

Digitalization, Innovation and Economic Growth in the United States: Analysis by Classical and Quantile Regression (QR And QQR)

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ABSTRACT

Introduction: Digitalization and innovation have become major drivers of economic growth, but their effects may vary considerably across different economic conditions. While conventional analyses often focus on average effects, they may overlook important heterogeneities and asymmetric relationships, particularly across low and high levels of economic growth. The United States provides a particularly relevant context for this analysis due to its highly digitized economy and its leading position in innovation and digital technologies.

Objectives: This study examines the impact of digitalization and innovation on US economic growth by comparing classical quantile regression (QR) and quantile-on-quantile regression (QQR). The objective is to identify whether the effects of digitalization and innovation differ across the distribution of economic growth and to determine whether these effects vary according to different economic regimes.

Methods: The analysis employs annual US data on economic growth, digitalization, and innovation. Digitalization is measured through the spread of broadband infrastructure, while innovation is proxied by research and development (R&D) expenditure. Quantile regression is first applied to examine the effects of these variables across different conditional GDP growth quantiles. Quantile-on-quantile regression is then employed to capture two-dimensional and conditional heterogeneity, allowing the effects of digitalization and innovation to be examined across different combinations of their own distributions and the GDP growth distribution.

Results: The results indicate that digitalization has a limited, and in some cases negative, effect at certain GDP growth quantiles, suggesting the presence of diminishing marginal returns in an already highly digitized economy. In contrast, innovation has a stronger positive effect on economic growth, particularly during periods of rapid expansion, highlighting its procyclical nature. The comparison between QR and QQR shows that conventional quantile regression tends to smooth the relationships and may conceal important heterogeneities. The QQR approach reveals a more complex pattern, characterized by negative effects at certain intermediate quantiles and substantially stronger positive effects at high quantiles.

Conclusions: The findings provide a more nuanced understanding of the relationship between technology and economic growth in the United States. They highlight the importance of accounting for heterogeneous and asymmetric effects when assessing the economic contribution of digitalization and innovation. The results are consistent with the coexistence of diminishing returns to digitalization in a mature digital economy and the increasing importance of innovation for sustained economic expansion. They also suggest that policies supporting digitalization and innovation should take into account the prevailing growth regime in order to enhance their effectiveness.

Keywords: Digitalization; Innovation; Economic growth; Quantile regression; Quantile-on-quantile regression (QQR); Heterogeneity of effects; United States.

INTRODUCTION

Over the past few decades, the US economy has undergone major structural transformations, largely driven by the rapid spread of digital technologies and the intensification of innovation activities. As a global leader in technological

progress, the United States provides a unique analytical framework for examining the mechanisms through which digitalization and innovation influence economic growth. The economic literature consistently emphasizes the central role of technological progress in long-term growth dynamics.(Solow, 1956);(Romer, 1990)And(Aghion & Howitt, 1992)), while more recent work highlights the growing importance of digital infrastructure in improving productivity and macroeconomic performance(Brynjolfsson & Hitt, 2000);(Czernich et al., 2011).

From an empirical standpoint, this study initially employs classical quantile regression (QR), introduced by Koenker & Bassett, (1978) This method aims to estimate the impact of digitalization and innovation at different quantiles of the economic growth distribution. It is particularly well-suited for analyzing economies characterized by high cyclical variability, such as that of the United States, and allows for distinguishing the effects observed during periods of low, medium, and high growth.

However, classical quantile regression does not fully capture the complex interactions between the distributions of the explanatory variables and that of the dependent variable. To overcome this limitation, the analysis is extended to quantile-on-quantile regression (QQR), developed by Sim & Zhou, (2015) This advanced methodological approach allows us to examine the effect of digitalization and innovation quantiles on economic growth quantiles, thus offering a more nuanced, non-linear, and regime-dependent representation of the relationships under study. Several recent works have highlighted the relevance of QQR in the analysis of complex macroeconomic relationships. (Shahbaz et al., 2018);(Brynjolfsson & Hitt, 2000).

The originality of this work lies on several levels. First, it offers an in-depth analysis of the link between digitalization, innovation, and economic growth in the specific context of the United States, using recognized indicators consistent with the theoretical literature. Second, unlike most existing studies that rely primarily on average approaches or classical quantile regressions, this research presents a complementary approach combining classical quantile regression (QR) and quantile-on-quantile regression (QQR). This dual approach highlights a more pronounced heterogeneity in the effects of digitalization and innovation depending on growth regimes and levels of technological development. The use of QQR allows for the identification of specific conditional effects, revealing how different levels of digitalization and innovation influence US economic growth depending on whether it is experiencing a slowdown or an expansion. In this sense, this study contributes to enriching the existing literature by providing a more nuanced and dynamic understanding of the mechanisms by which digital transformation and innovation drive economic growth. The results obtained thus offer important implications for public policies aimed at strengthening digital infrastructure and R&D investments in the United States.

In this context, the main research question can be formulated as follows : To what extent do digitalization and innovation influence economic growth in the United States, and how do these effects vary across different growth regimes and levels of digital and technological development ?

To answer this question, this work is structured around two complementary axes. The first axis, theoretical in nature, is devoted to analyzing the conceptual foundations and reviewing the literature on the links between digitalization, innovation, and economic growth in the case of the United States. The second axis, empirical, aims to evaluate these relationships in the case of the United States by employing classical quantile regression (QR) and quantile-on-quantile regression (QQR), in order to highlight the heterogeneity and complexity of the effects studied.

OBJECTIVES

Economic growth remains a fundamental indicator of macroeconomic performance and a central focus of applied economic analysis. It is traditionally measured by the growth rate of real gross domestic product (GDP), which summarizes the evolution of economic activity adjusted for inflation. In the case of the United States, this indicator captures both long-term structural dynamics and cyclical fluctuations associated with business cycles, while also reflecting the impact of technological factors on overall productivity.

In an advanced and technology-intensive economy like that of the United States, digitalization is a key driver of economic growth. It is measured by the number of fixed broadband subscriptions per 100 inhabitants, a proxy widely used in empirical literature to measure the level of digital infrastructure development and effective access to digital

services. Theoretically, the spread of broadband infrastructure fosters growth by improving the efficiency of production processes, reducing transaction costs, and facilitating the dissemination of information and knowledge. It also supports the adoption of advanced digital technologies and the development of new business models, thereby contributing to improved productivity and competitiveness in the US economy.

Furthermore, innovation occupies a central place in endogenous growth theories. Research and development (R&D) expenditure, expressed as a percentage of GDP, constitutes a standard measure of innovation effort and technological progress. In the American context, characterized by high levels of R&D investment and strong interaction between businesses, universities, and public institutions, innovation generates positive externalities, stimulates knowledge accumulation, and fosters sustainable long-term growth. The theoretical framework proposed by Aghion & Howitt, (1992) highlights the role of the creative destruction process, whereby innovations replace obsolete technologies and sustainably improve productivity.

In the case of the United States, economic growth results from the complementarity between digitalization and innovation. The development of digital infrastructure facilitates the dissemination and commercialization of innovations stemming from R&D activities, while innovation efforts strengthen the demand for more efficient digital technologies. This interaction constitutes a key mechanism for real GDP growth in a technology-intensive economy, although the intensity of its effects can vary depending on the phase of the economic cycle and the degree of technological maturity.

Thus, theoretically, American economic growth appears closely linked to the level of digitalization, measured by the spread of fixed broadband, and to the intensity of innovation efforts, measured by R&D spending. The choice of these variables is justified by their theoretical and empirical relevance for analyzing the determinants of growth in an advanced economy, and constitutes the conceptual foundation for the empirical analysis developed in the remainder of this study.

METHODS

In this study, we analyze the impact of digitalization and innovation on US economic growth using both classical quantile regression (QR) and quantile-on-quantile regression (QQR). The United States provides a particularly suitable framework for this analysis due to its advanced economy, high adoption of digital technologies, and leadership in innovation. The dependent variable is the annual growth rate of US real GDP, while the explanatory variables include digitalization, approximated by the percentage of individuals using the internet, and innovation, measured by research and development expenditure as a percentage of GDP (Table 1). The annual data cover the period 1990–2024 and are extracted from the World Development Indicators (WDI 2025) database.

Table 1. Variables selected for the empirical study

Variable type	Variable	Indicator	Measure	Theoretical justification
Dependent variable (Y)	Economic growth (GDP)	Real GDP growth rate	% annual	A key indicator of macroeconomic performance, widely used to analyze growth dynamics and economic cycles
Explanatory variable (X1)	Digitalization (DIGITAL)	Fixed broadband subscriptions	(per 100 people)	The standard proxy for the number of fixed broadband subscriptions per 100 inhabitants is retained as a proxy variable for digitalization, insofar as it reflects the level of development of digital infrastructures and effective access to digital services.
Explanatory variable (X2)	Innovation (INNOV)	Research and development expenditure	% of GDP	A key measure of innovation effort and technological progress, at the heart of endogenous growth models

Existing empirical literature shows that digitalization and innovation generally stimulate economic growth, although results vary depending on the context and time period. Toader et al., (2018) And Mohammed & Yacine, (2025) Recent work using quantile regression approaches has also demonstrated that the effects of innovation and information technologies are heterogeneous across levels of economic performance, often being more pronounced at the extremes of the growth distribution (Xu & Lin, (2023) And Chen & Ye, (2021) However, few studies have simultaneously explored quantile-on-quantile connectivity, which allows for capturing the cross-cutting and non-linear effects of digitalization and innovation on different growth quantiles. Hung, (2023).

Our main contribution is to present classical quantile regressions and the QQC approach, thus offering a more nuanced view of the asymmetric and dependent relationships within the economic regime. This methodology allows us to identify the specific interactions between phases of low, medium, and high growth and to formulate differentiated economic policy recommendations. The results are visualized using the obtained data, enabling us to provide new empirical insights into the differentiated roles of digitalization and innovation in the dynamics of US growth, while also enriching the existing literature.

RESULTS

Table 2. Descriptive statistics of the variables: digitalization (DIGITALI), economic growth (GDP), and innovation (INNOV)

Statistics	DIGITAL	GDP	INNOV
Mean	4.219044	1.626055	2.765287
Median	4.489154	1.829924	2.695920
Maximum	4.689383	5.888341	3.586230
Minimum	2.795683	-3.426832	2.450130
Std. Dev.	0.554032	1.835960	0.310929
Skewness	-1.274615	-0.783689	1.450635
Kurtosis	3.436385	4.817940	4.171297
Jarque-Bera	7.525131	6.481775	11.01297
Probability	0.023224	0.039129	0.004060
Sum	113.9142	43.90349	74.66276
Sum Sq. Dev.	7.980727	87.63948	2.513598
Observations	27	27	27

The descriptive statistics in Table 2 indicate that digitalization (DIGITALI) has a relatively high mean level (4.22) with a median of 4.49, reflecting a concentration of observations at higher levels, which is confirmed by a negative skewness (-1.27). Its dispersion remains moderate (standard deviation = 0.55), with values ranging from 2.80 to 4.69, suggesting a relatively stable evolution of digitalization over the period studied. Economic growth (GDP) shows a mean of 1.63 and a median of 1.83, moderate volatility (standard deviation = 1.84), and a wide range, from a minimum of -3.43 to a maximum of 5.89, reflecting alternating phases of recession and expansion. Its negative skewness (-0.78) indicates the presence of marked negative shocks. Innovation (INNOV) has a mean of 2.77 and a median of 2.70, with low dispersion (standard deviation = 0.31) and values ranging from 2.45 to 3.59; its positive skewness (1.45) reveals the existence of innovation peaks. For all three variables, the kurtosis coefficients are greater than 3 (3.44 for DIGITALI, 4.82 for GDP, and 4.17 for INNOV), indicating leptokurtic distributions with thick tails. Finally, the Jarque–Bera statistics are significant (7.53 for DIGITALI, 6.48 for GDP and 11.01 for INNOV, with respective p-

values of 0.023, 0.039 and 0.004), which leads to the rejection of the normality hypothesis and justifies the use of quantile regression and quantile-on-quantile connectivity to analyze the relationships between digitalization, innovation and economic growth.

Following this descriptive analysis, which highlights significant dispersion, marked asymmetries, and non-normality in the variable distributions, it is necessary to supplement the study with stationarity tests to verify the statistical properties of the time series before econometric estimation. In this context, Table 3 presents the results of the Augmented Dickey-Fuller (ADF) test, which allows us to assess the degree of integration of the variables considered.

Table 3: Stationarity test (the ADF test)

Variable	t-Statistic	Probability (p-value)	Stationary
DIGITAL	-2.507009	0.0139	I(1)
GDP	-3.312424	0.0016	I(0)
INNOV	-2.396853	0.0188	I(1)

Table 3 presents the results of unit root tests (Dickey-Fuller type) applied to the variables DIGITALI, GDP and INNOV, in order to examine their degree of stationarity.

The results indicate that the GDP variable is stationary in level, with a t-statistic of -3.3124 and a p-value of 0.0016, below the 5% threshold. The null hypothesis of the presence of a unit root is therefore rejected, which means that GDP is integrated of order zero (I(0)).

In contrast, the variables DIGITALI and INNOV are not stationary in level but become stationary after the first differentiation. The respective t-statistics (-2.5070 for DIGITALI and -2.3969 for INNOV), combined with p-values less than 5%, allow us to reject the null hypothesis of a unit root after differentiation. These variables are thus integrated of order one (I(1)).¹

Overall, these results highlight a mixed integration of variables, combining I(0) and I(1) series. This preliminary stationarity check is essential, as it confirms the validity and robustness of our empirical approach based on quantile regression, which does not require all variables to be integrated of the same order. Thus, the unit root tests reinforce the methodological coherence of our work and justify the application of quantile regression to analyze the impact of digitalization and innovation on economic growth.

On this solidly established methodological basis, the analysis can now focus on the operational implementation of quantile regression, specifying the quantiles retained in order to examine in a differentiated manner the impact of digitalization and innovation according to the different levels of economic growth.

Classical quantile regression

We therefore choose to analyze several quantiles of the distribution, generally $\tau = 0.1, 0.5$, and 0.9 . Each quantile allows us to examine the effect of the explanatory variables on different positions in the GDP distribution, ranging from the lowest to the highest levels of economic growth. The results from classical quantile regression are based on the approach developed by Koenker & Bassett, (1978)), which allows us to estimate the impact of an explanatory variable X not solely on the average of the dependent variable Y , but over its entire distribution, thus offering a more complete and heterogeneous analysis of economic relations (according to model (1)).

$$Q_y \left(\frac{\tau}{X} \right) = \alpha(\tau) + \beta(\tau)X \quad (1)$$

¹We note: DIG = Δ DIGITALI = DIGITALI_t - DIGITALI_{t-1} and INN = Δ INNOV = INNOV_t - INNOV_{t-1}

$\tau \in [0, 1]$: quantile of Y (0.1, 0.5, 0.9)

$\beta(\tau)$: Effect of X on the quantile τ of Y.

Based on this, the quantile regression model formalized in model (2) allows us to empirically translate the differentiated impact of digitalization and innovation on economic growth according to different GDP levels, by directly linking the estimates presented in Table 4 to the analysis of the coefficients by quantile. The model is specified as follows:

$$GDP_t = \beta_0(\tau) + \beta_1(\tau)DIG + \beta_2(\tau)INN + \varepsilon_\tau \quad (2)$$

Or :

GDP_τ represents economic growth at the quantile τ (0.1; 0.5; 0.9),

DIG and INN are the primary differences between the variables of digitalization and innovation.

$\beta_0(\tau)$; $\beta_1(\tau)$ et $\beta_2(\tau)$: are the estimated coefficients for each quantile,

is the quantile-specific error term ε_τ .

This approach allows us to examine how the impact of digitalization and innovation varies according to low, medium, and high levels of economic growth, offering a more nuanced and comprehensive view than traditional regression methods based on the mean. Interpreting the coefficients by quantile will highlight the heterogeneous effects of these variables on GDP growth.

Table 4: Quantile regression results (Bootstrap = 500)

Variables	Quantile 0.1	Quantile 0.5	Quantile 0.9
DIG	1.837 (0.898)	9.050 (0.020)	6.941 (0.382)
INN	-8.533 (0.414)	-3.055 (0.628)	1.607 (0.879)
Constant	-0.167 (0.937)	1.332 (0.003)	2.088 (0.206)
Pseudo R²	0.304	0.126	0.133
Observations	26	26	26

Note : The values in parentheses indicate the probabilities associated with the estimated coefficients (p-values), allowing us to assess the statistical significance of the variables at each quantile.

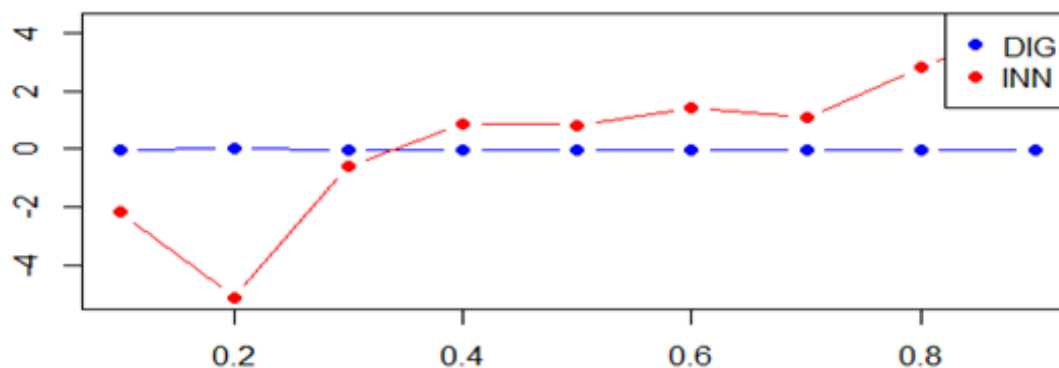
The results in the table above indicate a marked heterogeneity in the impact of digitalization and innovation on economic growth according to the quantiles of the distribution.

At the lower quantile (0.1), corresponding to periods of low economic growth, neither digitalization nor innovation has a statistically significant effect on GDP growth.

At the middle quantile (0.5), digitalization has a positive and statistically significant effect on economic growth, suggesting that improved digitalization promotes growth when the economy is operating around its normal level. In contrast, innovation remains insignificant.

At the top quantile (0.9), representing periods of strong growth, the coefficients associated with digitalization and innovation are positive but not statistically significant, indicating that these factors are not determining drivers of growth in phases of high expansion.

Overall, the quantile regression results show that the impact of digitalization on economic growth is nonlinear and dependent on the level of growth. Digitalization plays a significant role only at the median level of the growth distribution, while its effect is limited during periods of low or high growth. Furthermore, innovation has no statistically significant direct effect on economic growth at any quantile considered, which may be explained by adjustment lags, indirect effects, or an institutional environment that conditions its effectiveness. These results highlight the importance of using nonlinear approaches, such as quantile regression, to better understand the heterogeneity of the relationships between Digitalization, innovation and economic growth.



Graph 1. The evolution of DIG and INN according to the quantil

Figure 1 illustrates the evolution of the estimated coefficients of digitalization (DIG, in blue) and innovation (INN, in red) on GDP across different quantiles. The x-axis represents the quantiles of the GDP distribution, while the y-axis presents the values of the estimated coefficients, allowing us to assess the intensity and sign of the impact of each explanatory variable according to the level of economic growth.

For digitalization, the coefficients remain close to zero across all quantiles, indicating a non-significant effect of digitalization on GDP in our sample, regardless of the level of production. In other words, the impact of digitalization on economic performance appears neutral across the entire GDP distribution. In contrast, the coefficients associated with innovation show significant variability across quantiles: for the lower quantiles (0.1; 0.2), the effect of innovation on GDP is zero or slightly negative, while for the middle quantiles (0.3; 0.7), this effect becomes weak or slightly positive. For the higher quantiles (0.8; 0.9), innovation has a distinctly positive effect on GDP. These results suggest that the impact of innovation depends on the level of GDP, with countries or firms with high GDP benefiting more from the effects of innovation than those with low GDP. This heterogeneity could reflect the importance of initial conditions, such as infrastructure, human capital, or technological absorption capacity, for fully leveraging innovation. In conclusion, while digitalization does not appear significant in this analysis, innovation stimulates GDP in a differentiated way depending on the level of wealth or production, highlighting the importance of pre-existing contexts for maximizing its economic effects.

The Quantile-on-Quantile Method

To further the analysis, we also apply the Quantile-on-Quantile (QQR) method, which combines the concepts of quantile regressions and conditional distributions. This approach allows us to measure the effect of a specific quantile of an explanatory variable on each quantile of the dependent variable, thus providing a comprehensive map of heterogeneous relationships.

Formally, the QQR is expressed as:

$$Q_y \left(\tau / X = Q_x(\theta) \right) = \beta_0(\tau, \theta) + \beta_1(\tau, \theta) Q_x(\theta) + \varepsilon_{\tau, \theta} \quad (3)$$

$Q_y \left(\tau / X = Q_x(\theta) \right)$: Is the quantile τ of the dependent variable Y conditioned on the quantile θ of the explanatory variable X ,

$\beta_0(\tau, \theta)$ et $\beta_1(\tau, \theta)$: These are the estimated coefficients for each combination (τ, θ)

$\varepsilon_{\tau, \theta}$ Is the corresponding error term.

The QQR model estimates the quantiles of GDP conditional on the quantiles of digitalization or innovation. For digitalization, the quantile τ The GDP conditional on the quantile θ of DIG is given by the following model (3):

$$Q_{GDP}(\tau / DIG = Q_{DIG}(\theta)) = \beta_0(\tau, \theta) + \beta_1(\tau, \theta)Q_{DIG}(\theta) + \varepsilon_{\tau, \theta}^{DIG} \quad (4)$$

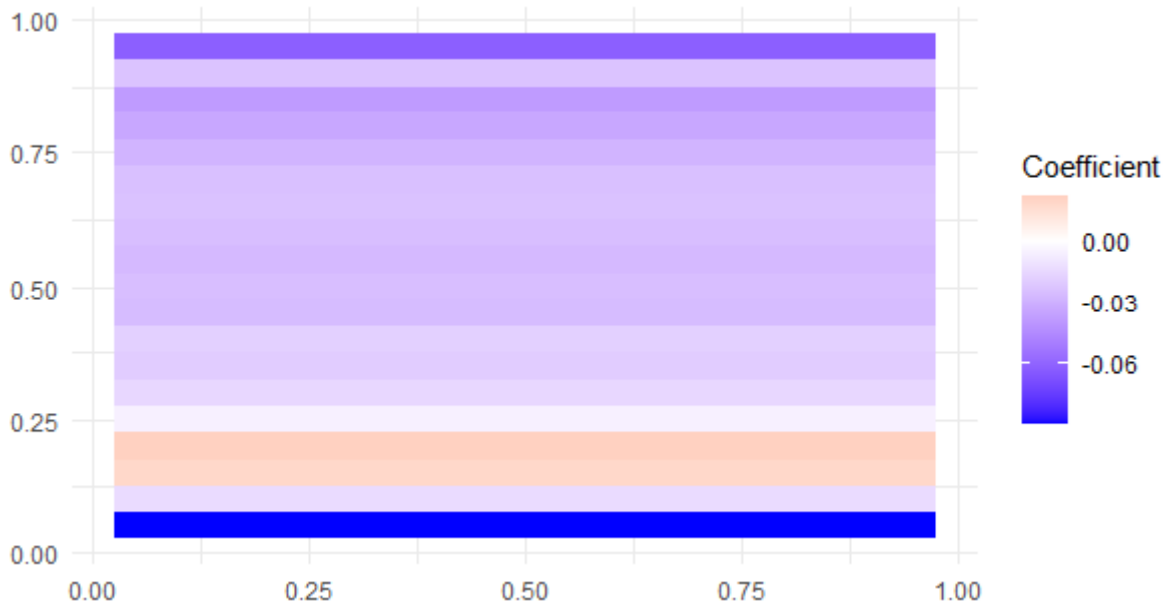
Whereas for innovation, it is formulated as follows in the previous model:

$$Q_{GDP}(\tau / INN = Q_{INN}(\theta)) = \beta_0^{INN}(\tau, \theta) + \beta_1^{INN}(\tau, \theta)Q_{INN}(\theta) + \varepsilon_{\tau, \theta}^{INN} \quad (5)$$

$\beta_0(\tau, \theta)$ et $\beta_1(\tau, \theta)$: Represent the y-intercept and the slope coefficient depending on the quantiles, $\varepsilon_{\tau, \theta}$ is the error term.

The advantage of this method is that it captures the non-linear and asymmetrical effects of digitalization and innovation on growth by simultaneously considering the distributions of both variables. This complements and enriches the analysis performed with classical quantile regression, highlighting the specific interactions between the levels of each variable.

Graph 2. QQR Matrix - Effect of DIG on GDP



The results from the QQR matrix (Figure 2) show that the effect of digitalization on GDP is generally negative across a wide range of quantiles, as indicated by the predominance of blue and purple hues throughout the graph. The y-axis represents GDP quantiles, while the x-axis represents digitalization quantiles, allowing for an analysis of the differentiated impact of digitalization on economic growth according to the various configurations of the joint distribution of the two variables.

More specifically, for the lower quantiles of GDP ($\tau_{GDP} \approx 0.05; 0.15$), the coefficients associated with digitalization reach their most negative values, fluctuating around -0.06 to -0.07 , represented by dark blue. This suggests that, during periods of low economic growth in the United States, the intensification of digitalization is associated with structural adjustment costs (sectoral reallocation, automation, labor market rigidities) that outweigh immediate productivity gains.

As we move towards the intermediate quantiles of GDP ($\tau_GDP \approx 0.40; 0.60$), the color gradually becomes light purple, reflecting a weakening of the negative effect, with coefficients close to -0.02 to -0.03 . This area reflects a better capacity for the US economy to absorb digitalization, where productivity gains begin to partially offset adjustment costs.

Finally, for the higher quantiles of GDP ($\tau_GDP \geq 0.80$), the effect of digitalization becomes negative again, albeit of a more moderate magnitude, with coefficients between -0.04 and -0.05 , illustrated by deeper shades of purple. This result suggests that, even during periods of strong growth, digitalization does not necessarily translate into proportional additional gains, which can be interpreted as the existence of diminishing returns or technological saturation in an advanced economy like that of the United States.

Furthermore, automation and the integration of advanced technologies in a context of strong growth can accentuate capital-labor substitution, leading to adjustments in the labor market that temporarily dampen aggregate demand. Thus, even during periods of economic expansion, digitalization can generate transition effects that partially offset its benefits to GDP.

This result represents an original empirical contribution compared to existing literature, which tends to mechanically link a high level of digitalization to superior macroeconomic performance. Our QQR approach shows, on the contrary, that in the case of the United States, digitalization can reach a zone of macroeconomic saturation, where its impact on growth becomes limited, or even negative, despite a favorable economic environment. This heterogeneity of effects, revealed solely through quantile-by-quantile methodology, challenges the conclusions drawn from linear models and underscores the need for a more nuanced analysis of digital transformation policies.

Table 5. Effects of digitalization and innovation on economic growth in the United States: results at the median quantile and implications for quantile-on-quantile regression (QQR)

Variable	Coefficient	Interpretation
(Intercept)	1.63345	Median value of GDP when DIG and INN are at 0. Here, the interval $[-11.21; 14.66]$ includes 0 $\rightarrow$ the y-intercept is not significant.
DIG	-0.02486	At the median quantile, a one-unit increase in digitalization reduces median GDP by 0.02486 units. The interval $[-0.02906; -0.01164]$ does not include 0, indicating that the effect is statistically significant. Slightly negative effect.
INN	0.83503	At the median quantile, one unit of innovation increases median GDP by 0.835 units. The interval $[-5.4937; 6.28734]$ includes 0, so the effect is not statistically significant.

The results reported in Table 5 highlight the estimated effects of digitalization and innovation on US economic growth at the middle quantile of real GDP. From a QQR perspective, these estimates provide a benchmark for interpreting how intermediate levels of digitalization and innovation interact with a median growth regime.

The coefficient associated with digitalization (DIG) is negative and statistically significant at the middle quantile. More specifically, a one-unit increase in the level of digitalization is associated with a 0.02486-unit decrease in median GDP. Within the QQR framework, this result suggests that, when the US economy is in a middle-growth regime, median levels of fixed broadband penetration may be associated with low, or even negative, marginal returns to economic growth. This relationship may reflect the existence of adjustment costs, digital infrastructure saturation effects, or inefficient resource reallocation during certain phases of the business cycle.

In contrast, the estimated coefficient for innovation (INN) is positive but not statistically significant at the median quantile. In a QQR reading, this result indicates that, for intermediate levels of R&D effort, the impact on median economic growth remains uncertain and likely depends on underlying economic conditions. The lack of significance

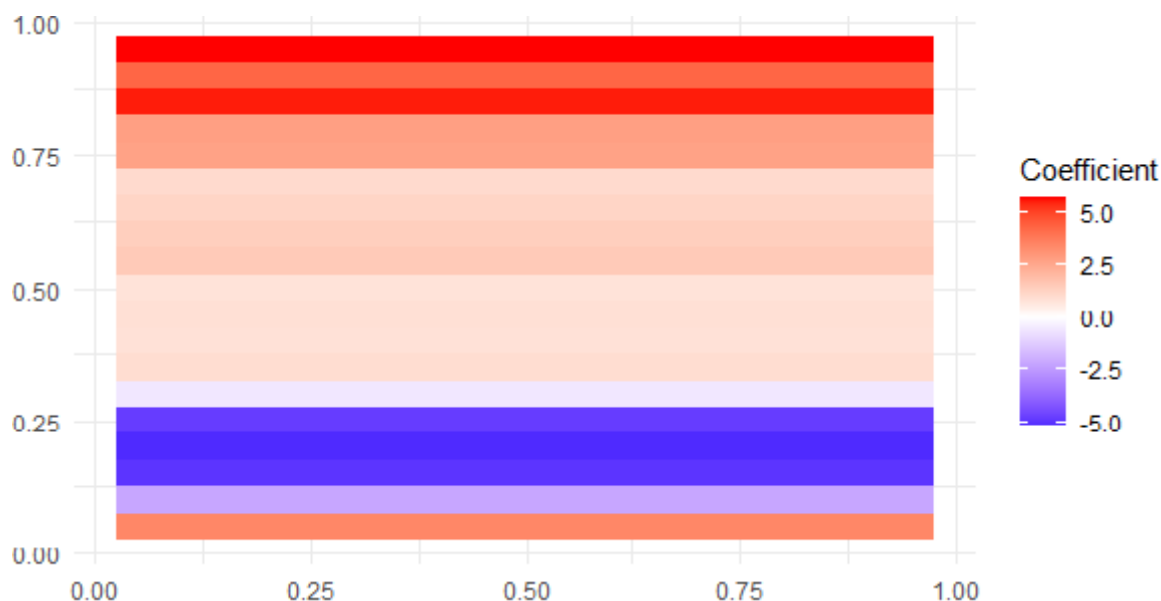
suggests that the benefits of innovation may be delayed or more pronounced in specific growth regimes, particularly during periods of strong expansion or economic slowdown.

Furthermore, the intercept is not statistically significant, indicating that in the absence of digitalization and innovation, median GDP growth does not exhibit a distinct structural level. This finding reinforces the idea that the dynamics of US growth are primarily driven by the interaction between technological factors and the specific economic regime.

Overall, these results highlight the value of the QQR approach for analyzing the heterogeneous effects of digitalization and innovation on economic growth. While median quantile analysis reveals a significant negative effect of digitalization and a non-significant effect of innovation, the QQR approach goes beyond this single observation by examining how these effects vary across quantiles of economic growth and levels of technological development. It thus offers a more nuanced and non-linear understanding of the mechanisms linking digital transformation, innovation efforts, and economic growth in the United States.

The graph below highlights a strongly asymmetric relationship between innovation and economic growth in the United States, indicating that the impact of R&D spending on real GDP depends mainly on the growth regime, with weak or negative effects in the lower quantiles of growth and distinctly positive effects in phases of strong expansion, regardless of the level of innovation.

Graph 3. QQR - Effect of INN on GDP



Graph 3, representing the QQR matrix of the effect of innovation (INN) on GDP (GDP), reveals a structure distinctly different from that observed for digitalization. Unlike the case of digitalization (DIG), the relationship between INN and GDP appears highly heterogeneous in sign and intensity, with marked contrasts across GDP quantiles. The y-axis corresponds to GDP quantiles, while the x-axis represents innovation quantiles (INN), highlighting the variability of innovation's impact on economic growth depending on different positions within the respective distributions.

Low GDP quantiles ($\tau_{GDP} \approx 0.05; 0.15$) In the lowest quantiles of economic growth, the coefficients associated with innovation are positive and moderate, as indicated by the light red shades, with approximate values between +2 and +3. This suggests that, even during periods of low growth in the United States, innovation plays a supporting role in the economic cycle, probably through the emergence of new products, gains in competitiveness, or the revival of certain technology sectors.

Lower intermediate quantiles of GDP ($\tau_{\text{GDP}} \approx 0.15; 0.30$): A distinct zone appears for these quantiles, marked by strongly negative coefficients, reaching approximately -4 to -5 , represented by dark blue colors. This pattern indicates that, during phases of still fragile but transitional growth, innovation can generate high adjustment costs: resource reallocation, innovation failures, time to market, or creative destruction, which temporarily weigh on GDP growth.

Intermediate to high quantiles of GDP ($\tau_{\text{GDP}} \approx 0.40; 0.70$) At these levels, the matrix becomes predominantly light red to orange, reflecting increasing positive coefficients, on the order of $+1$ to $+3$. This zone reflects a phase where the American economy has sufficient absorptive capacity to transform innovation into effective growth, via technological diffusion, increased productivity and market expansion.

High GDP quantiles ($\tau_{\text{GDP}} \geq 0.80$) Finally, in the upper quantiles of growth, the effect of innovation becomes strongly positive, with coefficients exceeding $+5$, represented by dark red hues. This indicates that, when the US economy is expanding rapidly, innovation acts as a growth amplifier, strengthening competitive advantages, economies of scale, and technological leadership.

These results indicate that digitalization and innovation are not synonymous at the macroeconomic level. Digitalization corresponds more to the adoption and diffusion of existing technologies, while innovation refers to the creation of new technologies, new products, or new processes.

The juxtaposition of the two graphs constitutes a major empirical contribution of this work. Thanks to the QQR methodology:

- The effects of DIG and INN on GDP are fundamentally asymmetric and dependent on the growth regime.
- Economic policies should not treat digitalization and innovation as equivalent levers.
- In an advanced economy like that of the United States, innovation appears as a more robust engine of growth than simply intensifying digitalization.

Comparing the QQR matrices reveals that, unlike digitalization, whose effect on US GDP is generally negative or limited, innovation has a strongly positive impact in the higher quantiles of growth. This contrast underscores that digital transformation alone is insufficient to sustainably stimulate growth, and that only genuine innovation processes can generate significant macroeconomic gains.

The combined analysis of the two graphs (2 and 3) shows that digitalization and innovation are complementary only under certain macroeconomic conditions. In particular:

- Digitalization appears to play a preparatory or infrastructural role.
- While innovation constitutes the true channel for transforming technologies into measurable growth.

Thus, digitalization without innovation can lead to technological saturation, while innovation without absorptive capacity can generate transiently negative effects (as observed in the lower intermediate quantiles of GDP).

Comparison between quantile regression (QR) and quantile-on-quantile regression (QQR)

The results from classical quantile regression (QR) and quantile-on-quantile regression (QQR) lead to distinct interpretations of the impact of digitalization and innovation on economic growth in the United States. This difference highlights the limitations of QR, which is based on conditional mean effects, and underscores the methodological contribution of QQR for analyzing nonlinear and regime-dependent relationships.

Classical quantile regression reveals relatively limited heterogeneity in technological effects along the growth distribution. At the lower quantiles of GDP ($\tau = 0.1$), neither digitalization nor innovation has a statistically significant effect, suggesting weak transmission of technological dynamics to growth during periods of economic slowdown. At the middle quantile ($\tau = 0.5$), digitalization has a positive and significant effect, indicating that it promotes growth when the economy is operating around its normal state, while innovation remains insignificant. Finally, at the upper quantiles ($\tau = 0.9$), the coefficients associated with digitalization and innovation are positive but not significant,

leading to the conclusion that these factors are not key drivers of growth during periods of sustained expansion. Overall, the QR suggests that digitalization plays a significant role only at the center of the growth distribution, while innovation has no robust direct effect at any quantile.

In contrast, the QQR approach reveals a much more pronounced and two-dimensional heterogeneity in technological effects, depending simultaneously on the growth quantile and the quantile of the explanatory variables. Regarding digitalization, QQR highlights a predominantly negative effect across a wide range of GDP quantiles, including during periods of strong growth—a result entirely masked by QR. Concerning innovation, while QR suggests a lack of significant impact, QQR shows that its effect becomes strongly positive in the higher growth quantiles, while being negative in some lower intermediate quantiles. These results indicate that innovation is not inefficient in itself, but that its impact depends closely on the macroeconomic regime and the economy's absorptive capacity.

Thus, a comparison between QR and QQR shows that conclusions drawn from traditional quantile approaches can be incomplete, or even misleading, when they fail to account for the profound heterogeneity of economic relationships. By revealing asymmetric and regime-dependent effects, QQR is a particularly relevant tool for analyzing the links between digitalization, innovation, and economic growth in an advanced economy like that of the United States.

DISCUSSION

Comparative results between classical quantile regression (QR) and quantile-on-quantile regression (QQR) highlight contrasting interpretations of the impact of digitalization and innovation on economic growth in the United States. As several studies indicate, Koenker & Bassett, (1978) and Machado & Santos Silva, (2019) the QR method allows us to analyze the effects of explanatory variables along the growth distribution, but it is limited to conditional mean effects and can mask significant heterogeneities.

Existing research shows that QQR can underestimate or ignore the asymmetric effects of technologies on growth, particularly during periods of low or high growth. Furthermore, the literature on QQR (Sim & Zhou, 2015) emphasizes that this approach reveals two-dimensional relationships between explanatory variables and growth distribution, making it possible to identify effects dependent on economic regimes.

Our empirical analysis shows that, unlike the QR model, the QQR model highlights a predominantly negative effect of digitalization on certain GDP quantiles, as well as a strongly positive impact of innovation at high quantiles but a negative impact on some intermediate quantiles. This dual dimension of heterogeneity, specific to the United States and the period studied, constitutes our original contribution, demonstrating that the QQR model provides a more nuanced and revealing interpretation of the interactions between technology and growth.

The QQR remains sensitive to the choice of quantiles and the quality of the data. The results are specific to the American context and do not allow for definitive causal conclusions. Further studies in other countries and time periods would be necessary to generalize these findings.

This study aimed to analyze the impact of digitalization and innovation on US economic growth, going beyond the limitations of traditional econometric approaches based on conditional averages. By employing advanced quantile methods, it highlights the fundamentally heterogeneous, nonlinear, and regime-dependent nature of technological effects on growth.

Methodologically, this work makes a major contribution to the empirical literature by introducing quantile-on-quantile regression (QQR) into the joint analysis of digitalization, innovation, and economic growth in the United States. Unlike classical approaches and standard quantile regression, QQR captures the complex interactions between the distributions of explanatory variables and that of growth, revealing asymmetric and conditional effects that have been largely overlooked until now. This approach proves particularly relevant for studying an advanced and structurally heterogeneous economy like that of the United States.

Empirically, the results highlight three key findings. First, digitalization, measured by the spread of fixed broadband infrastructure, has a generally limited, or even negative, effect on real GDP growth, suggesting the existence of

diminishing marginal returns in an already highly digitized economy. Second, innovation, measured by research and development spending, appears as a powerful driver of growth, but only in high-growth regimes, confirming the conditional and procyclical nature of its economic impact. Third, QQR analysis reveals marked heterogeneity in technological effects across different phases of the business cycle, which helps explain the diversity and sometimes contradiction of results observed in the existing literature.

Finally, this study contributes to enriching and clarifying the debate on the role of technology in economic growth. By showing that the impact of digitalization and innovation is closely linked to the growth regime, the results reconcile two major currents in the literature : on the one hand, studies highlighting the productivity paradox, and on the other hand, those emphasizing the central role of innovation in long-term growth. Thus, this analysis underscores that the benefits of technological transformations are neither automatic nor uniform, but are profoundly conditioned by the macroeconomic environment.

From this perspective, the results obtained offer important implications for public decision-makers, suggesting that policies supporting digitalisation and innovation must be differentiated and adapted to growth regimes in order to maximize their economic efficiency.

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