Future Business Journal

RESEARCH Open Access

Modeling the dynamic effects of tariffs on economic variables and trade policies

Hemendra Pal[1,2*]

Abstract

Tariffs, a key instrument of trade policy, are often viewed as tools to correct trade imbalances or protect domestic industries. However, their effects on an economy extend beyond immediate price changes, triggering complex feedback loops that unfold over time. This study explores tariffs as a feedback control mechanism within an economic system, emphasizing their role in influencing key variables such as inflation, trade balances, consumption, and monetary policy. By modeling these interactions using delayed differential equations (DDEs), the research demonstrates how time lags in economic adjustments — such as the delayed effects of tariffs on inflation and trade volume can amplify or attenuate the initial impact of policy changes. The feedback loop suggests that tariffs, while raising prices and reducing trade volume in the short term, also lead to inflationary pressures, which may prompt central bank responses, such as interest rate adjustments. These adjustments, in turn, affect investment and consumption, further influencing the economy. The research provides both a theoretical and practical framework for understanding the dynamic and delayed nature of tariffinduced economic changes, with insights into how policymakers can better anticipate and manage the consequences of trade policies. This model offers a comprehensive understanding of the broader economic adjustments and the role of time lags in shaping the long-term impact of tariffs on global trade and national economies.

Keywords Tariffs, Trade policy, Inflation, Trade balances, Monetary policy, Delayed - differential equations

Introduction

Tariffs have long been a key instrument in trade policy, used to address trade imbalances and protect domestic industries. While their immediate effects, such as higher prices for imported goods and reduced trade volumes, are readily observable, their broader economic consequences extend far beyond these short-term changes. Tariffs trigger complex feedback loops that can have delayed impacts on critical economic indicators, including inflation, trade balances, consumption, and monetary policy [1, 2].

This study explores tariffs as a feedback control mechanism within an economic system, focusing on their dynamic influence over time. The research utilizes delayed differential equations (DDEs) to capture the time-lagged effects of tariffs on inflation, trade balance, and other macroeconomic variables. The model highlights the interdependencies between tariffs and economic adjustments, such as inflationary pressures that prompt central bank responses, such as interest rate changes. These monetary policy shifts, in turn, influence investment and consumption, leading to further economic fluctuations [3, 4].

A key feature of this research is the delayed nature of economic adjustments. While tariffs initially raise prices and reduce trade volumes, their longer-term effects—amplified or mitigated by inflation dynamics, monetary policy, and trade relations—can lead to significant economic disruptions. As central banks adjust interest rates

*Correspondence:
Hemendra Pal
hpal00001@gmail.com
[1] Royal Holloway University of London, Egham, UK
[2] Texas A & M University, College Station, USA

to control inflation, they may inadvertently exacerbate or ease these disruptions. In interconnected economies like the United States, Canada, and Mexico, these tariff-induced fluctuations have profound implications for both domestic economic health and international trade relations [5, 6].

Through this theoretical research, the study provides valuable insights into how tariffs shape long-term economic outcomes. By incorporating the delayed effects of tariffs into economic modeling, policymakers can better anticipate and manage the unintended consequences of trade policies, ultimately improving the design and execution of future trade strategies [7, 8]. This research will model the economic impacts of tariffs using DDEs, analyze their effects on GDP and trade balances between the USA and other nations, and examine how tariffs influence inflation in both importing and exporting countries. Additionally, the study will explore the correlation between trade balance and GDP.

Literature review and research gap

The effects of tariffs on economic systems, particularly their dynamic nature and the time lags involved, have become central to the study of international economics. Early studies on tariffs primarily focused on immediate impacts on trade flows, consumer prices, and trade balances, with less attention given to how these effects evolve over time. Anderson et. al. (2004) were among the first to address tariffs as a form of trade cost and examine their immediate impact on trade volumes. Their work introduced a more comprehensive understanding of how tariffs alter international trade by increasing trade costs. However, their analysis assumes that the effects of tariffs are immediate, which overlooks the gradual adjustments made by firms and consumers [9]. This omission is important because tariffs do not immediately affect all aspects of the economy—rather, they set in motion a series of adjustments that take time to manifest in various economic indicators. Thus, the focus of much of the early literature was on static models or immediate changes, while the more nuanced, delayed impacts of tariff policies remained largely unexplored.

As trade and economic theory evolved, scholars recognized that the effects of tariffs are not instantaneous and that their impact on various economic variables unfolds over time. In a more recent study, Amiti et. al. (2019) examine the effects of the US-China trade war, revealing that tariffs can indeed have delayed effects on consumer prices. Their findings show that tariff- induced price increases on imported goods do not occur right away, as firms take time to pass on increased costs to consumers. This delay is crucial in understanding the broader economic impacts of tariff imposition, as it highlights the lag between when tariffs are implemented and when their effects are fully realized in consumer prices. By including time lags in their model, Amiti et. al. provide a more realistic depiction of the way tariffs affect the economy. Their analysis underscores the importance of examining the temporal dimension of economic responses to trade policy, which is a key area that has been addressed with greater sophistication in recent literature. [10].

One of the most effective ways of modeling the dynamic effects of tariffs over time is through the use of delayed differential equations (DDEs). These models are particularly useful in capturing the delayed responses of economic variables to policy changes. DDEs allow for the incorporation of time lags by assuming that the current state of an economic variable depends not only on its present value but also on its past states. This feature is crucial when analyzing how tariffs affect the economy because it reflects the gradual adjustments that take place over time. For example, tariffs might raise the prices of imported goods immediately, but it takes time for consumers and firms to adjust their purchasing behavior or alter their supply chains. Similarly, the effects on inflation, GDP, and employment are not instantaneous but occur over several periods. DDEs are particularly suited for studying these delayed effects because they incorporate the fact that economic systems are not static but evolve over time, responding to past policies and shocks in complex ways. Time lags in the long-term effects of tariffs are not fully captured in existing models. The economy might not fully adjust until much later, especially in cases of prolonged or escalating tariffs. The Melitz model [11], and its dynamic version [12] could be expanded to include more explicit time lags in how firms and economies adjust. By incorporating delayed differential equations into these models, researchers can capture gradual economic adjustments over months or years. The GTAP dynamic model can also be utilized in this regard since it already takes into account the dynamics of international trade, making it a suitable tool to examine long-term tariff effects.

One area where time lags are particularly evident is in the study of Global Value Chains (GVCs). Tariff impacts differ significantly across sectors, particularly for industries relying heavily on imported intermediates. Similarly, regional disparities arise due to varying local economic structures and trade dependencies. In a globalized economy, production is often fragmented across multiple countries, and goods are produced in various stages over time. The impact of tariffs on these complex production networks is not immediately felt. Chor et. al.(2012) argue that the fragmentation of production processes in GVCs means that tariffs affect trade and production over time, rather than instantaneously. Firms within

GVCs must adjust their supply chains in response to tariffs, which can take months or even years [13]. Existing dynamic trade models like the Melitz model [11] or the GTAP model could be adapted to incor- porate sectoral and regional heterogeneity. This could involve expanding the model to allow for distinct sectoral responses based on their reliance on imports or exports. For instance, tariffs on intermediate goods could be modeled to cause quicker disruptions in sectors that rely heavily on such goods. Moreover, models that incorporate regional trade networks could analyze how tariffs impact local economies with different export structures [14]. Grossman et. al.(2021) offer empirical evidence from China, demonstrating that tariffs disrupt supply chains, but these disruptions do not fully materialize until firms adjust their sourcing and production strategies. This delayed adjustment is crucial for understanding the broader impacts of tariff policies, particularly in countries with large, complex production networks. The delayed response in the context of GVCs further underscores the importance of incorporating time lags into models of tariff impacts [15].

The macroeconomic consequences of tariffs also unfold over time. While tariffs can have immediate effects on the trade balance and consumer prices, their broader impacts on aggregate demand, inflation, and employment take longer to materialize. Blanchard et. al.(2017) discuss the potential for tariffs to influence aggregate demand and output, but they emphasize that these effects are not instantaneous. For instance, the immediate reduction in imports may be offset by a later increase in domestic production, as firms adjust to new trade conditions [16]. Much of the existing literature focuses on macroeconomic effects, but there is a need to focus more on firm-level responses to tariffs, particularly in how they adjust their operations (e.g., shifting supply chains, changing production processes, altering prices). The Melitz model could be modified to better capture the heterogeneity of firm-level responses to tariffs. Firm-level adjustments could be modeled with delayed differential equations, which allow for time lags in the firm's decision-making process. The work by Barattieri et al also focuses on dynamic tariff effects on inflation and economic activity, which could be extended to examine the microeconomic, firm-level adjustments in response to tariff shocks [17]. Similarly, the effects of tariffs on inflation may not become evident until firms begin passing on higher costs to consumers. These delayed effects are crucial for policymakers to consider, as they highlight the need for a long-term perspective when evaluating the consequences of tariff policies. Limao et. al.(2017) expand on this by examining the role of policy uncertainty in shaping firm behavior. They argue that when firms face uncertain tariff regimes, they may delay investments or production decisions, leading to a further delay in the effects of tariffs on the broader economy [18]. The time lags involved in these decisions are central to understanding the full economic impact of trade policies.

While there has been significant progress in modeling the dynamic effects of tariffs, several important research gaps remain. Much of the existing literature focuses on the short-term impacts of tariffs, such as changes in trade volumes and consumer prices. However, there is a need for more research that explores the long-term dynamic effects, particularly in terms of GDP, inflation, and employment. Delayed differential equations (DDEs) present an opportunity to model these longer-term effects more accurately, as they account for the gradual adjustments in economic variables that take place over extended periods. More studies are needed to incorporate time lags into models of the long-term effects of tariffs, capturing how the economy evolves over months and years. This is especially relevant for countries that face prolonged or escalating tariff policies, as the full economic impact may not be realized until much later.

Another key gap in the literature is the lack of research on sectoral and regional differences in the delayed effects of tariffs. The impact of tariffs varies significantly across different sectors of the economy. For example, industries that rely heavily on imported intermediate goods may experience more immediate disruptions than others. Similarly, the effects of tariffs are likely to differ across regions, depending on the structure of local economies and their reliance on international trade. Research that specifically models these sectoral and regional differences in the delayed effects of tariffs is sparse, and more work is needed to better understand how these variations influence the overall economic response.

Additionally, much of the research on the economic impact of tariffs focuses on macroeconomic outcomes such as GDP and inflation, but there is a need for more studies that examine firm-level responses to tariffs. Firms often take time to adjust their operations, whether by changing production processes, altering supply chains, or adjusting prices. Understanding these firm-level adjustments and how they unfold over time is essential for building a comprehensive understanding of tariff impacts. Delayed differential equations offer a promising approach for modeling these firm-level adjustments, as they allow for the incorporation of time lags in firm behavior.

Finally, the interaction between tariffs and other policies, such as monetary or fiscal policies, remains underexplored. Tariffs might interact with interest rates, government spending, or other policy changes, potentially affecting the overall economic response. The Ghironi and Melitz (2005) [12] dynamic model could be extended to include interactions between tariffs and fiscal or monetary policies. For example, the model could be adapted to capture the effects of tariff changes alongside government spending changes or interest rate adjustments. Additionally, the GTAP dynamic model could be used to examine these interactions at a global level, considering the complex inter-dependencies between various economic policies and tariff shocks. [12]. In Ghironi and Melitz's model, time lags can be incorporated, but they aregenerally discrete. For example, the model might have the lag between a firm's decision to invest and the effect of that investment on its output in the next period (e.g., quarterly or annually). Delayed differential equations, however, model time delays in continuous time, meaning that the effect of a past event can influence the system continuously over time. The advantage of using continuous-time models lies in their ability to represent delays and dynamic feedbacks with greater accuracy than discrete-time models, which are limited by their fixed time steps [19].Tariffs do not exist in isolation, and their effects may be compounded or mitigated by other policies. For instance, changes in interest rates or government spending may interact with tariff policies in ways that influence the overall economic response. Research that models these interactions and incorporates the time lags involved is essential for understanding the full scope of tariff impacts. Given the complex nature of policy interactions, there is a need for more work that examines how the delayed effects of tariffs interact with other policy changes.

Discrete time vs. continuous time in economic models

In the context of economic models, the Ghironi and Melitz model operates in discrete time, where variables are updated at fixed intervals (e.g., annually or quarterly). These discrete-time models can incorporate time lags (delayed responses), but these lags are typically constrained to the time intervals between steps. In contrast, delayed differential equations (DDEs) operate in continuous time, meaning that the state of the system is continuously changing, and the effects of past states are integrated continuously, not just at discrete time points.

Advantages of continuous time models over discrete time models

Continuous Time models, such as those using DDEs, allow the modeling of gradual adjustments over time (e.g., how capital accumulation or technological changes evolve gradually, or how a shock's effects propagate over time). Discrete time models, while effective in capturing period-based dynamics, may struggle to model gradual transitions as smoothly as continuous models.

Smooth and Gradual Adjustments:

DDEs allow for modeling systems that evolve continuously, which is crucial for capturing long- term economic adjustments. As discussed by Sayama (2015), continuous-time models allow for the gradual buildup of economic variables over time, without the discrete jumps between time intervals inherent in discrete models [4].

Capturing Continuous Dynamics:

In continuous models, you can account for nonlinear dynamics and feedback effects that evolve continuously over time, which could be harder to achieve with discrete models. In some cases, this means better modeling of the persistence of shocks or the smoothness of dynamic adjust- ments over periods like months or years [5].

Applications of continuous time models

Gradual Adjustments over Long Time Frames:

Continuous time models are particularly useful in cases where economic variables changegradually over long periods. For example, capital accumulation, technological changes, or long- term policy adjustments require capturing smooth, continuous processes over time [4]. DDEs provide a natural framework to account for such gradual shifts.

Complex Delays and Feedbacks:

Another advantage of DDEs is their ability to model complex delayed feedback mechanisms, such as those in trade policy models or models of technological diffusion. In continuous-time models, the effect of a policy change or a technological innovation can propagate over time with its own distinct lag, which might be harder to model in discrete steps [20].

Economic Systems:

As described by Ghironi and Melitz (2005), their model uses discrete time to capture dynamics like market entry and exit, investment in capital, and adjustments in trade patterns. However, if researchers wanted to model gradual technological adoption or long-term capital accumulation, continuous-time models with DDEs could more effectively capture the continuous nature of these processes [12].

Introduction to economic systems with time lags

The study of economic systems with time lags is fundamental to understanding how various policies, like tariffs, impact economic variables such as inflation, trade balances, consumption, and monetary policy. Time lags refer to the delays in the response of economic variables to changes in policy variables, such as tariffs. To model these systems mathematically, delayed differential equations (DDEs) are often employed, as they incorporate the delayed effects of actions over time.

This section provides a detailed mathematical modeling of the effects of tariffs in economic systems with time lags and includes explanations of the relevant economic phenomena.

Time lags in economic adjustment and feedback loops

Time lags are crucial in understanding how tariffs affect the economy. The delayed effects are modeled using delayed differential equations (DDEs), where the influence of a variable on the economy at time t depends on the value of the same variable at an earlier time $t-\tau$, where τ is the time lag.

General formulation of feedback loops

The general mathematical model for a system with time lags can be written as:

$$\dot{x}(t) = A \cdot x(t) + B \cdot u(t-\tau) + C \cdot y(t-\tau)$$

where:

- $x^{\cdot}(t)$ represents the rate of change of an economic variable (e.g., inflation, trade balance).
- $x(t)$ is the economic variable itself.
- $u(t-\tau)$ represents the policy input (in this case, tariffs), with a time lag τ.
- $y(t-\tau)$ represents the influence of other economic factors, also with a time lag τ.
- A, B, and C are coefficients representing how sensitive the system is to changes in these variables.

This equation reflects the dynamic nature of economic systems, where changes in economic variables (like tariffs) are not felt instantaneously but instead influence other variables (like inflation or consumption) after a delay.

Mathematical explanation of economic phenomena with time lags

The effects of tariffs and other policy inputs manifest over time due to complex feedback loops. Below are some specific economic phenomena that can be modeled with time lags.

Initial economic reactions: price increases and reduced trade volume

When tariffs are first imposed, the immediate effects can be captured as:

Price increases (inflation)

The price level increases due to the tariff on imports, affecting inflation. The mathematical model for inflation can be written as [2]:

$$\dot{p}(t) = \alpha \cdot u(t) \tag{1}$$

- $p(t)$: This represents the price level (inflation) at time t. The inflation level is determined by the tariffs imposed on imported goods.
- α: This is a coefficient that captures how sensitive inflation is to changes in tariffs. It quantifies the impact of tariffs on the price level.
- $u(t)$: This is the Heaviside step function (unit step function), which represents the tariff imposed on imported goods. The function $u(t)$ is defined as:

$$u(t) = \begin{matrix} 0, \ t < 0 \\ 1, \ t \geq 0 \end{matrix}$$

The function $u(t)$ is 0 before time $t=0$ and 1 at and after $t=0$, indicating that the tariff starts at time $t=0$.

Reduced trade volume

As the price of imports rises, trade volumes adjust. The change in trade volume $T(t)$ due to tariffs can be modeled by: [9]

$$\dot{T}(t) = \beta \cdot u(t) \tag{2}$$

- $T(t)$: This represents the trade volume at time t.
- β: This is the elasticity of trade volume with respect to tariffs. It quantifies how sensitive the trade volume is to changes in tariffs.
- $u(t)$: This is the Heaviside step function (unit step function), which is defined as:

$$u(t) = \begin{matrix} 0, \ t < 0 \\ 1, \ t \geq 0 \end{matrix}$$

The function $u(t)$ is 0 for times before $t=0$ and 1 for times at or after $t=0$.

Medium-term effects: feedback loops in inflation and monetary policy

As time progresses, the immediate effects of tariffs feed back into the economy, leading to broader economic adjustments. This is captured by the feedback loop where inflation influences future inflation, and changes in interest rates affect investment.

Inflationary pressures

Inflation does not just increase initially but can persist, feeding back into the system. The rate of change of inflation over time with feedback is: [21]

$$\dot{p}(t) = \alpha \cdot u(t) + \lambda \cdot p(t-\tau) \tag{3}$$

- $p(t)$: This represents the price level (inflation) at time t.

- α: This is a coefficient that captures the direct impact of tariffs (or policy changes) on the price level.
- $u(t)$: This is the Heaviside step function (unit step function), which activates at $t=0$ (i.e., tariffs or changes are applied starting at time $t=0$). It is defined as: $u(t) = \begin{matrix} 0, & t < 0 \\ 1, & t \geq 0 \end{matrix}$
- λ: This is a coefficient that measures the influence of past price levels on the current price level. It captures the persistence of inflation.
- $p(t-\tau)$: This represents the price level at a previous time $t-\tau$, capturing the effect of past prices on current inflation (i.e., how previous inflation rates influence current inflation).

Monetary policy adjustment

Central banks may respond to inflation by adjusting interest rates. This response is delayed and can be modeled as: [22]

$$\dot{r}(t) = \mu \cdot p(t-\tau) \tag{4}$$

where:

- $r(t)$: This represents the rate of return (or any other relevant financial or economic variable) at time t.
- μ: This is a coefficient that measures how sensitive the rate of return is to past price levels.
- $p(t-\tau)$: This represents the price level (inflation) at time $t-\tau$, indicating that the rate of return at time t depends on the price level at a past time, specifically $t-\tau$.
- τ: This is the time lag between the price level and the rate of return, showing that changes in the price level affect the rate of return with a delay.

Long-term effects: structural adjustments in investment and supply chains

In the long run, the economy adjusts structurally. For example, businesses may diversify their supply chains or shift investment away from tariff-affected countries.

Supply chain diversification

The shift in investment toward alternative markets, reducing reliance on tariffed goods, can be modeled as: [13, 23]

$$\dot{I}(t) = \delta \cdot u(t-\tau) - \zeta \cdot T(t) \tag{5}$$

where:

- $I(t)$: This represents the investment in new markets at time t.
- δ: This coefficient determines how much investment shifts when a change in policy (like tariffs) occurs.
- $u(t-\tau)$: This is the Heaviside step function (unit step function) shifted by τ. It is defined as:

$$u(t-\tau) = \begin{matrix} 0, & t < \tau \\ 1, & t \geq \tau \end{matrix}$$

The function $u(t-\tau)$ activates at time $t=\tau$, meaning that the investment shift begins at this time.

- ζ: This coefficient models how changes in trade volume $T(t)$ influence the investment behavior.
- $T(t)$: This is a function representing trade volume over time. It quantifies how the overall trade volume affects the investment in alternative markets.

Investment shifts

As tariffs cause shifts in trade flows, capital might move to other regions. This can be represented by: [24]

$$\dot{K}(t) = \theta \cdot (T(t) - T_0) \tag{6}$$

where:

- $\dot{K}(t)$ is the rate of change of capital over time, indicating how capital is shifting.
- θ is a parameter representing the responsiveness of capital to changes in tariffs.
- $T(t)$ is the tariff level at time t.
- T_0 is the baseline or reference level of tariffs.

Unit step function and delayed differential equations

The unit step function causes a discrete jump in the tariff at t = 0, while the economic variables evolve continuously thereafter according to the differential equation. This combination allows the model to accurately capture the timing of the tariff imposition as well as the gradual evolution of economic variable in response to this policy change. The combination of the unit step function with DDEs provides a powerful modeling framework for capturing both discrete events and continuous dynamics in economic systems. This combination allows for precise modeling of policy interventions (such as tariffs) and their long-term dynamic effects on economic variables, such as inflation, trade volume, and investment. The unit step function captures the sudden change at a specific time, while the DDEs allow the system to adjust gradually in response to this change, creating a more realistic and flexible representation of real-world economic processes.

Advantages of combining DDEs with the unit step function

1. *Precise Event Timing*:

   The unit step function allows the model to pinpoint the exact time when a discrete event (such as a tariff) occurs. This ensures that the timing of the policy change is accurately captured in the model.
2. *Continuous Dynamics*:
   While the step function captures the discrete shock, the DDE model ensures that the system's response to the shock evolves continuously over time, reflecting the gradual adjustment of variables like inflation, trade volume, or capital accumulation.
3. *Real-World Complexity*:
   Economic systems often experience a combination of discrete shocks and continuous adjustments. The use of the unit step function in DDEs allows researchers to simulate these interactions, providing a more comprehensive model for real-world economic phenomena.
4. *Smooth Transitions and Feedbacks*:
   After a discrete intervention (such as the imposition of a tariff), the system adjusts gradually, with feedback effects propagating through the system over time. DDEs allow for this dynamic feedback, while the step function models the sudden event.

Tariffs affect industries differently, with some sectors more exposed to tariff shocks than others. For example, industries reliant on imported intermediate goods, such as manufacturing, face immediate disruptions when tariffs are imposed on imports. In contrast, industries that are less dependent on trade may experience a slower or smaller impact. Furthermore, regional economies are not equally affected by tariffs. The economic structure and trade dependencies of each region will influence how tariffs impact local economic activity [14].

Methods, results and discussion

"Methodology and assumptions for economic projections and analysis"

Model parameters and their selection

The selection of key economic indicators such as GDP (Gross Domestic Product), Inflation (CPI), and Trade Balances is essential for understanding economic performance and trade relationships. The GDP in constant 2015 USD helps adjust for inflation, ensuring a real economic comparison over time [25]. Inflation is often measured using the Consumer Price Index (CPI), which reflects the price level of a basket of goods and services [7]. The trade balance, the difference between exports and imports, indicates the health of a country's trade relationships [1].

Assumptions behind the parameters

The time frame for the data (2010–2023) allows for detailed analysis of economic trends and provides a strong basis for projections. The assumption that tariffs will impact trade balances and GDP growth starting in 2025 is informed by global trade policies and the ongoing shifts in international trade dynamics [2]. The inflation adjustments are based on the economic principle that tariffs directly influence domestic price levels by altering import prices [2].

Why these values are assumed

The assumption of constant GDP (adjusted for inflation) and CPI allows for consistent comparisons over time, eliminating distortions caused by currency fluctuations or inflationary trends [26]. The assumption that tariffs affect GDP and inflation aligns with established economic theory, where tariffs are expected to reduce trade and increase domestic prices [2]). The policy sensitivity assumption reflects ongoing trends in global trade relations, particularly the U.S.-China trade war and renegotiations of international agreements like NAFTA [6].

Figure 1 The method ensures that the data is successfully retrieved, with error handling to address any issues in fetching the data. Once the data is collected, the first few data points for each indicator are displayed to provide a preliminary overview. Finally, the method visualizes the trends in the data through a series of plots, showing the GDP, trade balance, and inflation trends Fig. 2. for each country. The plots are annotated with the latest data points, and color- coding is used to distinguish between countries, making it easier to compare their economic performance over time. This approach provides a clear view of the economic dynamics and trade relationships between these nations.

Method for projecting future economic conditions

The use of numerical integration methods, such as the ddeint function, to solve differential equations for projecting future economic conditions is a standard technique in economic modeling [3]. This method accounts for dynamic interactions and delayed effects, which are critical for projecting the long-term impact of tariffs and other economic variables.

The method outlined here is for projecting the future economic conditions of four countries—USA, Canada, China, and Mexico—using a differential equation model. The primary focus is on GDP, trade balances, and inflation, with specific consideration for tariff impacts starting in 2025. The approach is as follows:

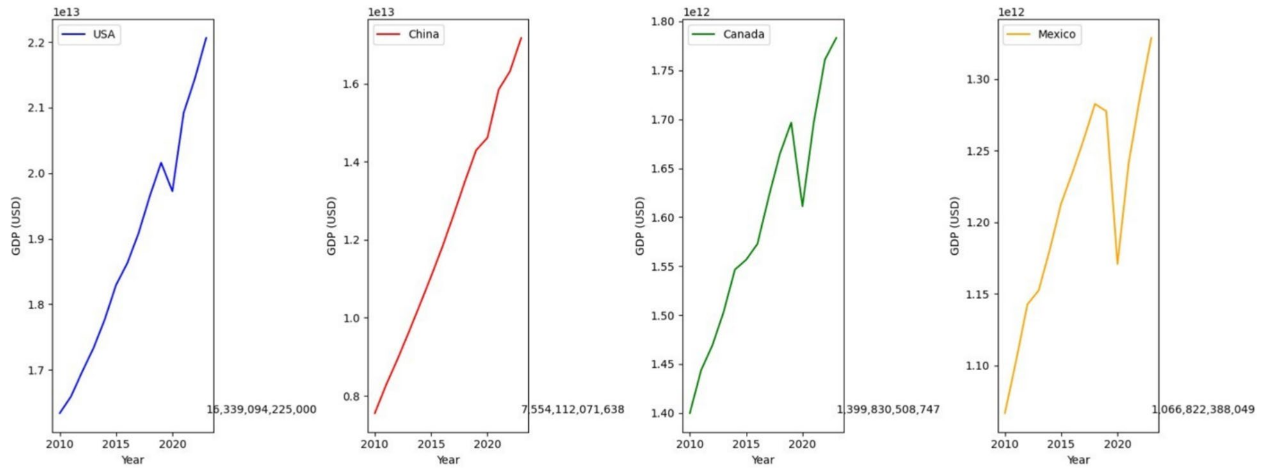


Fig. 1 The Plots show GDP figures for USA, Canada, Mexico and China for extracted data from year 2010 to year 2023

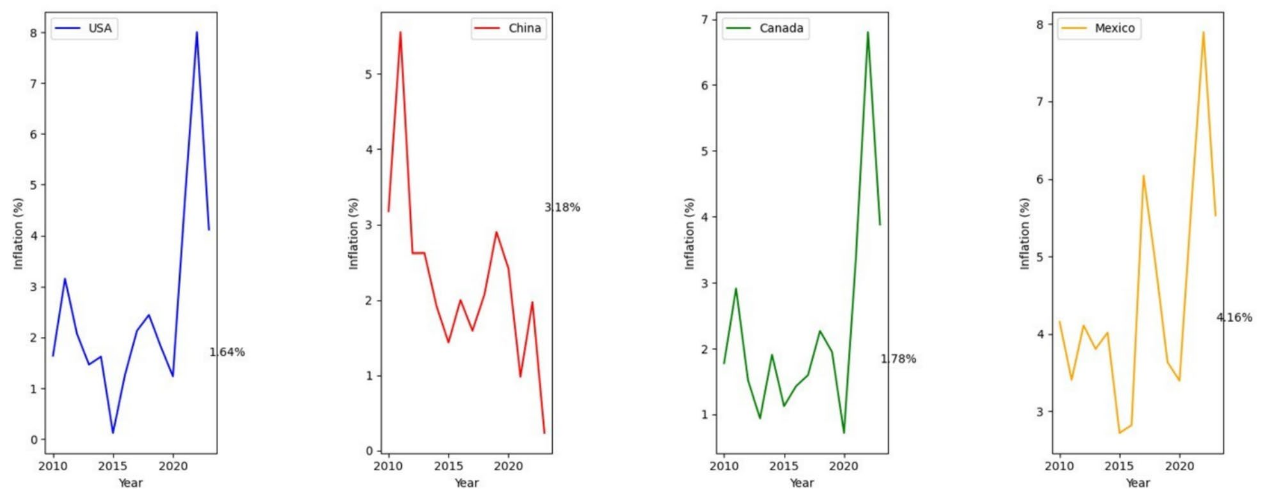


Fig. 2 The Plots show inflation figures for USA, Canada, Mexico and China for extracted data from year 2010 to year 2023

Model definition

The model represents the interactions between the countries' GDP, trade balance, and inflation. It uses differential equations to model the growth of these variables over time. GDP growth is specified for each country, with an adjustment in 2025 to account for tariff effects, such as reduced imports and changes in trade balances between the countries.

Tariff impact

For the years 2025 and beyond, the model assumes that tariffs will reduce GDP growth for some countries (e.g., USA and China) and alter trade balances. Trade balance equations are adjusted by applying tariffs (10% for China, 25% each for Canada and Mexico), which impacts the imports and exports between the countries.

Inflation adjustment

Inflation rates are affected by the trade balances and tariffs. The model introduces a delayed effect on inflation due to the trade policies implemented after 2025. A simple inflation model is used, with inflation rates for each country responding to internal economic changes and the external tariff policy.

Initial conditions

The method starts with known initial conditions for GDP, trade balances, and inflation for each country in

2023. These are used as starting points for the differential equations.

Time integration

The model is solved over a period from 2020 to 2030 using numerical integration methods (specifically, the `ddeint` function), which accounts for the delayed effects of tariffs and their impacts on the variables.

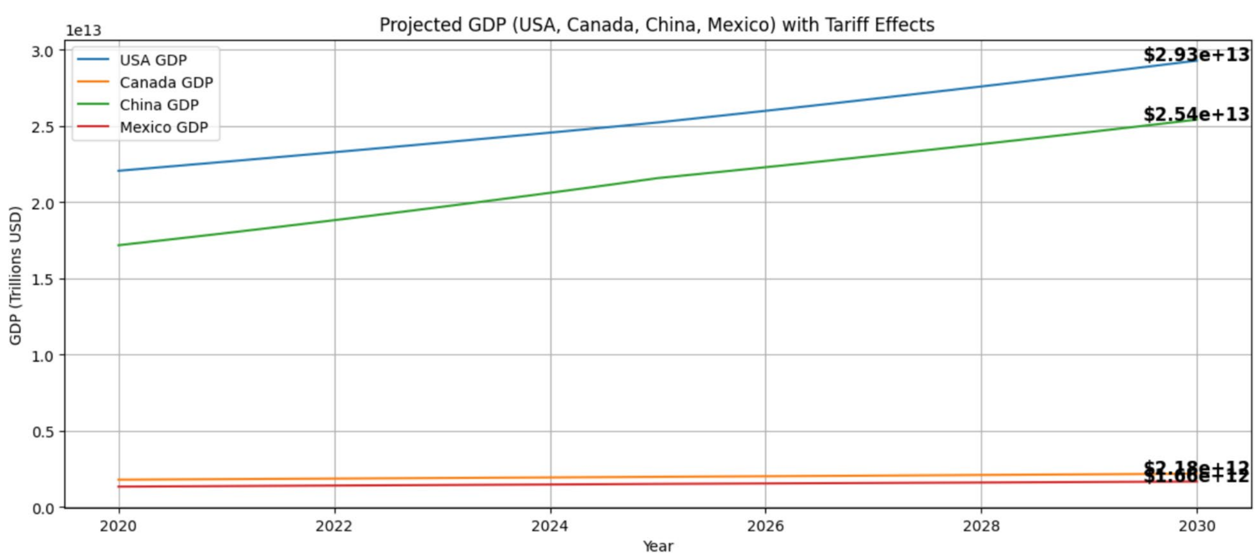
Projection and visualization

The results of the integration (GDP, trade balance, and inflation) are extracted and visualized over the projected time frame. A plot is generated to show how the GDP for each country evolves from 2020 to 2030, with annotations for specific years (e.g., 2025, 2030). A table is also included under the plot to present the GDP values for 2025, 2026, and 2030.

This method allows for the projection of key economic indicators, incorporating dynamic interactions between economic growth, trade policies (tariffs), and inflation. It is particularly useful for understanding the potential impacts of trade policy changes on economic performance over time.

The imposition of tariffs by the United States on China (10%), Canada (25%), and Mexico (25%) has significant economic consequences, as illustrated in the projected indicators for GDP, trade balance, and inflation. Figure 3 presents the projected GDP for the USA, Canada,

China, and Mexico based on a delayed differential equation model. The delayed effect of these tariffs is expected to materialize after a year, with 2030 as the final year of consideration. The results indicate that tariff imposition leads to initial economic stability followed by a gradual decline in GDP for affected nations, particularly Canada and Mexico, which face higher tariff rates. The impact on the USA is less pronounced initially but becomes evident over time due to shifts in trade dynamics. Figure 4 further highlights the delayed effects of tariffs on GDP and trade balance indicators for Canada, China, and Mexico concerning the USA. This delayed reaction is crucial in understanding the long-term economic disruptions caused by protectionist policies. In Figure 5, the inflationary effects of tariffs on the USA, Canada, China, and Mexico are examined. The results show that while Mexico and Canada experience the highest inflationary pressures due to reduced trade competitiveness and increased import costs, the USA is not immune to inflation. Higher costs of imported goods, combined with increased production costs in tariff-affected nations, contribute to inflationary pressures in the US economy. A detailed table further illustrates the delayed effects of tariffs on inflation figures across these economies, providing



Year	USA	Canada	China	Mexico
2025	$2.52e+13	$1.97e+12	$2.16e+13	$1.50e+12
2026	$2.60e+13	$2.01e+12	$2.23e+13	$1.54e+12
2030	$2.93e+13	$2.18e+12	$2.54e+13	$1.66e+12

Fig. 3 Projected GDP for USA, Canada, China, and Mexico after tariff imposition based on delayed differential equations. USA imposes tariffs of 10% on China, 25% on Canada, and 25% onMexico. The delayed effect appears after a year, with 2030 as the final year of projection

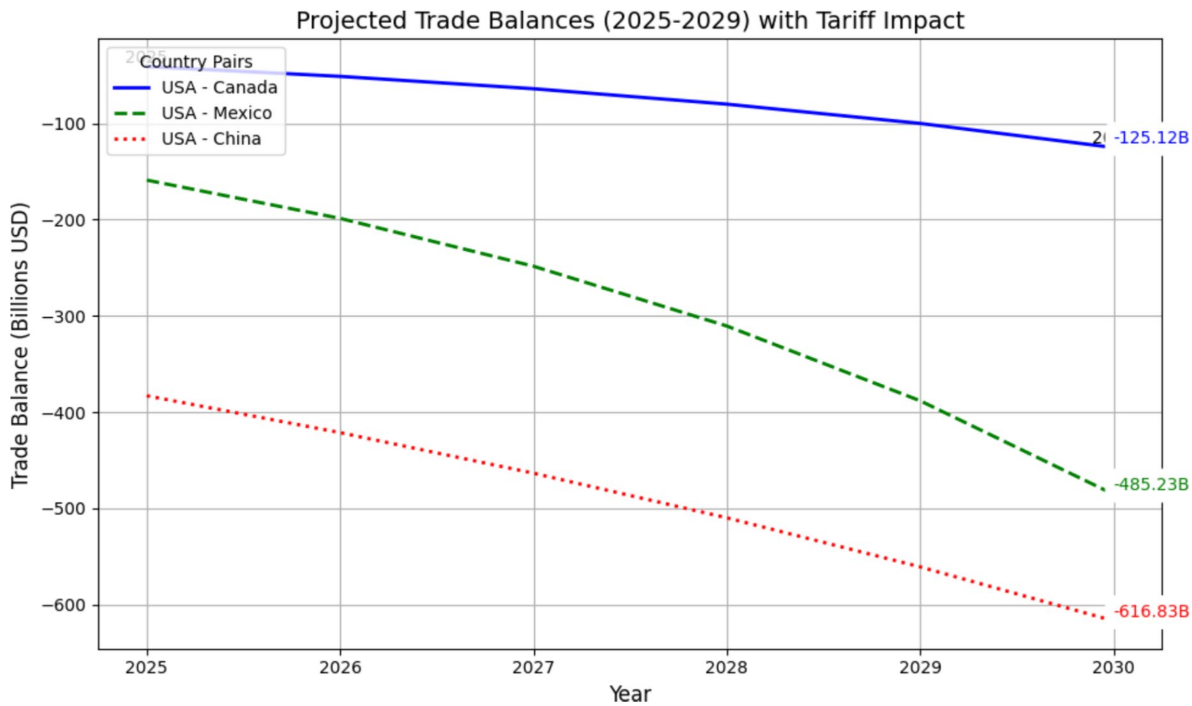


Fig. 4 Delayed effects of tariffs on GDP and trade balance indicators for Canada, China, and Mexico with respect to the USA. The impact becomes evident a year after the tariff imposition. The Trade balance in projected until year 2030 and delayed affect of US Tariffs are evident in Year 2026

numerical validation of the observed trends. Finally, Figure 6 explores the correlation between trade balance and GDP, demonstrating how shifts in trade balance due to tariffs impact national economic growth. The analysis confirms that tariffs disrupt trade equilibrium, leading to a decline in trade surplus for Canada and Mexico while simultaneously altering the USA's trade balance projections. The combined insights from these figures provide a comprehensive understanding of the macroeconomic implications of tariff imposition and highlight the necessity of evaluating long-term economic policies beyond their immediate protective benefits.

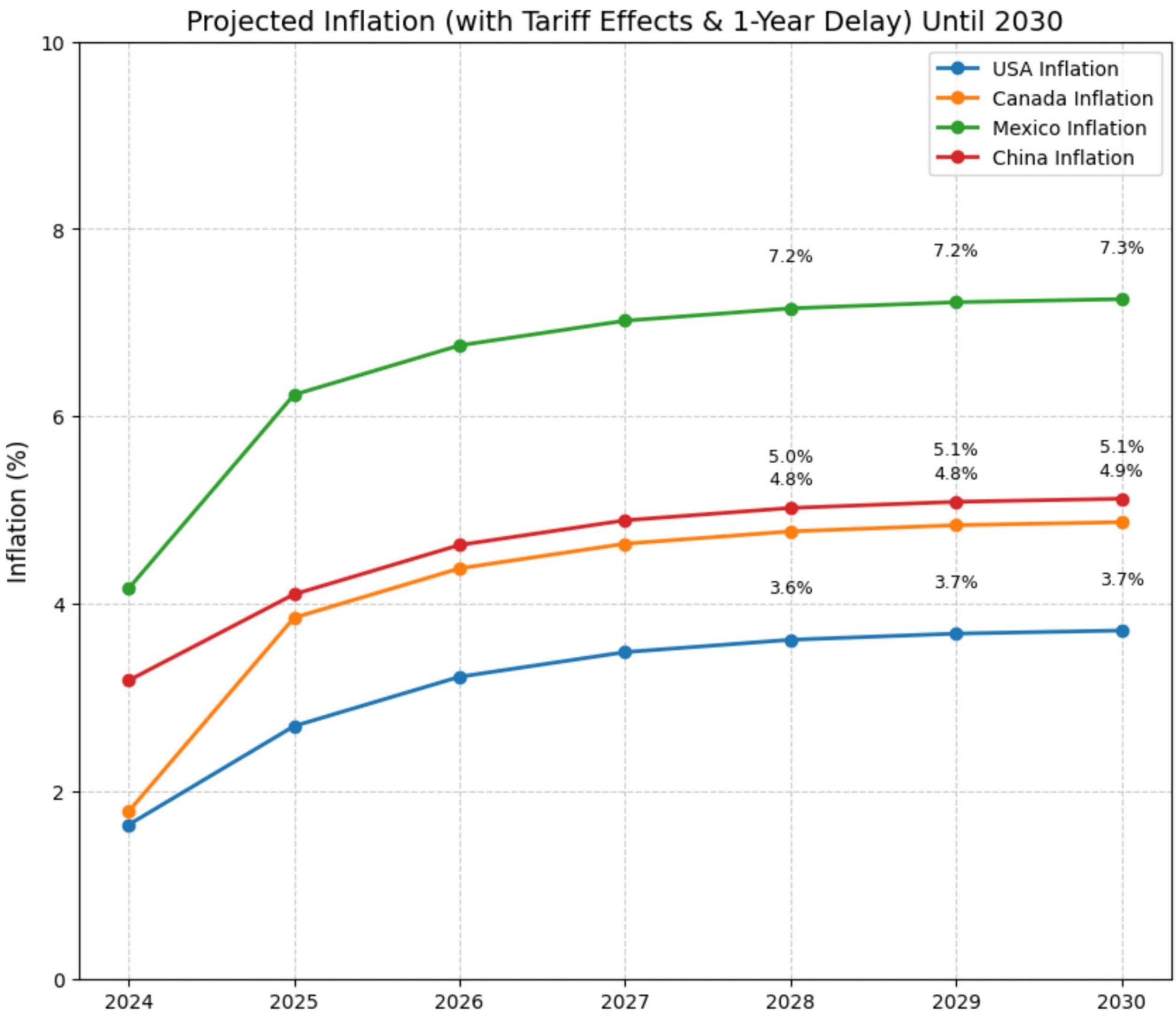
Analysis of results

1. *Projected GDP*: The projected GDP for the year 2030 for the United States is at $29.3 T, China is at $25.4 T, Canada is at $2.18 T, and Mexico is at $1.66 T. It is evident that due to the imposition of 25% tariffs, the projected GDP growth for both Mexico and Canada has slowed significantly. After the imposition of Tariffs and their delayed impact the GDP of USA stands at $26 T, Canada at $2.01 T, China at $22.3 T, Mexico at $1.54 T.
2. *Projected Trade Balance*: The projected trade balances for the year 2030 indicate a substantial trade deficit for the United States: −$125.12B with Canada, −$485.24B with Mexico, and −$616.83B with China. This highlights the persistent trade imbalances despite tariff impositions.
3. *Inflation*: The impact of tariffs on inflation is evident. One year after implementation, U.S. inflation increased from 1.6% to 2.7%, with a projected inflation rate of 3.7% in 2030. Canada's inflation surged from 1.6% to 3.7% within a year, reaching a projected 4.9% in 2030. Mexico experienced the most significant inflationary impact, rising from 4.2% to 6.2% within a year, with a 2030 projection of 7.3%. China's inflation increased from 3.2% to 4.1% after a year, with a projected 5.1% in 2030.

Analyzing the correlations

US-Canada Trade Balance (Blue):

1. The blue data points show a **negative correlation**. As the US GDP increases, the US- Canada trade balance tends to become more negative (larger deficit for the US).
2. This suggests that as the US economy grows, it imports more from Canada than it exports, leading to a widening trade deficit.
3. The data points are clustered fairly tightly, suggesting a relatively consistent relationship.



Year	USA	Canada	Mexico	China
2024	1.6%	1.8%	4.2%	3.2%
2025	2.7%	3.9%	6.2%	4.1%
2026	3.2%	4.4%	6.8%	4.6%
2027	3.5%	4.6%	7.0%	4.9%
2028	3.6%	4.8%	7.2%	5.0%
2029	3.7%	4.8%	7.2%	5.1%
2030	3.7%	4.9%	7.3%	5.1%

Fig. 5 Impact of tariffs on inflation in the USA, Canada, China, and Mexico. Although Mexico and Canada experience the highest impact, the USA also faces inflationary pressures due to higher costs of imported goods and production. A table illustrating the delayed effect of tariffs on inflation figures is included

China-US Trade Balance (Orange):

1. The orange data points show a **strong positive correlation**. As China's GDP increases, the China-US trade balance becomes increasingly positive (larger surplus for China, larger deficit for the US).
2. This indicates that as China's economy expands, its trade surplus with the US grows significantly.

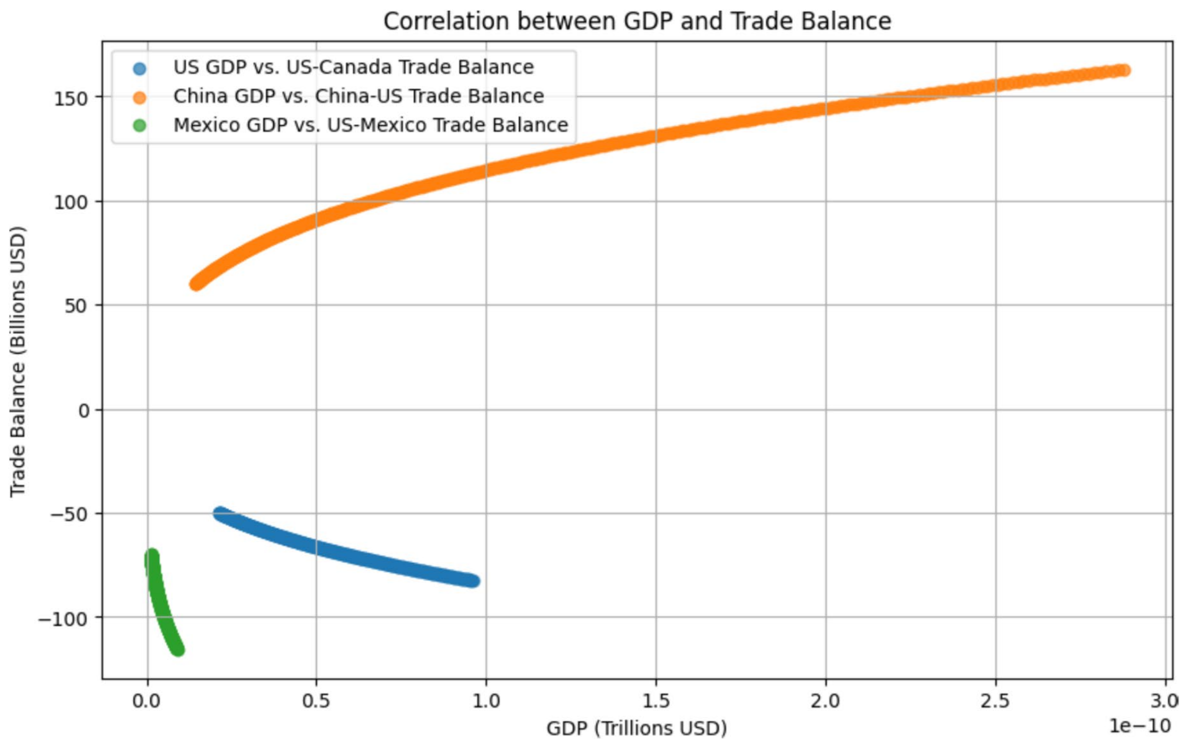


Fig. 6 Correlation between trade balance and GDP. The impact of tariffs is analyzed through trade balance projections in response to imposed tariffs on Canada, China, and Mexico

3. The data points form a clear upward curve, demonstrating a strong and consistent trend.

US-Mexico Trade Balance (Green):

1. The green data points show a **negative correlation**, similar to the US-Canada relationship. As Mexico's GDP increases, the US-Mexico trade balance tends to become slightly more negative (a larger deficit for the US). However, the range of both GDP and trade balance values is smaller compared to the other two relationships.
2. The data points are also clustered, indicating a fairly consistent, but less dramatic, relationship.
3. These findings indicate that while tariffs aim to protect domestic industries, they also contribute to inflationary pressures and trade imbalances, influencing long-term economic stability.

Conclusion and limitations of the research

Conclusion

In summary, the impact of tariffs on an economy is not immediate but unfolds over time due to the presence of feedback loops and time lags. These effects can be modeled using delayed differential equations (DDEs), which account for the delayed response of economic variables to changes in policy. This research has examined the delayed and dynamic effects of tariffs on key economic variables, including inflation, trade balances, and consumption. By utilizing mathematical models, particularly delayed differential equations, we have highlighted the critical role of time lags and feedback loops in understanding how tariffs impact the economy over time.

Tariffs do not produce immediate effects; instead, their influence is transmitted gradually through time, with delays in the responses of economic variables. For instance, while tariffsinitially cause price increases and reduced trade volumes, the broader economic consequences unfold over time, impacting consumption, inflation, and investment. These delayed responses are captured through feedback loops, where initial economic shifts (e.g., rising inflation) prompt further policy adjustments (e.g., interest rate hikes), which in turn affect other variables like exchange rates and investment flows.

Medium- and long-term structural adjustments also occur, such as changes in investment flows and supply chain diversification, as businesses adapt to the new trade environment. These shifts, though mitigating some impacts, can have far-reaching consequences on the global economy.

Overall, the study emphasizes the importance of time lags and feedback mechanisms in policy design. Policymakers must understand the delayed nature of tariff impacts to avoid unintended consequences. Future research could refine these models with empirical data to provide more specific insights into sectoral and regional variations in tariff effects. Future research should aim to address these gaps and develop more comprehensive models that capture the delayed effects of tariffs across various economic variables.

Limitations of the research

While the research provides robust theoretical research into the delayed and dynamic effects of tariffs on the economy, it also has certain limitations that should be acknowledged:

Data Limitations: The model used in this research relies on several assumptions about economic variables and feedback mechanisms. Empirical validation with real-world data is necessary to test the model's robustness and its ability to accurately predict the impact of tariffs across different countries, industries, and economic conditions.

Model Assumptions: The use of Delayed Differential Equations (DDEs) and the unit step function to model sudden tariff impositions introduces simplifications in the representation of real-world economic processes. In practice, tariffs can vary in magnitude, duration, and application, which may not be fully captured by these mathematical tools. Further refinement of the model is needed to account for these variations more accurately.

Exclusion of Other Factors: While the study focuses on the effects of tariffs, other external factors—such as global economic shocks, technological advancements, and changes in consumer behavior—can also influence economic variables. These factors were not incorporated into the model, and their omission may limit the generalizability of the findings.

Simplification of Economic Complexities: Economic systems are highly complex, with multiple interdependent variables. The models used in this research, while valuable for capturing broad trends, may oversimplify certain aspects of economic behavior, such as the multifaceted impact of tariffs on different sectors of the economy.

Author contributions

Author Contributions Statement- Hemendra Pal: Conceptualization, Methodology, Software, Formal Analysis, Investigation, Data Curation, Writing—Original Draft, Writing—Review & Editing, Supervision. Hemendra Pal contributed to the overall design and structure of the study, developed the economic model, and conducted the analysis using delayed differential equations (DDEs). He was responsible for drafting the initial manuscript, as well as revising and refining the manuscript based on feedback. Additionally, he created the draft and supervised the research process, ensuring its alignment with the research objectives. Funding- "The author declares that no funding was received for the research". Future Business Journal is sponsored by Specialized Presidential Council for Education and Scientific Research, the publication costs of the article are covered through the sponsor's agreement with Springer Nature. Acknowledgement—Hemendra Pal, "ALTREICH THINKTANK", D/G004 Moti Residency, Raj Nagar Extension, Near Morta, Ghaziabad, 201003. Uttar Pradesh, INDIA

Funding

The author declares that no funding was received for the research.

Availability of data and materials

Data for research papers is provided within the manuscript—Online Links in the references. Books presented in the reference are readily available on different platforms. The Data used for the research has been downloaded from World Bank Website.

Declarations

Ethics approval and consent to participate

This study does not involve human participants, human data, or human tissue. Therefore, ethical approval and consent to participate are not applicable to this manuscript. This study does not involve direct participation of individuals or the collection of primary data from participants. Statement: Not applicable.

Consent for publication

This manuscript does not include the individual data, images, or videos of any person. Therefore, consent for publication is not applicable. Statement: Not applicable.

Competing interests

The authors declare no competing interests.

Received: 4 January 2025 Accepted: 25 March 2025
Published online: 18 April 2025

References

1. Baldwin RE (2019) The Great Convergence: Information Technology and the New Globalization. Harvard University Press.
2. Krugman P, Obstfeld M, Melitz M (2009) International Economics: Theory and Policy, 8th edn. Pearson Education, Boston
3. Novales A, Ferna´ndez E, Ruiz J (2022) Economic Growth Theory and Numerical Solution Methods. Springer.
4. Sayama H (2015) Introduction to the modeling and analysis of complex systems. Open SUNY Textbooks. Retrieved from https://textbooks.opensuny.org
5. Ghosh B. (Ed.) (2024) Special Issue: Models and Applications of Delay Differential Equations. Retrieved from https://www.researchgate.net/publication/375696720
6. Phelan C. (2020). U.S.-China Trade War: Economic Impact and Global Responses. Jour- nal of Economic Policy, 24(1), 35–50.
7. International Monetary Fund. (2023). Inflation, Consumer Prices (Annual %). Retrieved from https://www.imf.org
8. McKinney, W. (2018). Python for Data Analysis: Data Wrangling with Pandas, NumPy, and IPython (2nd ed.). O'Reilly Media.
9. Anderson JE, van Wincoop E (2004) Trade Costs. National Bureau of Economic Research Working Paper No. 10480. https://www.nber.org/papers/w10480
10. Amiti M, Redding SJ, Weinstein DE (2019) The Impact of the 2018 Trade War on U.S. Prices and Welfare. National Bureau of Economic Research Working Paper No. 25672. https://www.nber.org/papers/w25672
11. Melitz MJ (2003) The Impact of Trade on Intra-Industry Real locations and Aggregate Industry Productivity. Econometrica 71(6):1695–1725
12. Ghironi F, Melitz MJ (2005) International Trade and Macroe conomic Dynamics with Heterogeneous Firms. Q J Econ 120(3):865–915
13. Chor D, Manova KB (2009) Off the Cliff and Back? Credit Condi- tions and International Trade During the Global Financial Crisis. Available at SSRN:

https://ssrn.com/abstract=1502911 or https://doi.org/10.2139/ssrn.1502911
14. Global Trade Analysis Project (GTAP) (2023). Dynamic Model. Retrieved from GTAP website.
15. Grossman, G. M., Helpman, E. (2021). When Tariffs Disrupt Global Supply Chains. (October 2021). https://scholar.harvard.edu/
16. Blanchard O (2017) Macroeconomics, 7th edn. Pearson Education, Boston
17. Barattieri A, Cacciatore M, Ghironi F (2021) Protectionism and the business cycle. J of Int Econ Elsevier. https://doi.org/10.1016/j.jinteco.2020.103417
18. Handley K, Limao N (2017) Trade and Investment under Policy Uncertainty: The- ory and Firm Evidence. Am Econo Rev 107(9):2957–2989
19. SciML, Delay differential equations example. Retrieved March 23, 2025, from https://docs.sciml.ai/DiffEqDocs/stable/tutorials/ddeexample/
20. Raffoul YN (2022) Advanced Differential Equations, Elsevier/Academic Press, April 19,2022. https://www.elsevier.com/books/advanced-differential-equations/raffoul/978–0–323–99280
21. Barro RJ (1997) Macroeconomics: A Modern Approach, 3rd edn. McGraw-Hill, New York
22. Woodford M (2003) Interest and Prices: Foundations of a Theory of Monetary Policy. Princeton: Princeton University Press.
23. Baldwin R (2006) The Great Trade Collapse: What Caused It and What Will Come Next? Centre for Economic Policy Research, Policy Insight No. 26.
24. Eaton J, Kortum S (2002) Technology, Geography, and Trade. Econometrica 70(5):1741–1779
25. World Bank (2023) WorldDevelopment Indicators. Retrieved from https://data.worldbank.org
26. Acemoglu D (2009) Introduction to Modern Economic Growth. Princeton University Press

Publisher's Note