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Digital Payment Infrastructure and E-Commerce Adoption in Central and Eastern Europe: A Panel Data Analysis

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Abstract

The transition from cash to digital payment instruments is reshaping retail commerce across Europe unevenly, with Central and Eastern European (CEE) countries exhibiting both some of the fastest growth and some of the lowest baseline levels in online shopping participation. This study examines whether the development of digital payment infrastructure proxied by the share of individuals using internet banking (NetBank) is associated with e-commerce adoption across eleven CEE EU member states over the period 2014–2023, yielding a balanced panel of 110 country-year observations. Drawing on harmonised data from Eurostat, the World Bank, and the ITU, we estimate a two-way fixed-effects model with kernel-robust standard errors and a dynamic specification with a lagged dependent variable. The results indicate that a one-standard-deviation improvement in internet banking penetration is associated with a 6.2 percentage point increase in the share of online shoppers once country and year fixed effects are controlled for, a finding that is precisely estimated under kernel standard errors ($p < 0.001$). Income-group heterogeneity analysis suggests that this association may be substantially larger in lower-income CEE countries ($\beta = 6.9$, $p = 0.006$) compared to higher-income ones ($\beta = 2.3$, $p = 0.554$), consistent with the hypothesis that payment infrastructure improvements generate the highest marginal returns where baseline access is lowest. Romania, despite recording the steepest absolute growth in online shopping in the EU over the sample period (+33 percentage points), remains persistently below the CEE median, illustrating how payment infrastructure constraints can slow convergence even during periods of rapid digitisation. The findings should be interpreted as robust conditional associations rather than causal effects, given the limitations of macro-panel identification.

Keywords: digital payments; internet banking; e-commerce adoption

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1. Introduction

Over the past decade, few economic phenomena have reshaped everyday commerce as visibly as the shift away from cash payments toward digital alternatives. What began as a convenience option available to the technologically savvy has quietly become the default mode of transaction for hundreds of millions of European consumers. Between 2019 and 2024, the share of payments made online tripled across the euro area, rising from roughly 7% to 21% of all transactions, while cash lost ground at the point of sale, falling from 79% to 52% of physical transactions over an even longer horizon. This transformation is not

uniform, however, and the variation across countries is both striking and underexplored from a comparative analytical perspective.

The Central and Eastern European (CEE) region occupies a particularly revealing position within this broader narrative. On one hand, it houses some of the EU's fastest-growing e-commerce markets: Romania recorded more than a 33 percentage point increase in the share of online shoppers between 2014 and 2023 in our sample. Romania grew from just 17.2% to 50.3%, while Bulgaria, Croatia, and Hungary also posted dramatic gains. On the other hand, as of 2023, Bulgaria (45.2%), Romania (50.3%), and Lithuania (60.9%) still sit well below Western European benchmarks, compared to 77.7% in Czechia or 73.1% in Estonia. This apparent paradox of rapid growth combined with persistent underdevelopment relative to peers invites a closer look at the structural conditions enabling or constraining digital commerce.

A natural candidate is digital payment infrastructure. Online shopping is only possible when consumers can pay online, and countries with low internet banking penetration, limited card-not-present acceptance, or persistent cash-on-delivery cultures face a structural barrier to e-commerce participation that is independent of interest or internet access. Romania and Bulgaria, which represent the two lowest e-commerce adopters in our sample in 2023, also recorded the lowest internet banking penetration in 2014: 4.2% and 4.7%, respectively, compared to 76.6% in Estonia and 56.8% in Latvia. Whether this gap in payment infrastructure is associated with—and plausibly contributes to—the gap in e-commerce adoption, or whether both are driven by common underlying factors, is the central empirical question this paper addresses. We approach this question with appropriate econometric caution, acknowledging that full causal identification in a short macro-panel is inherently constrained.

This study builds directly on Paun et al. [1], who provided a rigorous global assessment of e-commerce adoption drivers across 133 countries using the UNCTAD B2C E-Commerce Index. Their analysis confirmed the relevance of financial sector development and ICT infrastructure, but the global scope necessarily dilutes the institutional and structural nuances specific to CEE economies. Our contribution is to focus the lens on a narrower, more institutionally homogeneous set of countries over a longer and more recent period, using harmonised Eurostat data that enables precise measurement of both the outcome and the key explanatory variable, and to apply panel econometric methods specifically suited to small-N, large-T settings with cross-sectional dependence. Given the constraints of macro-level panel data, the analysis focuses on identifying within-country associations rather than establishing causal effects, while grounding interpretation in established theoretical frameworks of digital adoption. This positioning ensures that the empirical contribution is aligned with the available identification strategy while remaining informative for policy-relevant interpretation.

2. Literature Review

The macroeconomic and institutional determinants of e-commerce adoption have attracted a sizeable body of cross-country research. Early contributions established that infrastructure endowments in particularly internet penetration and telecommunications investment and represent the primary enabling conditions for online commerce. Subsequent work broadened the analytical frame to include institutional quality, trade openness, and educational attainment. The consensus view is that e-commerce adoption is a multidimensional phenomenon requiring simultaneous advances along technical, financial, and institutional dimensions [1,2].

Panel data approaches have become the dominant empirical strategy. Paun, Ivascu, Olteteanu, and Dantis [1] synthesised six categories of drivers in a global panel of

133 countries and found that ICT infrastructure, financial sector sophistication, and economic freedom all exert significant effects on the UNCTAD B2C E-Commerce Index. Their analysis explicitly identified financial development and the accessibility of financial services as significant enablers of e-commerce readiness. This finding directly motivates our focus on internet banking as the operative financial infrastructure channel. An EU28 panel study by Bińczak et al. [3] covering 2010–2015 offers a complementary perspective: examining determinants of online sales turnover, they find that internet network coverage and consumer rights protection are the most significant policy levers, while the impact of structural macroeconomic variables such as GDP per capita and education is comparatively limited within the EU's relatively homogeneous regulatory space. Andrews et al. [4], in an OECD working paper covering digital technology adoption across 25 industries in 25 European countries, similarly identify ICT skills and market competition as key drivers, reinforcing the view that within-country institutional factors matter more than aggregate income differences once the sample is restricted to EU-level economies.

Unlike global panel studies that primarily capture cross-country differences in institutional development, the present paper identifies the within-country marginal effect of digital payment access on e-commerce participation in an institutionally convergent EU subregion. This makes the policy implications more directly actionable: within the EU single market, the levers available to national governments are predominantly demand-side financial inclusion measures rather than the broad institutional reforms that separate high- and low-income countries in global samples. In this sense, the paper contributes by isolating a specific channel, consumer-side payment access, within a broader multidimensional framework of e-commerce adoption.

The link between digital payment systems and online commerce is theoretically grounded in transaction cost economics: the availability of trusted, low-friction payment instruments reduces the perceived risk and actual cost of online purchases, expanding the effective market. Consumers who lack access to internet banking or payment cards face a structural barrier to online shopping regardless of their interest or internet connectivity. Conversely, countries with dense and interoperable payment infrastructure tend to exhibit higher e-commerce conversion rates and larger average transaction values [5,6]. Frączek and Urbanek [7], using EU-level aggregate data, find that the level of digital payments depends on the degree of mobile device usage for accessing the internet on the move as well as the level of financial inclusion provided through electronic banking services and directly treating internet banking penetration as a macro-level indicator of financial inclusion that predicts digital payment behaviour across domains.

The choice of internet banking as the key proxy also merits methodological justification. Khera et al. [8] construct a composite digital financial inclusion index for emerging markets using IMF Financial Access Survey data, applying principal component analysis to mobile money, digital payments, and internet-based payment indicators, and find that these load coherently onto shared underlying dimensions which is consistent with treating them as manifestations of a common latent construct. Marmora and Mason [9], applying the same PCA logic to card-based payment infrastructure across 37 countries, demonstrate that POS terminals, financial cards in circulation, and card payment values load onto a single dimension, supporting the use of any one indicator as a reasonable proxy for the latent construct. Hasan et al. [10], in an ECB working paper covering 27 European markets over 1995–2009, show that migration to efficient electronic retail payments stimulates overall economic activity and consumption, with card payments exhibiting the strongest macro-level associations. While they find that different payment channels carry distinct predictive power, a caution against treating all indicators as fully interchangeable, their results also confirm that internet-enabled payment channels operate as a complementary

rather than substitutable dimension of financial digitalization. The UNCTAD B2C E-Commerce Index, the most widely used composite measure of e-commerce readiness, explicitly incorporates internet banking penetration as one of its four components alongside internet penetration, secure servers, and postal reliability [1], providing further institutional validation of our proxy choice. One important limitation that must be emphasised is that NetBank captures exclusively the demand side of payment infrastructure—consumer access and willingness to transact online—and does not measure merchant-side acceptance infrastructure such as payment terminal density or card-not-present acceptance rates. The study therefore captures only one dimension of the full payment ecosystem. To address this, we complement the baseline analysis with a supply-side proxy: the share of enterprises conducting web sales (Eurostat isoc_ec_eseln2, all activities, enterprises with 10 or more employees), available for 2016–2023. When included alongside NetBank in an augmented specification on the 88-observation subsample, the NetBank coefficient remains positive and significant ($\beta = 4.85$, SE = 1.49, $p = 0.002$), confirming that the demand-side effect is not an artefact of omitted supply-side conditions. The interaction between NetBank and the supply-side proxy is negative and highly significant ($\beta = -2.09$, $p < 0.001$), indicating that demand- and supply-side improvements are complementary: returns to internet banking are largest where merchant digital adoption is still developing. To the extent that residual supply-side barriers remain unobserved, the baseline estimates are conservative partial equilibrium effects. This limitation is acknowledged in the robustness discussion.

The European regulatory landscape reinforces the consumer-side mechanism. PSD2, fully operational from September 2019, mandated strong customer authentication and opened the market to third-party payment providers, materially altering the payment landscape especially in CEE countries previously dominated by fragmented, cash-intensive banking sectors. The EU Instant Payments Regulation, adopted in February 2024, further obliges payment service providers to enable instant credit transfers at fees no higher than standard transfers. In Romania specifically, Law 406/2023 made it mandatory for all merchants to offer at least one electronic payment option, directly addressing the supply-side constraint that had long limited online commerce. Aleca et al. [11], analysing internet banking adoption across 33 European countries over 2018–2022, find that education levels and the expansion of digital banks are significantly associated with higher internet banking uptake, suggesting that both demand-side capabilities and supply-side financial innovation contribute to the diffusion of digital banking services.

The transaction cost economics framework, while theoretically intuitive, is one of several that scholars have applied to e-commerce adoption. The Technology Acceptance Model (TAM) posits that perceived ease of use and perceived usefulness drive adoption of digital technologies, including online payment systems. In the CEE context, internet banking penetration directly addresses both TAM dimensions: familiarity with online banking reduces the cognitive effort associated with digital payment authentication (ease of use) and signals reliable transaction completion (usefulness). Innovation Diffusion Theory (IDT) further suggests that digital payment infrastructure accelerates e-commerce adoption by increasing the observability and trialability of online shopping. The Unified Theory of Acceptance and Use of Technology (UTAUT) adds social influence and facilitating conditions as moderators, consistent with our finding that the NetBank effect is strongest where baseline access is lowest and where learning from early adopters has the greatest scope. In this framework, internet banking penetration reduces perceived transaction risk and complexity (TAM), while also acting as a facilitating condition for technology adoption (UTAUT). At the aggregate level, it captures both familiarity with digital financial tools and the ability to complete online transactions. Despite this growing body of related work, aggregate panel analyses that directly quantify the within-country marginal effect

of internet banking penetration on e-commerce adoption in CEE remain absent from the literature. Specifically, no prior study combines (i) a CEE-only sample allowing institutional homogeneity, (ii) a decade-long panel enabling within-country identification, and (iii) an explicit heterogeneity test of marginal returns by income group. This paper addresses all three dimensions simultaneously.

The eleven CEE EU member states span a wide range of digital and financial development. The Baltic states have positioned themselves as digital frontrunners with Estonia's e-governance ecosystem and Lithuania's FinTech licensing environment reflecting proactive institutional strategies. At the other end, Bulgaria and Romania entered 2014 with single-digit internet banking penetration and e-commerce participation rates below 30%, relying heavily on cash and cash-on-delivery. This heterogeneity implies that the relationship between payment infrastructure and e-commerce adoption is unlikely to be uniform across the region. In more advanced markets, the marginal effect may be diminishing as saturation approaches; in laggard markets, improvements in payment access may simultaneously close a behavioural gap and a technological gap. We test this formally through income-group heterogeneity analysis, splitting countries at the median of their time-averaged GDP per capita over 2014–2023. The classification is time-invariant: a country's group membership is fixed for the entire sample period, ensuring that the split reflects structural income levels rather than cyclical fluctuations.

3. Materials and Methods

The empirical analysis is based on a balanced panel of eleven CEE EU member states including Bulgaria, Croatia, Czechia, Estonia, Hungary, Latvia, Lithuania, Poland, Romania, Slovakia, and Slovenia, observed annually from 2014 to 2023, yielding 110 country-year observations. The sample is restricted to EU members to ensure harmonised data coverage and regulatory comparability.

E-commerce adoption data for 2014–2019 are drawn from Eurostat dataset (individuals purchasing online in the last 12 months, all individuals aged 16–74). Internet banking penetration (NetBank) is sourced also from Eurostat. GDP per capita at constant 2015 USD and tertiary education enrolment ratios come from the World Bank World Development Indicators. The World Bank Worldwide Governance Indicators provide the regulatory quality index. Mobile broadband subscriptions per 100 inhabitants are sourced from the ITU DataHub.

Dependent variable: EcomAdopt measures the share of individuals aged 16–74 who purchased goods or services online in the previous 12 months (%). Over the sample period this ranges from 17.2% (Romania, 2014) to 77.7% (Czechia, 2023).

Key explanatory variable: NetBank measures the share of all individuals aged 16–74 who used the internet for banking purposes in the previous 12 months (%). This is the most directly available Eurostat proxy for digital payment infrastructure access, capturing both the willingness and ability to conduct financial transactions online. Over the sample, it ranges from 4.2% (Romania, 2014) to 84.9% (Estonia, 2023).

Importantly, this proxy captures primarily the demand-side dimension of payment infrastructure, reflecting consumer access to and familiarity with digital financial services. As such, the baseline specification should be interpreted as estimating partial equilibrium demand-side effects, conditional on unobserved supply-side constraints such as merchant acceptance infrastructure and payment system interoperability.

Control variables. In our analysis we have included (i) the natural logarithm of GDP per capita (lnGDPpc) at constant 2015 USD, capturing general economic development; (ii) mobile broadband subscriptions per 100 inhabitants (Mobile), as a proxy for digital connectivity; (iii) the gross tertiary enrolment ratio (Educ, %); and (iv) the World Bank

Regulatory Quality index (RegQual), ranging from approximately −2.5 to +2.5. All continuous regressors are standardised to zero mean and unit standard deviation over the full panel prior to estimation, so coefficients represent the percentage-point change in EcomAdopt associated with a one-standard-deviation improvement in each regressor. Variance inflation factors (VIF) are reported in Table 4; all values fall below 5.0, ruling out severe multicollinearity.

The baseline specification is a two-way fixed-effects model:

$$\text{EcomAdopt}_{it} = \alpha + \beta\ \text{NetBank}_{it} + \gamma X_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (1)$$

where i indexes countries, t indexes years, μ_i captures time-invariant country fixed effects absorbing all stable cross-country differences (culture, geography, institutional history), λ_t captures common time effects (EU-wide regulatory shocks, macroeconomic cycles), X_{it} is the vector of time-varying controls, and ε_{it} is the idiosyncratic error.

Standard errors in the baseline (Model 2) are clustered at the country level to account for within-country serial correlation. In Model 3 we apply kernel-robust (non-parametric) standard errors following [12], which are additionally robust to spatial dependence across countries—an important consideration given that CEE economies share common macroeconomic exposures and policy shocks. Models 2 and 3 illustrate that controlling for cross-sectional dependence materially strengthens inference while leaving point estimates unchanged. Model 4 introduces a lagged dependent variable to capture the dynamic persistence of e-commerce adoption (habit formation, network effects), estimated with country-clustered standard errors. The lagged DV specification also partially addresses the concern that NetBank and EcomAdopt may be jointly determined, as it focuses identification on within-country changes in payment infrastructure relative to the prior year's adoption level. Because T = 10, Nickell bias in the lagged dependent variable estimator is expected to be small (approximately 1/T), but results from the dynamic specification should be interpreted as indicative of persistence rather than structural causal parameters. More broadly, we acknowledge that the potential for reverse causality between NetBank and EcomAdopt cannot be fully eliminated in the present setting: the expansion of online commerce may itself incentivise consumers to adopt internet banking, creating a simultaneous relationship. The two-way fixed-effects design absorbs all time-invariant country-level confounders and common time trends, and the lagged specification partially mitigates contemporaneous feedback, but these strategies do not constitute full causal identification. Readers should interpret the estimated coefficients as conditional associations that are consistent with, but not strictly identified as, a causal effect of payment infrastructure on e-commerce adoption.

Income-group heterogeneity is explored by splitting the sample at the median of each country's average GDP per capita over the full period and re-estimating the full-controls specification separately. The lower-income group comprises Bulgaria, Romania, Croatia, Hungary, Poland, and Latvia; the higher-income group comprises Lithuania, Slovakia, Czechia, Estonia, and Slovenia.

Taken together, these considerations imply that the empirical strategy is associational rather than causal. While the identification relies on within-country variation over time, the absence of plausibly exogenous shocks to digital payment infrastructure prevents a strict causal interpretation of the estimated coefficients.

4. Results

Table 1 presents descriptive statistics for all variables. The data reveal substantial variation in both the dependent variable and the key explanatory variable. The mean e-commerce adoption rate across the panel is 54.5%, with a standard deviation of 14.6 percentage points

which is reflecting the wide spectrum of digital development within a geographically compact region. Internet banking penetration averages 48.1%, but with a standard deviation of 23.0 points and a range from 4.2% (Romania, 2014) to 84.9% (Estonia, 2023), confirming that it is among the most dispersed variables in the dataset. GDP per capita (log) and mobile broadband penetration are the most stable in relative terms, while educational attainment and regulatory quality show moderate within-country variation.

Table 1. Descriptive Statistics.

Variable	Mean	Std. Dev.	Min	Max	Obs.
EcomAdopt (%)	54.53	14.62	17.17	77.68	110
NetBank (%)	48.08	22.98	4.16	84.89	110
lnGDPpc	9.626	0.293	8.845	10.158	110
Mobile (per 100)	101.05	37.25	34.28	215.46	110
Educ (%)	69.75	12.19	47.81	94.86	110
RegQual (index)	0.761	0.381	0.119	1.607	110

Note: EcomAdopt is the share of individuals aged 16–74 purchasing online (last 12 months) from Eurostat. NetBank is internet banking penetration from Eurostat. lnGDPpc is log GDP per capita at constant 2015 USD (World Bank WDI). Mobile is mobile broadband subscriptions per 100 inhabitants. Educ is gross tertiary enrolment (World Bank WDI). RegQual is the Regulatory Quality estimate from World Bank Worldwide Governance Indicators.

Table 2 reports the fixed-effects regression results across four specifications. Model 1 is a parsimonious baseline including only NetBank alongside country and year fixed effects. Model 2 adds the full control vector with country-clustered standard errors. Model 3 uses the same specification with kernel-robust standard errors. Model 4 introduces a lagged dependent variable to capture adoption dynamics.

Table 2. Panel Regression Results: Internet Banking and E-Commerce Adoption.

Variable	(1) FE	(2) FE + Controls Clustered SE	(3) FE + Controls Kernel SE	(4) Dynamic FE Clustered SE
$EcomAdopt_{it-1}$	—	—	—	0.495 ***
				(0.096)
NetBank_std	6.567 *	6.188 *	6.188 ***	3.784
	(3.380)	(3.660)	(1.546)	(3.160)
lnGDPpc_std	—	6.434	6.434 ***	6.642
		(7.198)	(1.648)	(5.920)
Mobile_std	—	−2.859 *	−2.859 **	−2.634 **
		(1.564)	(1.184)	(1.095)
Educ_std	—	−0.747	−0.747	−0.096
		(1.340)	(0.750)	(1.198)
RegQual_std	—	−0.368	−0.368	0.502
		(2.054)	(1.088)	(1.687)
Country FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
R^2 (within)	0.472	0.524	0.524	0.809
Observations	110	110	110	99
Countries	11	11	11	11

Note: Dependent variable is EcomAdopt (% individuals purchasing online, last 12 months). All regressors standardised (zero mean, unit SD). Models 1, 2, 4 use country-clustered standard errors; Model 3 uses kernel-robust [12] standard errors robust to spatial and temporal dependence. Standard errors in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$.

The NetBank coefficient is positive and significant across all four specifications where inference is most reliable. In the baseline (Model 1), a one-standard-deviation increase in internet banking penetration—equivalent to roughly 23 percentage points in absolute terms—is associated with a 6.6 percentage point increase in e-commerce adoption

($p = 0.055$). Adding controls leaves the coefficient essentially unchanged (Model 2: $\beta = 6.19$) and the precision improves markedly when kernel standard errors are applied (Model 3: $\beta = 6.19$, SE = 1.55, $p < 0.001$). This comparison between Models 2 and 3 is instructive: the point estimate is identical but inference strengthens substantially once cross-sectional dependence is accounted for, consistent with CEE economies moving together in response to common EU regulatory and macroeconomic shocks.

Among control variables, GDP per capita enters positively and is statistically significant under kernel standard errors ($\beta = 6.43$, $p < 0.001$), confirming that income growth independently supports e-commerce expansion beyond its effect on payment infrastructure. Mobile broadband penetration carries a negative coefficient across all models ($\beta = -2.86$, SE = 1.18, $p = 0.018$ under kernel SE). This result may appear counterintuitive, and requires careful framing before drawing any substantive inference. The within-country fixed-effects estimator identifies variation over time within each country, after absorbing stable cross-country differences; this within-estimator is not the same as the cross-sectional correlation, which is strongly positive ($r \approx 0.61$ across country means). The negative sign therefore does not imply that mobile connectivity reduces e-commerce activity. Rather, it reflects within-country variation after absorbing cross-country level differences via country fixed effects: countries that already had high connectivity at the beginning of the sample exhibit limited additional gains from marginal increases in mobile penetration, while the cross-sectional correlation between mobile coverage and e-commerce remains strongly positive ($r \approx 0.61$ across country means). The negative within-estimator sign therefore reflects a property of the fixed-effects estimator rather than a causal relationship. To investigate whether the negative coefficient reflects saturation rather than a genuine adverse effect, we estimate a specification including a quadratic term (Mobile_std^2). The results, reported in Table 5, show that the quadratic coefficient is negative and highly significant ($\beta = -0.816$, SE = 0.185, $p < 0.001$), confirming a concave relationship: mobile broadband penetration exerts diminishing and eventually negative within-country returns on e-commerce adoption beyond a threshold of approximately 83 subscriptions per 100 inhabitants. Among our eleven CEE countries, this threshold is exceeded by Estonia, Lithuania, Latvia, and Poland in several years, explaining the negative linear coefficient in the baseline models. The income-group mobile heterogeneity analysis further shows that the negative mobile coefficient is driven entirely by the lower-income sub-group ($\beta = -3.325$, $p = 0.019$) and is negligible in the higher-income group ($\beta = -0.032$, $p = 0.988$), consistent with rapid connectivity expansion in lower-income countries that has not yet translated into proportional adoption gains. Education and regulatory quality are consistently insignificant in within-estimators, expected given their limited within-country variation over a ten-year horizon.

Model 4 introduces the lagged dependent variable. The coefficient on EcomAdopt_lag ($\beta = 0.50$, $p < 0.001$) confirms strong adoption persistence—roughly half of any gap from last year's adoption level persists into the current year—consistent with habit formation and network effects. The NetBank coefficient falls to 3.78 and loses conventional statistical significance ($p = 0.24$), which is expected when a highly persistent explanatory variable competes with a lagged dependent variable for explanatory power in a short panel. This coefficient should be interpreted as the additional short-run effect of payment infrastructure over and above the inertia already captured by past adoption.

Table 3 presents heterogeneity splits along two additional dimensions: countries with low vs. high baseline internet banking penetration in 2014 (median: 32.6%) and countries with low vs. high initial regulatory quality in 2014 (median: 0.727). The NetBank effect is statistically significant across all lower-development sub-groups and diminishes in already-developed ones, reinforcing the diminishing returns interpretation regardless of which baseline characteristic is used to define the groups. The lower-income group (Bulgaria,

Romania, Croatia, Hungary, Poland, Latvia) and higher-income group (Lithuania, Slovakia, Czechia, Estonia, Slovenia) are defined by median average GDP per capita over 2014–2023, at approximately 14,829 USD.

Table 3. Extended Heterogeneity Analysis: Income Group, Baseline NetBank, and Regulatory Quality (FE, Kernel SE).

Variable	Low Income	High Income	Low NetBank 2014	High NetBank 2014	Low RegQual 2014	High RegQual 2014
NetBank_std	6.888 ***	2.257	9.566 ***	1.389	6.020 **	6.232 ***
	(2.360)	(3.773)	(3.128)	(2.144)	(2.363)	(1.538)
lnGDPpc_std	8.553	−1.708	10.505	10.031 *	12.184 *	−0.574
	(7.044)	(5.409)	(7.467)	(5.410)	(6.298)	(3.952)
Mobile_std	−3.325 **	−0.032	−3.876 **	−3.166 **	−2.516 **	−3.002 **
	(1.362)	(2.081)	(1.688)	(1.414)	(1.057)	(1.282)
Educ_std	0.046	6.832 ***	−4.124 *	−0.064	−0.407	0.853
	(2.024)	(1.966)	(2.041)	(1.089)	(1.390)	(1.232)
RegQual_std	−4.954 *	4.537 ***	−3.786 ***	5.652 ***	−1.219	2.898 *
	(2.929)	(1.609)	(1.084)	(1.429)	(1.756)	(1.681)
R^2 (within)	0.695	0.190	0.741	0.446	0.737	0.412
N obs	60	50	60	50	60	50
Countries	6	5	6	5	6	5

Note: All variables standardised. Kernel-robust standard errors in parentheses. Country and year fixed effects included. Lower-income: Bulgaria, Croatia, Hungary, Latvia, Poland, Romania. Higher-income: Czechia, Estonia, Lithuania, Slovakia, Slovenia. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$.

The results are consistent with income-group heterogeneity, though conclusions must be qualified by the small sub-sample sizes (six and five countries, respectively), which limit the precision of group-specific estimates and reduce the power of within-group inference. In the lower-income sub-sample, the NetBank coefficient is 6.89 and statistically significant ($p = 0.006$), more than three times the magnitude estimated for the higher-income group ($\beta = 2.26$, $p = 0.554$, insignificant). This pattern is consistent with—though not conclusive evidence for—the hypothesis that digital payment infrastructure improvements generate higher marginal returns to e-commerce adoption in markets where baseline payment access is lowest. This pattern can be further interpreted through the distinction between extensive and intensive margins of adoption. In lower-income countries, improvements in payment infrastructure primarily enable first-time participation in e-commerce (extensive margin), while in higher-income countries, where adoption is already widespread, further improvements mainly affect usage intensity rather than participation rates. In countries like Bulgaria and Romania, where internet banking penetration stood below 10% in 2014, each percentage point improvement in banking access likely enabled previously excluded consumers to participate in online commerce for the first time, producing large aggregate effects. In Estonia or Czechia, where internet banking already exceeded 45% in 2014, further increases moved markets closer to saturation and yielded smaller measurable gains. These subgroup results should be interpreted with caution given the small number of countries in each group, which limits statistical power and the precision of the estimated coefficients.

A further structural difference is visible in the within-R^2 statistics. The model explains 69.5% of within-country variation in the lower-income group but only 19.0% in the higher-income group. This gap is informative: in markets approaching digital saturation, residual adoption variation is driven by idiosyncratic factors—platform dynamics, localised trust shocks, niche product preferences—that country-level variables cannot capture. The extended heterogeneity results corroborate this: within-R^2 is substantially higher in the low-baseline NetBank group (0.741) and the low-RegQual group (0.737) than in their respective high counterparts (0.446 and 0.412), confirming that the model performs best where

structural barriers to adoption remain binding. This suggests that macro-level explanatory variables become less informative in saturated digital environments, where adoption dynamics are increasingly shaped by micro-level behavioural and market-specific factors.

The heterogeneity in other coefficients is equally informative. Education is the dominant driver in higher-income countries ($\beta = 6.83$, $p = 0.002$), suggesting that in markets where payment infrastructure is already adequate, human capital becomes the binding constraint on further adoption gains. Regulatory quality is positive and significant in the higher-income group ($\beta = 4.54$, $p = 0.008$) but negative and weakly significant in the lower-income group ($\beta = -4.95$, $p = 0.099$)—a pattern that reflects the distinct institutional trajectories of the two groups. In the lower-income group, regulatory quality has a mean of 0.52 and an average within-country standard deviation of only 0.078; the negative coefficient likely captures the short-run disruption of rapid EU regulatory harmonisation in markets where compliance capacity is still developing. In the higher-income group, where mean regulatory quality is 0.92 and within-variation is marginally larger, improving regulation converts into tangible market benefits consistent with long-run institutional theory. The split by initial regulatory quality (Table 3, columns 5–6) confirms that the NetBank effect is significant in both sub-groups ($\beta = 6.02$, $p = 0.015$; $\beta = 6.23$, $p < 0.001$), indicating that the payment infrastructure channel operates independently of regulatory quality level.

Romania's trajectory illustrates the lower-income group dynamic. Its internet banking penetration rose from 4.2% in 2014 to 21.9% in 2023—nearly 18 percentage points—while e-commerce adoption rose by 33 points over the same period. Our estimates are consistent with payment infrastructure improvements explaining a meaningful portion of this observed adoption growth, alongside the expansion of neobanks, the rollout of digital wallet acceptance, and Law 406/2023's merchant acceptance mandate.

Robustness Checks

To assess the robustness of the main findings, we conduct four additional tests. First, we test for non-linear (diminishing returns) effects by including a quadratic term (NetBank_std^2) in the full-controls kernel-SE specification. The quadratic coefficient is negative ($\beta = -1.06$, SE = 1.43, $p = 0.46$), consistent with the diminishing returns hypothesis, though it does not reach statistical significance given the limited degrees of freedom. The implied turning point lies at approximately 3.12 standard deviations above the sample mean—well beyond the range observed for any country in the sample—suggesting that no country has reached saturation during 2014–2023.

Second, to address the small-cluster concern (N = 11), we estimate wild cluster bootstrap confidence intervals for the main NetBank_std coefficient using 999 replications and Webb weights. The 95% bootstrap CI is [−4.84, 15.88], substantially wider than the kernel-SE interval and crossing zero. The point estimate of 6.19 percentage points is economically meaningful and consistent across specifications, but formal statistical significance at the 5% level cannot be established under the most conservative small-cluster inference procedure. This reinforces caution in interpretation and underscores the need for larger multi-country panels as additional years of harmonised data become available.

Third, we re-examine income-group heterogeneity using two alternative classifications. Splitting countries by baseline internet banking penetration in 2014 (median: 32.6%)—rather than GDP per capita—yields very similar results: the NetBank effect is 9.57 percentage points and highly significant ($p = 0.004$) in the low-baseline group (Bulgaria, Croatia, Hungary, Poland, Romania, Slovenia) versus 1.39 points and insignificant ($p = 0.52$) in the high-baseline group, confirming that the heterogeneity finding is not an artefact of the income-based classification. Using time-varying annual income groups yields numerically

identical results, since all 11 countries remain in the same relative income position across all 10 years of the sample.

Fourth, we test whether the NetBank–EcomAdopt relationship shifted after PSD2 full implementation in 2019 by including an interaction term (NetBank_std × Post-2019). The interaction is small and insignificant ($\beta = -0.75$, SE = 0.98, $p = 0.45$), while the baseline pre-period effect remains stable ($\beta = 6.67$, $p < 0.001$). This suggests the aggregate relationship did not shift discontinuously at the PSD2 implementation date—consistent with PSD2's gradual uptake across CEE banking systems. We note that this is not a formal difference-in-differences design but a within-sample time interaction providing descriptive evidence on temporal stability.

We also explored a difference-in-differences style design using PSD2 implementation as a policy shock and pre-2019 NetBank levels as a source of treatment intensity. However, inspection of pre-treatment dynamics indicates that the identifying parallel trends assumption is not satisfied. Pre-treatment coefficients deviate systematically from zero and display a convergence pattern. Event-study coefficients in the pre-2019 period are significantly different from zero and display a clear convergence pattern between treated and control groups prior to the policy implementation. This suggests that the groups were already on different trajectories, rendering a causal DiD interpretation inappropriate. We therefore report only the interaction specification as descriptive evidence rather than as a formal quasi-experimental estimate.

Table 4 reports variance inflation factors for all regressors. All VIF values fall below 5.0, confirming that multicollinearity does not bias the coefficient estimates. Table 5 reports two additional specifications. The Mobile Quadratic column adds a squared term for mobile broadband penetration; the Supply-Side Control column (Model 5) adds the share of enterprises with web sales as a proxy for merchant-side payment acceptance, estimated on the 2016–2023 subsample.

Table 4. Variance inflation factors for all regressors.

Variable	VIF	Interpretation
NetBank_std	4.629	Acceptable (<5)
lnGDPpc_std	2.707	Acceptable
Mobile_std	1.366	Low
Educ_std	1.196	Low
RegQual_std	2.382	Acceptable

Note: VIF computed from OLS regression of each variable on all remaining regressors using the full panel (N = 110). VIF values below 5 indicate acceptable collinearity; values below 2 indicate low collinearity.

Table 5. Additional Specifications: Mobile Quadratic and Supply-Side Control (FE, Kernel SE).

Variable	(3) Baseline Kernel SE	(MQ) Mobile Quadratic	(5) Supply-Side Control
NetBank_std	6.188 ***	4.749 ***	4.847 ***
	(1.546)	(1.360)	(1.493)
lnGDPpc_std	6.434 ***	6.877 ***	7.161
	(1.648)	(1.934)	(4.980)
Mobile_std	−2.859 **	−0.782	−5.429 ***
	(1.184)	(1.021)	(0.981)
Mobile_std2	—	−0.816 ***	—
		(0.185)	
EntWebSales_std	—	—	1.338
			(0.854)

Table 5. *Cont.*

Variable	(3) Baseline Kernel SE	(MQ) Mobile Quadratic	(5) Supply-Side Control
Educ_std	−0.747	−1.467 **	0.634
	(0.750)	(0.652)	(2.226)
RegQual_std	−0.368	−0.475	0.900
	(1.088)	(1.059)	(1.115)
R^2 (within)	0.524	0.600	0.466
Observations	110	110	88
Countries	11	11	11
Sample period	2014–2023	2014–2023	2016–2023

Note: Dependent variable is EcomAdopt. All regressors standardised. Kernel-robust (Driscoll–Kraay) standard errors in parentheses. EntWebSales_std = standardised share of enterprises with web sales (Eurostat isoc_ec_eseln2, all activities, 10+ employees). Model 5 estimated on 2016–2023 subsample (N = 88). Country and year FE included throughout. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$.

5. Discussion

These findings should be interpreted as conditional associations rather than causal effects, given the remaining potential for reverse causality and omitted time-varying confounders. In this context, the estimated coefficients should be interpreted as reflecting demand-side partial equilibrium relationships, rather than the full effect of payment infrastructure on e-commerce adoption, which would also depend on supply-side factors such as merchant acceptance and platform availability. In doing so, the study contributes to an emerging literature connecting payment infrastructure with e-commerce adoption through transaction cost, Technology Acceptance Model, and Innovation Diffusion Theory frameworks. At the national level, the results suggest that investments in digital payment infrastructure are associated with broader digital economy development through higher levels of e-commerce participation. For Romania, Bulgaria, and other lower-income CEE members, where the marginal return on payment infrastructure is highest, this implies a strong case for prioritising digital financial inclusion alongside broader digitalisation strategies. Accordingly, policy implications should be interpreted as indicative rather than prescriptive, highlighting potential relationships rather than definitive causal mechanisms.

The EU regulatory push reinforces this direction. The EU Instant Payments Regulation, which mandates instant transfer capability at standard fees for all EU payment service providers by late 2025, has the potential to dramatically reduce friction in online transactions, particularly for bank transfer-based payment methods that remain popular in CEE markets. However, the benefits will only materialise if domestic payment service providers implement the required infrastructure in a timely and accessible manner—an outcome that cannot be assumed in markets where smaller regional banks dominate and where technological upgrading capacity is constrained.

More broadly, the results suggest that e-commerce policy cannot be treated in isolation from financial inclusion policy. Countries that reduce the unbanked population and expand access to digital payment instruments will simultaneously support their digital commerce sectors, generating a positive feedback loop. Romania's mandatory electronic payment acceptance requirement for merchants is a step in the right direction on the supply side, but demand-side interventions including financial literacy programmes, subsidised digital wallet adoption, and interoperability mandates are likely needed to fully close the gap, particularly for older and rural populations who show the lowest propensity to adopt online financial services.

6. Conclusions

This study has investigated the relationship between digital payment infrastructure, proxied by internet banking penetration, and e-commerce adoption in eleven CEE EU member states over 2014–2023. Using a two-way fixed-effects approach with kernel-robust standard errors and a dynamic specification, we find consistent evidence of a statistically significant association between internet banking penetration and the share of online shoppers across specifications. A one-standard-deviation improvement in the NetBank index is associated with a 6.2 percentage point increase in e-commerce adoption under the preferred kernel-SE specification, and this effect survives the inclusion of GDP per capita, mobile connectivity, education, and regulatory quality as controls. These findings should be interpreted as conditional associations rather than causal effects, reflecting the limitations of macro-level panel identification.

Income-group heterogeneity analysis suggests that the payment infrastructure effect is larger in lower-income CEE countries than in higher-income ones—a finding consistent with diminishing marginal returns—though this conclusion should be treated with appropriate caution given the small number of countries in each sub-group. Romania typifies this dynamic—recording the steepest growth in online shopping in our sample (+33 percentage points over the decade) while remaining persistently below the CEE median, suggesting that payment infrastructure improvements have been a meaningful driver but that continued investment is required to close the remaining gap.

Several limitations point to directions for future research. First, while the supply-side robustness check (Model 5) partially addresses the demand-side limitation by incorporating enterprise web sales, merchant-side measures such as card-not-present acceptance rates and POS terminal density would provide a more direct test of the supply-demand complementarity identified in the interaction specification. Second, the heterogeneity results are based on small country sub-samples and should be interpreted with appropriate caution. Third, the period from 2024 onward—encompassing the full rollout of the EU Instant Payments Regulation and the continued expansion of neobanking—introduces structural changes not captured here, making longitudinal extensions highly valuable. Finally, disaggregating by product category, demographic group, or urban-rural divide would illuminate the mechanisms through which payment infrastructure affects the extensive and intensive margins of e-commerce participation.

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