilateral border policies normalize. The key contribution is the broader notion that cross-border spillovers operate through a transmission mechanism that can be activated by reform but constrained by institutional conditions on the receiving side.

Taken together, these findings demonstrate that geographic proximity and observable interface are necessary but insufficient to generate cross-border economic spillovers. Instead, the extent to which shocks propagate across borders depends on whether local interaction can be translated into economic activity within the institutional environment of the neighboring country.

The analysis does not identify the specific mechanisms underlying this attenuation, and future work incorporating direct measures of bilateral trade flows, cross-border mobility, or firm-level activity could isolate them. Applying the benchmark residual design in other border settings – particularly where institutional permeability varies across a clear gradient as it does across the three Central Asian frontiers studied here – would help establish the generality of the transmission framework.

Methodologically, the paper highlights the value of combining high-resolution spatial data with transmission-based empirical frameworks. Estimating cross-border elasticities and evaluating deviations from connectivity-based benchmarks provides a general approach to studying how economic shocks propagate across space and where that propagation breaks down.

More broadly, the paper proposes a shift in how spillovers are conceptualized. Reforms in one country do not automatically generate positive spillovers in neighboring regions, even when those regions are geographically proximate and connected by observable infrastructure. Institutional permeability plays a central role in determining whether such spillovers materialize. Future research could extend this framework by incorporating direct measures of cross-border interaction, such as trade flows, mobility data, or firm-level activity, to more precisely identify the mechanisms underlying transmission. Applying similar designs in other border settings where institutional permeability varies would help assess the generality of these findings.

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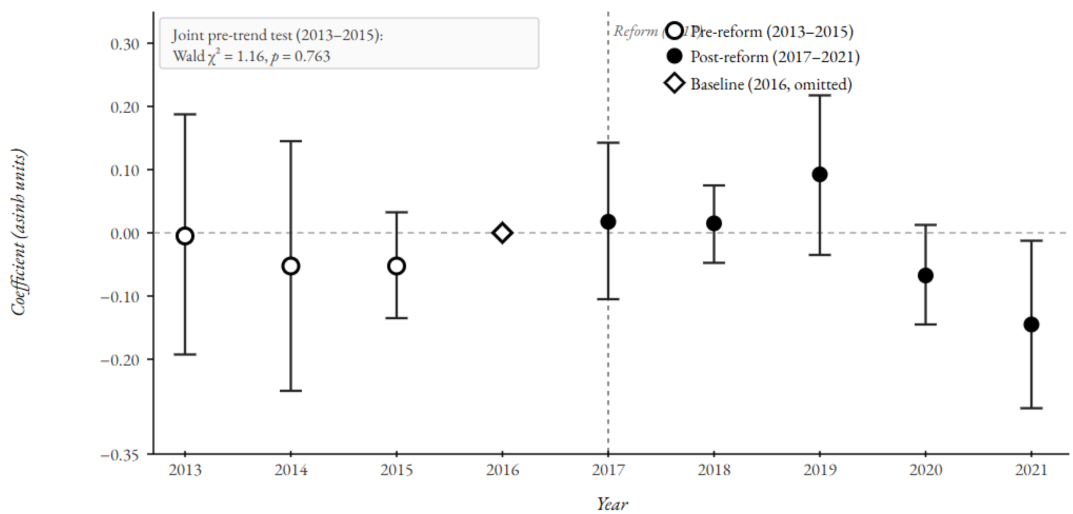
Appendix

Appendix Figure A1: Event Study – Uzbek-Turkmen Frontier (One-Sided)

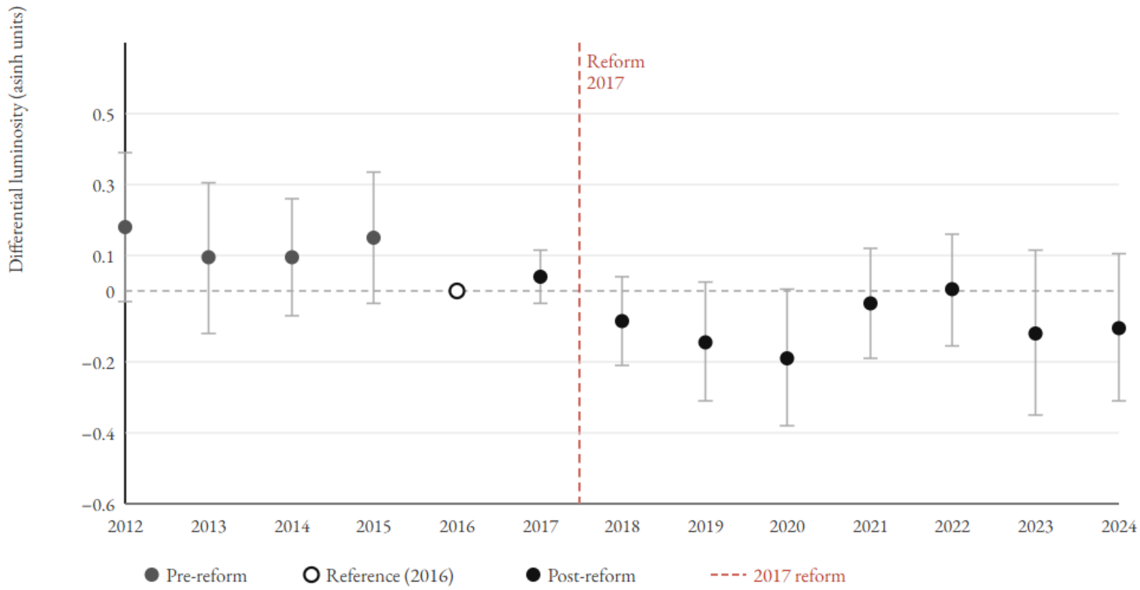
Border × Year coefficients (baseline: 2016); town FE, year FE, town-specific linear trends; 90% confidence intervals, clustered SE



Notes: Event-study estimates of Border × Year interactions for Turkmenistan, relative to the omitted baseline year (2016). The sample compares Turkmen border towns (within 20 km of the Uzbek frontier) to interior towns. Specification includes town fixed effects, year fixed effects, and town-specific linear trends. Whiskers denote 90% confidence intervals based on standard errors clustered at the town level. The joint pre-trend test (2013–2015) fails to reject zero (Wald χ^2=1.16, p=0.763), supporting parallel trends within the Turkmen one-sided design. Post-reform coefficients are small and statistically indistinguishable from zero through 2019; the 2021 coefficient is negative and marginally significant, reflecting COVID-era disruptions. This figure is presented for descriptive purposes; the paper's primary identification relies on the paired-border transmission and benchmark residual designs reported in the main text.

Appendix Figure A2: Event Study – Uzbek-Kyrgyz Frontier (One-Sided)

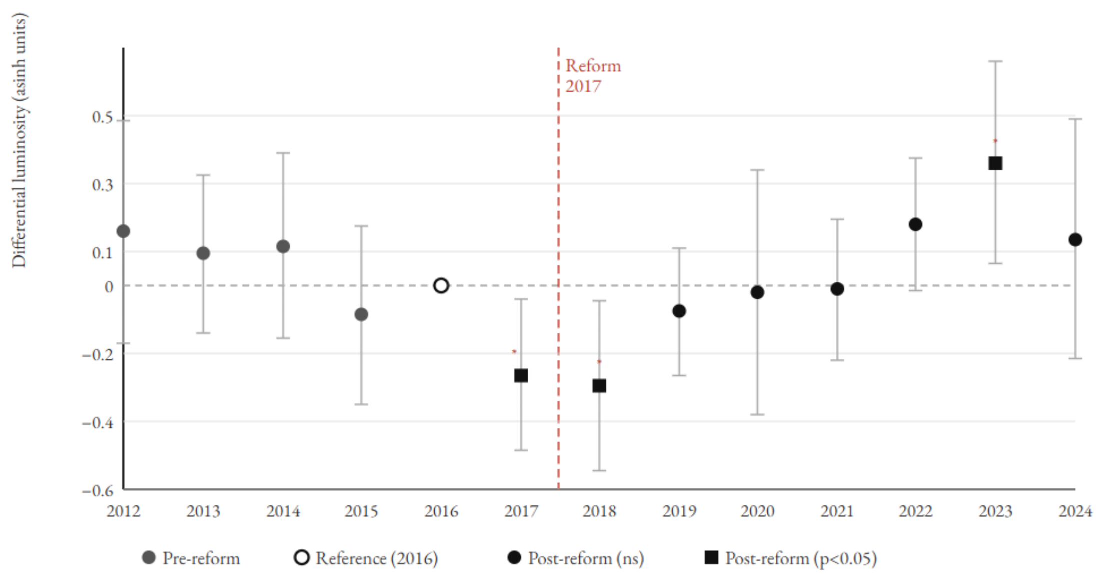
Differential luminosity of Kyrgyz border settlements relative to interior settlements; year 2016 = reference; 95% confidence intervals



Notes: Event-study coefficients from the one-sided difference-in-differences specification estimated on Kyrgyz settlements only. The dependent variable is asinh-transformed VIIRS night-time luminosity. The specification compares border settlements (within 20 km of the Uzbek border) to middle and far interior settlements, with settlement and year fixed effects. Year 2016 is the omitted reference year. Bars show 95% confidence intervals with standard errors clustered at the settlement level. Pre-reform coefficients (2012–2015) are all statistically insignificant; the Wald test for joint pre-trend significance yields χ^2=7.35, p=0.119, failing to reject parallel pre-trends. However, post-reform coefficients are also not significantly different from zero, indicating that the one-sided design detects no significant border gradient in Kyrgyzstan following the reform — consistent with the diffuse nature of the reform's effects across Uzbekistan's economy. This figure is presented as descriptive context; the paper's main identification relies on the paired-border and transmission designs.

Appendix Figure A3: Event Study – Uzbek-Tajik Frontier (One-Sided)

Differential luminosity of Tajik border settlements relative to interior settlements; year 2016 = reference; 95% confidence intervals



Notes: Event-study coefficients from the one-sided difference-in-differences specification estimated on Tajik settlements only. The dependent variable is asinh-transformed VIIRS night-time luminosity. The specification compares border settlements (within 20 km of the Uzbek border) to middle and far interior settlements, with settlement and year fixed effects. Year 2016 is the omitted reference year. Bars show 95% confidence intervals with standard errors clustered at the settlement level. Pre-reform coefficients (2012–2015) are statistically insignificant; the Wald test for joint pre-trend significance yields χ^2=2.67, p=0.615, failing to reject parallel pre-trends. However, 2017 and 2018 show negative and significant coefficients, indicating that Tajik border settlements declined relative to interior settlements following the reform — an unexpected pattern. This may reflect the broader disruption of Fergana Valley trade networks or other country-specific factors contemporaneous with the Uzbek reform. The 2023 positive coefficient coincides with Tajikistan's gradual bilateral normalization with Uzbekistan. Given these complexities, the one-sided Tajik design is presented as descriptive context only; the paper's main identification relies on the paired-border and transmission designs, which do not require parallel trends assumptions.

Appendix Table A4: Event Study – Summary Statistics by Country (Border Settlements)

	Uzbekistan N = 19 towns				Kyrgyzstan N = 7 towns				Tajikistan N = 6 towns				Turkmenistan N = 6 towns			
	Mean	SD	Min	Max	Mean	SD	Min	Max	Mean	SD	Min	Max	Mean	SD	Min	Max
A. Night-time luminosity (pooled 2012–2024, N obs = 247 / 91 / 78 / 78)																
NTL (raw, pre-asinh)	1414.1	1470.1	11.3	8452.0	1198.6	1035.4	148.1	4615.8	435.2	402.7	24.8	1586.4	4502.1	4461.7	348.7	14273.3
NTL (asinh-transformed)	7.387	1.283	3.122	9.735	7.439	0.851	5.691	9.130	6.237	1.149	3.903	8.062	8.532	1.146	6.547	10.259
% zero values (raw)	0.0%	—	—	—	0.0%	—	—	—	0.0%	—	—	—	0.0%	—	—	—
B. Interface measures (time-invariant, 2019 OSM; one observation per town)																
Shop density (shops/km²)	1.033	2.373	0.000	9.496	0.286	0.423	0.018	1.140	0.088	0.120	0.006	0.322	0.366	0.487	0.024	1.322
Road capacity density (km/km²)	0.253	0.182	0.073	0.709	0.167	0.063	0.090	0.246	0.129	0.096	0.039	0.314	0.250	0.095	0.108	0.372
Intersection density (per km²)	9.046	8.247	0.116	29.227	6.260	5.300	2.309	17.235	4.565	4.623	0.451	12.365	7.246	5.779	1.889	14.592
Distance to nearest city (km)	19.365	17.485	0.089	52.069	27.624	24.101	0.534	64.531	27.022	35.346	0.168	79.601	0.401	0.387	0.106	1.124
Crossing intensity index	0.123	0.666	−0.662	1.449	−0.152	0.471	−0.564	0.623	−0.433	0.221	−0.703	−0.055	−0.072	0.191	−0.375	0.156

Notes: Statistics are restricted to border settlements only (within 20 km of the Uzbek border on each side). Luminosity statistics pool all annual observations from 2012–2024; interface statistics use a single time-invariant value per town constructed from 2019 OpenStreetMap data. The crossing intensity index is a standardized composite of shop density, intersection density, and road capacity density z-scores. All NTL values are positive (no zero-value crossing towns), confirming the asinh transformation does not introduce systematic bias. Uzbek-side border towns (N=19, including both Uzbek-Kyrgyz, Uzbek-Tajik, and Uzbek-Turkmen frontier towns) show the highest mean NTL and shop density. Turkmen border towns show notably high raw NTL relative to their crossing intensity index, reflecting that Dashoguz, Turkmenabat, and Konye-Urgench are large regional cities whose luminosity reflects domestic urban activity rather than cross-border commercial density. Turkmen border towns also show very low distance-to-nearest-city values (mean 0.4 km), confirming these are urban rather than rural settlements. Tajik border towns show the lowest luminosity and interface measures across all dimensions, consistent with the Uzbek–Tajik frontier being the least commercially active of the three benchmark frontiers.