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## Article

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# Modeling Dynamic Correlation and Volatility of the Visegrad Group Fuel Markets

Monika Krawiec<sup>1</sup> , Bolesław Borkowski<sup>2</sup> , and Yochanan Shachmurove<sup>3</sup> 

## ABSTRACT

The paper focuses on investigating the correlation and volatility of fuel markets in four countries of the Visegrad region, namely Hungary, the Czech Republic, Poland, and Slovakia. The primary objective of the paper is to explore regional fuel markets and retail prices in these countries by employing VAR models and Johansen procedures to analyze the interrelationships between Visegrad fuel markets. Additionally, the paper uses multivariate dynamic conditional GARCH (DCC GARCH-M) models to examine the volatility and covariance of fuel prices in these nations. The results of the study indicate that there are no long-term connections between Visegrad gasoline prices. The performance of the domestic price is independent of other markets. The research also shows long-term relations of diesel prices only among some countries. Overall, the size of these relations is small and mostly statistically insignificant. These findings provide valuable insights into the fuel markets of the Visegrad countries and can be useful in formulating policies related to energy and fuel price regulation. Overall, the study contributes to the literature on fuel markets in the Visegrad region and provides policymakers and stakeholders with essential information necessary for making informed decisions.

## KEY WORDS:

Visegrad Group, fuel prices, cointegration, Johansen test, multivariate dynamic conditional correlation GARCH (DCC GARCH-M) model.

## JEL Classification:

C10, C58, Q02, Q40.

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## 1. Introduction

The Visegrad Group was formed in February 1991 in Visegrad, Hungary, as a political alliance of three Central East European (CEE) leaders: Lech Wałęsa representing Poland, Václav Havel representing Czechoslovakia, and József Antall representing Hungary. The aim was to coordinate the process of the post-communist transformation, often referred to as “a joint return to Europe.” After the January 1993 “velvet divorce” between Czechs and Slovaks, the Visegrad Triangle (V3) became the Visegrad V4 Group – now consisting of Hungary, the Czech Republic, Poland, and Slovakia (Pakulski,

2016). The creation of the Visegrad Group served not only political but also economic purposes. One of them was the spatial integration of V4 markets allowing the beneficial and free trade between the Visegrad countries (Roehner, 1995; (Xie and Yuan, 2023; Sunley, 2001; Fujita et al., 1999). At first, integrated markets were defined as locations that had high price correlations. Market integration was also interpreted as spatial locations connected by trade or as locations that had one-for-one price changes. More recently, market integration is associated with price efficiency, suggesting that integrated locations would lead to cointegrated prices (McNew, 1996). The literature presents various methods for study-

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ing the spatial integration of commodity markets (see Hamulczuk, 2018).

In 2004 the Visegrad countries joined the European Union. Since then they have undergone a colossal transformation making them the sixth economic force in Europe. In the period 1991-2019, their GDP increased by over 150% and their share in the global economy grew to 1.4%. In 2019, GDP per capita in the V4 was nearly 72% of that in the European Union 15 (EU 15) and as much as 86% of that in selected southern European countries. This region is also the third-largest consumer market in the EU, behind Germany and France, with 64 million people, which is 14.3% of the EU 27's population.

The Visegrad countries are an important manufacturing center for the European Union (EU) market. Since the 1990s, V4 countries have been attracting foreign investments more rapidly than the EU as a whole. The cumulative value of foreign direct investments increased 118-fold from USD 5 billion in 1991 to USD 565 billion in 2019. Apart from the socio-economic development, defense and energy security have been highly important for the Visegrad Group. However, all four countries are dependent on imports of energy resources (Ambroziak et al., 2020).

Since the main goal of the V4 alliance, cooperation with the European Union and NATO by becoming members is achieved, the group is working together to support, promote, and develop economic and cultural cooperation, scientific exchange, research in the field of education, youth exchange, cross-border cooperation, tourism, energy and military cooperation (Grodzicki, 2020). The cooperation between the Visegrad Group (V4) countries heavily influences their economies. Thus, there exists a plethora of papers examining different issues, such as business performance and interrelationships between V4 capital markets, energy transition, or innovative development of industrial and agricultural sectors.

This paper investigates the dynamic correlation and volatility of fuel markets in the Visegrad countries. The paper contributes to the existing literature in several ways. First, unlike the majority of studies that usually investigate volatility and

interrelationships between global oil markets, this research focuses on regional (V4) markets and fuel retail prices. Next, to analyze the interrelationships between Visegrad fuel markets, we estimate Vector Autoregressive (VAR) models and perform the Johansen procedure for multiple equation models.

Moreover, in order to examine the dynamic relationships between the volatility and covariance of fuel prices in the V4 countries, we estimate multivariate dynamic conditional correlation GARCH (DCC GARCH-M) models. The results revealed that there are no long-term relationships between gasoline prices in the Visegrad Group, i.e., the performance of the domestic price was independent of any other. This is because a small number of the movements in gasoline prices in each country could be explained by the movements in prices in other countries. Initially, the Czech, Hungarian, Polish, and Slovakian gasoline markets seemed to be exogenous.

However, the study exposes the long-term relationships that exist between diesel prices. In the long term, the increase in diesel prices in Poland and Slovakia resulted, on average, in a slight decrease in diesel prices in the Czech Republic. What is more, the statistically significant relations between diesel prices in Hungary and diesel prices in Poland and Slovakia exhibit different directions of long-term dependencies, i.e., negative for Poland and positive for Slovakia. Estimation of multivariate dynamic conditional correlation GARCH models (DCC GARCH-M) allows the study of dynamic relationships between the volatilities and covariances of gasoline prices in the V4 countries.

Generally, the examination of volatility in multidimensional settings confirms the previous conclusions with regard to the greater importance of differentiating fuel prices in internal markets than the impact of volatility on other markets. Thus, this paper aims at investigating the dynamic correlation and volatility in the V4 fuel markets through the analysis of co-integration and offers an estimation of multivariate conditional correlation GARCH models. The empirical research is based on average weekly prices of unleaded gasoline (Pb 95) and diesel in the Czech Republic, Hungary, Poland, and Slovakia, from January 2016 through December 2020.

The remainder of the paper is organized as follows. Section 2 reviews the literature. Section 3 describes the methodology and data. Section 4 presents the results. Section 5 concludes.

## 2. Literature Review

As the cooperation among the Visegrad Group countries continues to heavily influence their economies, a plethora of papers examining this matter exists. For example, Bolotov (2015) analyzes the main changes in business performance, (defined by five indicators: business density, value-added per business entity, investment in fixed capital per business density, inward foreign direct investment stock per business entity, and exports of goods and services per business entity) of the Visegrad Group from 2004 to 2014, using Pearson correlations, Chow and Granger causality tests. He finds that business performance, hence the business environment, in the V4 Group, has diverged since the EU accession (except for internalization indicators). His findings indicate the necessity for managers to adjust to the specific characteristics of each particular country.

Meyer (2021) aims at determining the relationships between the country risk index, economic performance, and good governance in the Visegrad countries from 1996 to 2019 using a quantitative research methodology with panel models. His results indicate the existence of both long- and short-run relationships. According to different estimation models, both Gross Domestic Product (GDP) and good governance significantly impact the country's risk index. Moreover, the Granger causality results indicate that both GDP and good governance caused changes in the country's risk indexes and that good governance causes an increase in economic performance. In conclusion, the study shows clear evidence that a lower country risk index is important for both attracting investment and sustained economic growth, where good governance has a critical role in this process.

Dobešova and Hampel (2014) analyze changes in monetary policy impact on inflation during the financial crisis in the Visegrad Group countries. They test the causality between inflation and base

interest rates. The analysis compares models for "before the crisis" and "during the crisis." Granger causality is tested for both sub-models and the entire dataset for the period from January 2002 until August 2012. They find that the causation of monetary policy instruments on the growth of price level has changed during the financial crisis, i.e., a change of structure is identified.

Su et al. (2018) identify macroeconomic factors that affect foreign direct investment (FDI) in the Visegrad countries after the European Union enlargement. They employ time series and panel datasets. The empirical results, based on data for the period from 2005 to 2016, show that perceived corruption was the common factor affecting FDI inflows in V4 countries. The panel approach, based on a panel ARDL model, identifies a significant relationship between FDI, a corruption index, and a labor force with advanced education. However, this causality is only detected in the long run. According to Granger causality, using the panel dataset, the attraction of FDI inflows succeeds in generating changes in the total tax rate. However, the issues related to corruption are not reduced, at an acceptable level of statistical significance, for foreign investors in Poland, Slovakia, and the Czech Republic.

Šimáková (2016) studies the long-term effects of the level of exchange rates on trade balances for the Visegrad countries by applying the Johansen cointegration analysis. This empirical research is performed for the period 1999 Q1 – 2014 Q3. It reveals that bilateral and a majority of partial trade balances are cointegrated with bilateral exchange rates in the long term. Thus, the bulk of total and partial bilateral trade balances are characterized by a common long-term development with domestic and foreign GDP and bilateral exchange rates.

Meyer and Meyer (2019) examine the impact of entrepreneurial activity on employment and growth in the Visegrad countries from 2006 to 2017. The purpose of their study is to determine the relationships between established business ownership (EBO), new business density (NBD), employment (E), and economic growth (GDP) rates using an econometric analysis method. A pooled panel analysis is used to test the long and

short-run relationships among the variables. The first pooled panel analysis tested the relationship between GDP, NBD, and EBO rates, while the second pooled panel analysis tested the relationship between E, NBD, and EBO rates. Results indicate a long-run relationship between the variables by using the Fisher-Johansen cointegration analysis. Further results of the analysis indicate that both EBO and NBD are significant predictors at 5% and 10% significance levels, respectively, of economic growth (GDP), while for employment (E) as the dependent variable, EBO is a significant predictor at the 5% level and NBD is not a significant predictor. In conclusion, the study proves that links between the mentioned variables do exist and that entrepreneurial activity should be stimulated and supported as it has a significant impact on economic growth and employment to various degrees of impact.

Salamaga (2015) focuses on testing the effectiveness of selected macroeconomic variables in stimulating foreign trade in the Visegrad Group countries from 2002 through 2013. The analysis of exogeneity is based on VEC and VAR models, which enables the explanation of dynamic relations among variables in foreign trade. The obtained results for strong and weak exogeneity make it possible to formulate methodological conclusions as well as conclusions concerning the effectiveness of various macroeconomic instruments for the development of foreign trade for individual countries.

Łącka et al. (2020) search for long-term correlations between the level of economic growth and the level of export and import using cointegration analysis for the V4 countries. The research covers the period from 1996 until 2018. They use the Engle-Granger cointegration test. The results confirm that only in the case of Poland and Hungary there are two-way long-term interdependencies. For Poland, it was a pair of variables (GNP and export value), and for Hungary (GNP and import value). No long-term correlation between economic growth and the value of foreign trade is confirmed for Slovakia and the Czech Republic.

Burdiuzha (2021) analyzes innovative

development trends of the agricultural sector in the Visegrad Group countries from 1995 until 2019. She investigates the impact of innovation on value added to GDP by sector of the economy and patent activity. She estimates OLS models and performs Granger causality tests. First, the composition of R&D expenses in each Visegrad country is examined. Then, its relationship to agricultural GDP and the number of patents granted is tested utilizing OLS models. Forecasting the relationships among examined variables is carried out by running Granger causality tests. Results revealed a constant growth in agricultural innovation activity investment from 1995 until 2019. Innovation activity has a positive impact on the value-added to GDP by agriculture and on the number of patents granted.

Krkošková (2021) confirms a long-run relationship between energy consumption and real GDP for V4 countries from 2005 to 2019. Her analysis is based on the unit root, co-integration, and causality tests. It finds that in the long run, the energy consumption Granger caused GDP in Slovakia, Hungary, and the Czech Republic. It means that energy consumption could have caused economic growth in these countries. The only country with no significant relationship between energy consumption and GDP was Poland.

Fałdziński et al. (2016) investigated interdependencies among capital markets of Germany, Poland, the Czech Republic, and Hungary. They assume a similar course and changes in the interdependences, applying a DCC-GARCH model that allowed for estimating conditional correlations indicating the strength of the interrelationships among the markets. Then, the cointegration analysis of the conditional correlations is performed. The results confirm that in the period under consideration (July 1, 1997 – September 30, 2015) the capital markets of Germany, Poland, the Czech Republic, and Hungary are characterized by a similar long-term path. The research also shows that, in the long run, changes in the direction and strength of the interrelationships among the studied markets are determined by the German capital market.

Pražák and Stavárek (2017) examine the effect

of specific macroeconomic factors on stock prices for selected financial sector companies listed on Budapest, Prague, Bratislava, and Warsaw Stock Exchanges. They investigate the nature of causal relationships between macroeconomic factors and stock prices, long-term causality (using the Johansen cointegration test), and short-run dynamics among the variables, using a vector error correction model (VECM) model. Their research is based on quarterly data from 2005 until 2014. They confirm that macroeconomic fundamentals have a negative impact on stock prices. However, they hardly find examples of macroeconomic variables that explained changes in stock prices within the VECM framework.

Finally, Živkov et al. (2020) study the strength of interdependence between the Brent oil market and the stock markets of oil-importing Visegrad group countries together with oil-exporting Russia for different time horizons. They use a bivariate DCC-EGARCH model, wavelet correlations, and phase differences. The results of the DCC model show that all dynamic correlations between Brent oil and the selected stock indices are low for the daily frequency level. The magnitude of mutual correlations does not exceed 20% for Visegrad countries, while for Russia it exceeds 30%. Wavelet correlations in the short-term confirm the DCC results, whereby these relatively weak connections are found for up to 32 days. For mid-term and long-term, wavelet correlations strengthen and increase above 50% in mid-term and even beyond 80% in the long-term for a majority of the indices. Slovakian SAX index has a stronger wavelet correlation in 32 days than in 64 days reaching 23%. This means that SAX could be coupled with Brent oil for diversification purposes in both short-term and mid-term portfolios. It could also serve well for hedging purposes.

The purpose of this paper is to look into the dynamic correlation and volatility of V4 fuel markets. In several ways, the paper adds to the existing literature. To begin, unlike most studies, this one focuses on regional (V4) markets and fuel retail prices rather than global oil market volatility and interrelationships. Furthermore, the paper examines the interdependence of

Visegrad fuel markets by estimating VAR models and running Johansen procedures on multiple equation models. Finally, we estimate multivariate dynamic conditional correlation GARCH (DCC GARCH-M) models to investigate the dynamic relationships between the volatility and covariance of fuel prices in V4 countries.

### 3. Data and Methodology

#### 3.1. Data

The data cover weekly prices (260 observations) of basic fuels: unleaded gasoline (Pb 95) and diesel in the Czech Republic, Hungary, Poland, and Slovakia from January 2016 through December 2020. Prices are expressed in domestic currencies per 1 liter. The data are provided by e-petrol.pl published every Wednesday at 3 pm on the website ([www.e-petrol.pl](http://www.e-petrol.pl)). The data are proprietary and purchased from the above website. The quantitative analysis is based on logarithmic transformations of prices (log prices). The program used is EViews 11, serial number: 10Z00322-4E3F7A50-DE744461.

#### 3.2. Methodology

In order to analyze the correlation between fuel prices in the countries of the Visegrad Group, we conduct a study of their correlation over time (dynamic conditional correlation). Modeling and forecasting volatility and correlation in dynamic terms is now the focus of financial econometrics, including volatility and correlation estimates, which are required for portfolio optimization, risk management, and hedging strategies. Bollerslev et al. (1988) estimate a multivariate GARCH model for returns to US Treasury Bills, gilts, and stocks. GARCH-M models can be categorized into three or four groups, depending on the specification of the equation for the variance (Bauwens et al., 2006; Orskaug, 2009).

The main difference between univariate and multivariate GARCH models is that the latter also includes the changes over time to covariances between all instruments (assets). The literature lists several different approaches to multivariate GARCH, including the VECH, the diagonal VECH, and the BEKK models (the detailed discussion can be found in Brooks (2012)

or Kroner and Ng (1998)). In this paper, we use the multivariate GARCH model DCC GARCH-M: Dynamic Conditional Correlation (Engle, 2002) of the following form (the diagonal VECH):

$$y_t = \mu_t + \varepsilon_t, \varepsilon_t \sim N(0, \Sigma_t)$$

$$\Sigma_t = D_t P_t D_t$$

$$D_t = \text{diag}(\sqrt{h_{1t}}, \sqrt{h_{2t}}, \dots, \sqrt{h_{Nt}})$$

$P_t$  – conditional correlation

$$h_{it} = \gamma_i + \alpha_i \varepsilon_{i,t-1}^2 + \beta_i h_{it-1} \quad \text{for } i = 1, 2, \dots, N$$

With an extended DCC-GARCH

$$h_{it} = \gamma_i + \sum_{j=1}^N \alpha_{ij} \varepsilon_{j,t-1}^2 + \sum_{j=1}^N \beta_{ij} h_{jt-1} \quad \text{for } i = 1, 2, \dots, N$$

Assuming conditional normality, the parameters of multivariate GARCH models are estimated by maximizing the log-likelihood function. Note that if the correlation matrix  $P_t$  is a constant matrix, then this methodology is called Constant Conditional Correlation (CCC-) GARCH, which is the basic form of the DCC-GARCH model (Bollerslev, 1990).

The DCC-GARCH model nowadays becomes a popular way to capture the time-varying dynamics and volatilities in economics research. Acatrinei et al. (2013) explore the risk in the Romanian capital market using the DCC-GARCH model. Ghosh et al. (2021) study the dynamic correlations and co-movement between the global financial and energy market with the DCC-GARCH model in a non-linear framework. Gargallo et al. (2021) observe the co-movement of EU ETS with the energy market and its transmission mechanism with the VAR-DCC-GARCH approach. Chen et al. (2020) use a similar VAR-DCC-GARCH to investigate the dynamic correlations among new energy, rare earth market in China, and international crude oil.

Recent literature also raises several modifications and improvements for the DCC-GARCH model. For example, Cappiello et al. (2003) introduce asymmetry in the DCC-GARCH model to incorporate the effect of asymmetric information. Del Brio et al. (2011) create a semi-nonparametric version of the DCC-GARCH model which produces a better in-sample fit than the Gaussian DCC model. Fioruci et

al. (2014) develop a Bayesian approach to the DCC-GARCH model with various skewed distributions. Singhal and Ghosh (2016) De-GARCH the residual of an unrestricted VAR system in three different ways and then apply DCC-GARCH to testify the time-varying co-movements. Ghosh et al. (2021) use multi-resolution analysis based on Wavelet decomposition prior to DCC-GARCH to capture long-run temporal dynamics.

The paper also analyzes the relationships between fuel prices in the Visegrad Group countries based on unrestricted VAR models. In the first stage of the analysis, we focus on separately identifying appropriate VAR models for gasoline and diesel logarithmic returns (log-returns). After defining the appropriate VAR model, we analyze the occurrences of long-term relationships (cointegration) between fuel prices for the analyzed countries. We utilize Johansen tests for this purpose.

The concept of cointegration is introduced by Engle and Granger (Granger, 1981; Engle and Granger, 1987). It specifies that if there is a long-term relationship between two (or more) non-stationary variables, then the deviations from the long-term path are stationary. This means that a long-term, time-independent, equilibrium path between economic processes can be determined, where the values, located elsewhere, are short-term deviations from the equilibrium that depends on time. Thus, cointegrated processes are characterized by a common long-term growth path where the difference between them is almost constant. On the other hand, non-cointegrated processes diverge in the long term and the difference between them changes over time.

A method that allows for the evaluation of cointegration of the analyzed series is the Johansen test (1988) which is widely used in energy market analysis. For instance, Siliverstovs et al. (2005) use the Johansen test to study the level of cointegration of natural gas prices in Europe, North America, and Japan. Asche et al. (2006) investigate whether the gas price in the UK is decoupling from other energy prices such as oil and electricity with the Johansen test. Lyulyov et al. (2021) summarize the effect of government policies on the energy efficiency gap by cointegration analysis using the Johansen test.

Johansen test is based on VECM (vector error cor-

rection model) that for the vector  $\mathbf{X}_t$  containing  $p$  analyzed time series given by:

$$\Delta \mathbf{X}_t = \boldsymbol{\alpha}_0 + \sum_{i=1}^{k-1} \boldsymbol{\Gamma}_i \Delta \mathbf{X}_{t-i} + \boldsymbol{\Pi} \mathbf{X}_{t-1} + \boldsymbol{\varepsilon}_t$$

The interest is to focus on the order of the matrix  $\boldsymbol{\Pi}$ . If it equals  $p$ , the vector  $\mathbf{X}_t$  contains stationary series. However, if it equals 0, the matrix  $\boldsymbol{\Pi}$  does not contain any information on long-term relationships between the variables. Cointegration takes place if the order of the matrix  $\boldsymbol{\Pi}$  equals  $r < p$ . Test statistics are given by the characteristics of the matrix  $\boldsymbol{\Pi}$  estimator (Johansen, 1988):

$$\hat{\lambda}_{trace} = -T \sum_{i=r+1}^n \ln(1 - \hat{\lambda}_i)$$

or

$$\hat{\lambda}_{max} = -T \ln(1 - \hat{\lambda}_{r+1}),$$

where

$\hat{\lambda}_i$  – estimated eigenvalues ( ),

$T$  – sample size.

## 4. Results

### 4.1. Preliminary Statistical Analysis

The basic properties of the studied time series (logarithmic prices of Pb 95 gasoline and diesel) are similar to the distribution of financial time series (stock prices, stock index values, interest rates, exchange rates, commodity prices, etc.). All-time series (see Table 1) are characterized by distributions that are other than normal (with a negative asymmetry of distribution and a negative kurtosis). The data show that there are fat tails and, at the same time, higher peaks of the density functions, as compared with the normal distribution. The probability of observations is far from mean values significantly higher than for the normal distribution (see Table 1).

We also observed volatility clustering. In this way, variances are grouped. [Since the variances of random components for different observations are related to each other, and the squares of the model residuals for neighboring observations are probably correlated with each other, i.e., the covariance of random components is different from zero.] Hence,

**Table 1**  
Summary Statistics, Normality, and Stationarity Tests for Pb95 Gasoline and Diesel Weekly Log-prices

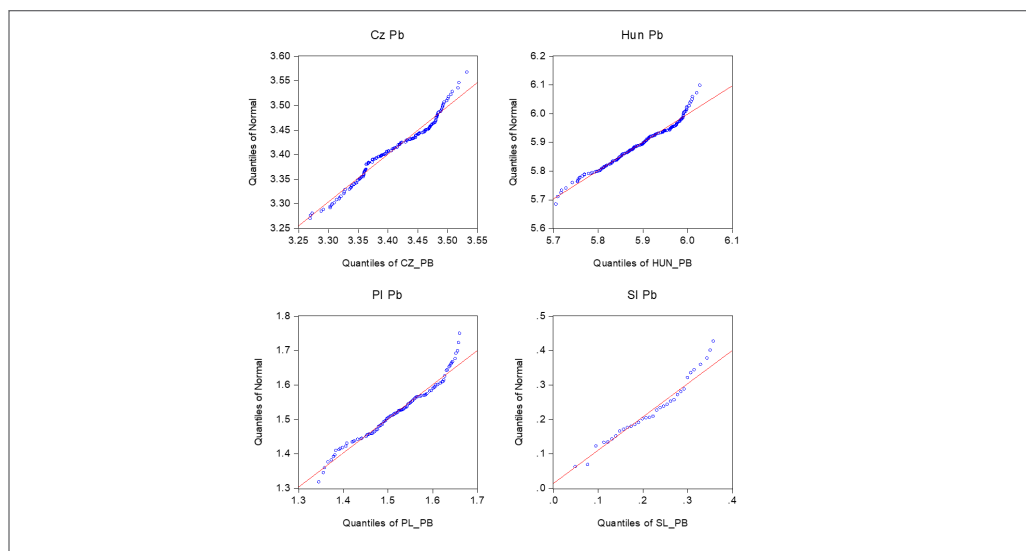
Measure	Variable							
	Cz Pb	Hun Pb	Pl Pb	Sl Pb	Cz D	Hun D	Pl D	Sl D
Mean	3.3991	5.8915	1.5343	0.2168	3.3704	5.9015	1.5187	0.1262
Median	3.3908	5.8974	1.5390	0.2311	3.3676	5.9107	1.5118	0.1398
Variance	0.0034	0.0051	0.0056	0.0053	0.0055	0.0061	0.0086	0.0083
Std. dev.	0.0583	0.0716	0.0747	0.0728	0.0740	0.0779	0.0930	0.0910
Coeff. V.	1.7151	1.2161	4.8667	33.6080	2.1967	1.3214	6.1236	72.1310
Asymmetry	0.0967	-0.3105	-0.3632	-0.3438	-0.0824	-0.5780	-0.2192	-0.1729
Kurtosis	-0.7658	-0.4713	-0.5375	-0.8248	-0.8982	-0.0388	-0.9367	-1.3433
JB	6.895 (0.032)	6.681 (0.035)	8.934 (0.011)	12.565 (0.002)	9.144 (0.010)	14.352 (0.001)	11.667 (0.003)	20.751 (0.000)
KPSS (levels)	1.221 (<0.01)	1.473 (<0.01)	0.916 (<0.01)	0.654 (0.022)	1.136 (<0.01)	1.941 (<0.01)	1.532 (<0.01)	1.168 (<0.01)
KPSS (1st diff.)	0.054 (>0.10)	0.055 (>0.01)	0.131 (>0.01)	0.093 (>0.01)	0.062 (>0.01)	0.097 (>0.01)	0.016 (>0.01)	0.303 (>0.01)

Source: own calculation and elaboration using EViews 11 Note: (·) – p-values



**Figure 1**

*Distribution of Pb95 Gasoline Logarithmic Weekly Prices in the Visegrad Group.*



Source: own calculation and elaboration using EViews 11

the tested time series is not stationary (see Table 1 - Stationarity test KPSS). These features limit the use of commonly used data analysis methods based on OLS and indicate the use of ARMA/VAR class models for the prediction of expected values and ARCH/GARCH class models to predict risk expressed by variance (differentiation) instead.

The research also shows a high correlation between gasoline and diesel prices (log prices) in the Visegrad Group countries (see Table 2) and a much weaker correlation between gasoline prices after eliminating the influence of the correlation between gasoline prices and diesel prices (see Table 3).

Generally, we observe strongly correlated gasoline prices with diesel prices within a given country. Furthermore, Polish gasoline prices are strongly and statistically significantly correlated with both gasoline and diesel prices in other countries. After eliminating the impact of diesel prices, the correlation between gasoline prices is not high, although still statistically significant. The strongest "net" correlation is the correlation between gasoline prices in Poland and gasoline prices in Hungary and

Slovakia. This is the result of close cooperation between these countries in the production and sale of gasoline (Polish oil-processing company Orlen operates in Hungary and Slovakia).

An important problem in the construction of VAR models is the determination of the appropriate number of delays for the variables included in the VAR system. Two methods are used in the literature to determine the optimal lag length: cross-equations and information criteria (see Brooks, 2012). To determine the equal length of the lags for all equations, we use the F test separately for the set of lags in each equation and the block F-test for the entire VAR system, as well as an information criterion for individual equations.

The analysis shows that the best models fulfilling the statistical criteria and the information criteria of Akaike, Schwartz-Bayesian, and Hannan-Quinn turn out to be VAR (3) models with three lags. Moreover, the likelihood ratio test for log-returns gasoline, estimated for the 4-lag model, was:  $F = \text{Chi-square}(16) = 20.3525 [0.2048]$ . For further analysis of the empirical data, we adopt VAR (3)

**Table 2***Matrix of Correlation Coefficients Between Logarithmic Fuel Prices in the Visegrad Group Countries*

Measure	Variable							
	Cz Pb	Hun Pb	Pl Pb	Sl Pb	Cz D	Hun D	Pl D	Sl D
Cz Pb	1.0000							
Hun Pb	0.8184	1.0000						
Pl Pb	0.8380	0.8857	1.0000					
Sl Pb	0.8024	0.7039	0.8605	1.0000				
Cz D	0.8313	0.7625	0.8684	0.8420	1.0000			
Hun D	0.8291	0.8806	0.8634	0.7245	0.8293	1.0000		
Pl D	0.8442	0.8569	0.9429	0.8313	0.9029	0.9337	1.0000	
Sl D	0.8436	0.7409	0.8557	0.9027	0.8869	0.8294	0.9118	1.0000

Source: own elaboration in Statistica 12

**Table 3***Matrix of Partial Correlation Coefficients Between Logarithmic Fuel Prices (After Eliminating All Correlations with Diesel Prices)*

Measure	Variable			
	Cz Pb	Hun Pb	Pl Pb	Sl Pb
Cz Pb	1.0000			
Hun Pb	0.3711	1.0000		
Pl Pb	0.2985	0.5775	1.0000	
Sl Pb	0.2110	0.2353	0.5351	1.0000

Source: own elaboration in Statistica 12 Note: coefficients are significant at 0.05 level

models for both gasoline and diesel prices estimated on log returns.

The estimated VAR models (3) are characterized by high  $R^2$  values, low estimation errors, high F-statistics, and the lowest values of information criteria for individual equations (see Table 4). First, we conduct a separate cointegration test (studies of long-term dependency) according to Johansen's methodology (Johansen, 1988), for gasoline and oil prices. The literature recommends various methods for studying cointegration between vectors, starting from the use of the Dickey-Fuller and Engle-Granger tests, through the Cointegrating Regression Durbin Watson (CRDW) test for single equation (see Clare et al., 1995) to the use of Johansen's procedure for multiple equation models (see Johansen, 1988). In our study, we employ Johansen's technique (results are reported in Table 5). Thus, for gasoline prices, the research shows no cointegrating vectors (see Table 5), so there are no long-term relationships between gasoline prices in the Visegrad Group countries.

Table 5 shows that the trace test indicates 4 cointegrating equations at the 0.05 level. Order  $\pi = N$ , the process  $Z_t$  is integrated to the degree zero for the variance. The series is stationary and the VAR model is an unrestricted VAR model cf. Granger representation theorem (Engle and Granger, 1991).

However, the results show the existence of a long-term relationship between diesel prices. The Maximum Eigenvalue and trace tests indicate 2 cointegrating equations at the 0.05 level (see Table 6).

Generally, we can state that diesel prices in the Visegrad Group Countries are characterized by long-term relationships. The first long-term relationship concern diesel prices in the Czech Republic and Hungary, Poland, and Slovakia (see Table 7). The second long-term relation concern diesel prices in Hungary and Poland as well as Slovakia (see Table 8).

A statistically significant relationship is observed for a long-term relationship between the prices of diesel in the Czech Republic and the prices of die-

**Table 4***Model Fit Measures for Unrestricted VAR for Logarithmic Fuel Prices*

Parameters	Cz Pb	Hun Pb	PI Pb	SI Pb
R-squared	0.8811	0.9614	0.9780	0.9460
Adj. R-squared	0.8753	0.9595	0.9769	0.9434
Sum sq. resids	0.1037	0.0500	0.0307	0.0736
S.E. equation	0.0206	0.0143	0.0112	0.0174
F-statistic	150.69	505.95	902.53	356.52
Log-likelihood	639.57	733.44	795.87	683.62
Akaike AIC	-4.88	-5.61	-6.09	-5.22
Schwarz SC	-4.70	-5.43	-5.91	-5.04
Mean dependent	3.40	5.89	1.54	0.22
S.D. dependent	0.06	0.07	0.07	0.07
Parameters	Cz D	Hun D	PI D	SI D
R-squared	0.8850	0.9593	0.9892	0.9678
Adj. R-squared	0.8793	0.9572	0.9886	0.9662
Sum sq. resids	0.1620	0.0611	0.0235	0.0671
S.E. equation	0.0258	0.0158	0.0098	0.0166
F-statistic	156.46	478.68	1853.71	611.52
Log-likelihood	582.28	707.63	830.40	695.46
Akaike AIC	-4.43	-5.41	-6.36	-5.31
Schwarz SC	-4.25	-5.23	-6.18	-5.13
Mean dependent	3.37	5.90	1.52	0.13
S.D. dependent	0.07	0.08	0.09	0.09

Source: own calculation using EViews 11

**Table 5***Testing for Estimating Cointegrating System Using the Johansen Technique on VARs for Gasoline*

Hypothesized No. of CE(s)	Eigenvalue	Trace Statistic	0.05 Critical Value	Prob.**
None *	0.10771	73.94781	47.8561	3.7E-05
At most 1 *	0.09347	44.77208	29.7971	4.9E-04
At most 2 *	0.05781	19.64938	15.4947	1.1E-02
At most 3 *	0.01705	4.40280	3.8415	3.6E-02

Source: own calculation and elaboration in EViews 11

**Table 6***Testing for Estimating Cointegrating System Using the Johansen Technique on VARs for Diesel*

Hypothesized No. of CE(s)	Eigenvalue	Trace Statistic	0.05 Critical Value	Prob.**
None *	0.1688	84.93	47.85	0.0000
At most 1 *	0.0947	37.58	29.79	0.0052
At most 2	0.0318	12.08	15.49	0.1527
At most 3	0.0147	3.80	3.84	0.0511

Source: own calculation and elaboration in EViews 11

sel in Poland and Slovakia. In the long term, the increase in diesel prices in Poland and Slovakia resulted, on average, in a slight decrease in diesel prices in the Czech Republic. The deviations from this long-term trend are slight, positive, and statistically insignificant.

The relation between diesel prices in Hungary and diesel prices in Poland and Slovakia are statistically significant with a different direction for long-term dependency (negative for Poland and positive for Slovakia). The error correction mechanism for the long-term path's deviations is different for the estimated cointegrating vectors. Overall, the size of these relations is small and statistically insignificant.

The lack of cointegrating vectors for gasoline prices in the analyzed group of countries shows that the performance of domestic prices has been independent (significantly independent of one another). The variance decompositions (see Table 9), which show the proportion of the movements in the dependent variables that are due to their "own"

shocks versus shocks to the other variables, seem to suggest that the Czech, Hungarian, Polish, and Slovakian gasoline markets are to a certain extent exogenous in this system. The variance decomposition and impulse responses for VARs are given in Tables 9 and 10, respectively.

That is, little of the movements in gasoline prices in each country of the Visegrad Group can be explained by movements in other countries. Generally, for the first 4 weeks, changes in fuel prices (gasoline) are explained by changes in prices within a given country. However, for example, in the Slovakian case, after four weeks nearly 90% of movements in the Slovakian market are explained by the Slovakian gasoline prices. The Slovakian gasoline market seems to be particularly influenced by Poland (about 7% after 4 weeks), Hungary (6.16% after 10 weeks), and The Czech Republic (1.27 % after 10 weeks). The Polish market is the most sensitive one. Changes in gasoline prices in this market are determined in particular by the gasoline prices in Hungary (approximately 21% after 10 weeks).

**Table 7**

*First Cointegrating Equation(s) - Normalized Cointegrating Coefficients and Adjustment Coefficients*

Normalized cointegrating coefficients			
Cz D	Hun D	Pl D	Sl D
1	-0.0230 (0.1187)	-0.5125 (0.1405)	-0.2556 (0.0940)
Adjustment coefficients			
-0.5418 (0.0821)	-0.0247 (0.0516)	0.0389 (0.0316)	0.0360 (0.0536)

Source: own calculation using EViews 11 Note: standard error in parentheses

**Table 8**

*Second Cointegrating Equation(s) - Normalized Cointegrating Coefficients and Adjustment Coefficients*

Normalized cointegrating coefficients			
Hun D	Pl D	Sl D	Sl D
1	-1.3731 (0.1800)	0.6876 (0.1881)	-0.2556 (0.0940)
Adjustment coefficients			
-0.0331 0.0502	0.0402 (0.0316)	0.0298 (0.0528)	0.0360 (0.0536)

Source: own calculation using EViews 11 Note: standard error in parentheses

**Table 9**  
*Variance Decompositions for VAR for Gasoline Prices*

Explaining movements		Explained by movements in				
in						
Cz Pb	Weeks ahead	Cz Pb	Hun Pb	Pl Pb	Sl Pb	
	1	100	0	0	0	
	2	97.41	0.09	2.30	0.20	
	3	89.43	2.90	7.48	0.20	
	4	80.69	7.42	11.62	0.27	
	5	72.36	10.90	16.35	0.39	
	8	50.15	19.84	29.68	0.34	
	10	40.86	22.63	36.24	0.27	
	Hun Pb	Weeks ahead	Cz Pb	Hun Pb	Pl Pb	Sl Pb
		1	0.81	99.19	0.00	0.00
2		0.37	97.87	8.32	0.03	
3		0.43	87.73	11.82	0.02	
4		0.33	83.60	16.06	0.02	
5		0.39	80.02	19.52	0.08	
8		1.05	71.17	27.29	0.49	
10		1.78	66.54	30.85	0.83	
Pl Pb		Weeks ahead	CZ Pb	Hun Pb	Pl Pb	Sl Pb
		1	0.75	12.07	87.18	0.00
	2	0.49	21.50	77.30	0.70	
	3	1.17	23.70	73.57	1.56	
	4	1.44	24.90	72.00	1.65	
	5	1.80	24.93	71.71	1.56	
	8	3.36	22.78	72.77	1.09	
	10	4.44	20.95	73.73	0.89	
	Sl Pb	Weeks ahead	Cz Pb	Hun Pb	Pl Pb	Sl Pb
		1	0.74	1.73	0.00	97.53
2		0.44	1.39	0.92	97.25	
3		0.97	2.82	2.45	93.76	
4		0.93	3.59	6.78	88.69	
5		0.81	4.37	12.24	82.58	
8		0.81	5.88	29.77	63.54	
10		1.27	6.16	39.33	53.23	

Source: own calculation using EViews 11

A similar pattern is shown using the impulse response functions, which show the effect of a unit shock applied separately to the error of each equation of the VAR. The markets appear relatively independent of one another, and also informationally efficient in the sense that shocks work through the system very quickly. There is never a response of

more than 1% to shocks in any series, four weeks after the shock has happened. In most cases, shocks work through the system in two weeks. Such results indicate that the possibilities of saving gasoline costs by purchasing them in various markets are minute.

In the last stage of the analysis, we use multivariate GARCH (DCC GARCH - M) to determine the

**Table 10**  
*Impulse Responses to Gasoline Prices*

Response of Cz Pb to innovations in				
Weeks after shock	Cz Pb	Hun Pb	Pl Pb	Sl Pb
1	0.0206	0.0000	0.0000	0.0000
2	0.0101	-0.0007	0.0035	0.0010
3	0.0040	0.0041	0.0057	0.0003
4	0.0050	0.0059	0.0060	0.0009
8	0.0000	0.0071	0.0090	0.0003
Response of Hun Pb to innovations in				
Weeks after shock	Cz Pb	Hun Pb	Pl Pb	Sl Pb
1	0.0013	0.0143	0.0000	0.0000
2	0.0000	0.0143	0.0061	0.0003
3	0.0012	0.0151	0.0070	0.0000
4	-0.0005	0.0150	0.0089	-0.0002
8	-0.0030	0.0125	0.0112	-0.0022
Response of Pl Pb to innovations in				
Weeks after shock	Cz Pb	Hun Pb	Pl Pb	Sl Pb
1	-0.0010	0.0039	0.0105	0.0000
2	-0.0007	0.0067	0.0104	0.0014
3	-0.0021	0.0078	0.0126	0.0025
4	-0.0022	0.0082	0.0130	0.0021
8	-0.0042	0.0068	0.0141	0.0008
Response of Sl Pb to innovations in				
Weeks after shock	Cz Pb	Hun Pb	Pl Pb	Sl Pb
1	0.0015	0.0023	-0.0001	0.0172
2	0.0004	0.0016	0.0022	0.0155
3	0.0021	0.0036	0.0035	0.0119
4	0.0011	0.0033	0.0064	0.0098
8	-0.0016	0.0038	0.0111	0.0049

Source: own calculation using EViews 11

reaction of variability over time and its persistence, i.e., a general measurement of volatility. We use multivariate GARCH (DCC GARCH - M), first, to study the dynamic relationships between volatility and covariance of the analyzed gasoline price markets in the group of Visegrad countries. The volatility of gasoline prices in one of the analyzed countries is transferred to other markets directly, through its conditional variance, and indirectly, through its conditional covariance.

Table 11 presents the transformed variance coefficients (covariance specification - Diagonal VECH). The first part of the table presents the conditional mean estimates, indicated as  $M(\cdot)$ . The

estimates are statistically significant and vary considerably among the countries under consideration. The research shows that the conditional mean value of gasoline prices in Hungary is the highest, whereas the lowest value of the conditional mean value is observed for Poland. The conditional mean between the studied countries is at a much lower level and in some cases, there are no statistical significance levels (i.e.,  $M(1, 3)$ ,  $M(1, 4)$ ,  $M(2, 4)$ ,  $M(3, 4)$ ).

The estimated parameters of the GARCH model - M Alpha (ARCH term) show how volatility reacts to "new information", Beta (GARCH term) represents the persistence of volatility. The sum of the estimated values of Alpha and Beta is lower than

one, which indicates

the stationarity of the stochastic process. We have not found the persistence of volatility for each case. Note that not all of the estimated parameters of the GARCH - M model are statistically significant, in particular regarding the covariance between Polish price volatility and gasoline prices in Hungary and Slovakia (B(2, 3), B(3, 3), and B(3, 4)). The conditional variations of gasoline prices in the individual countries are all statistically significant.

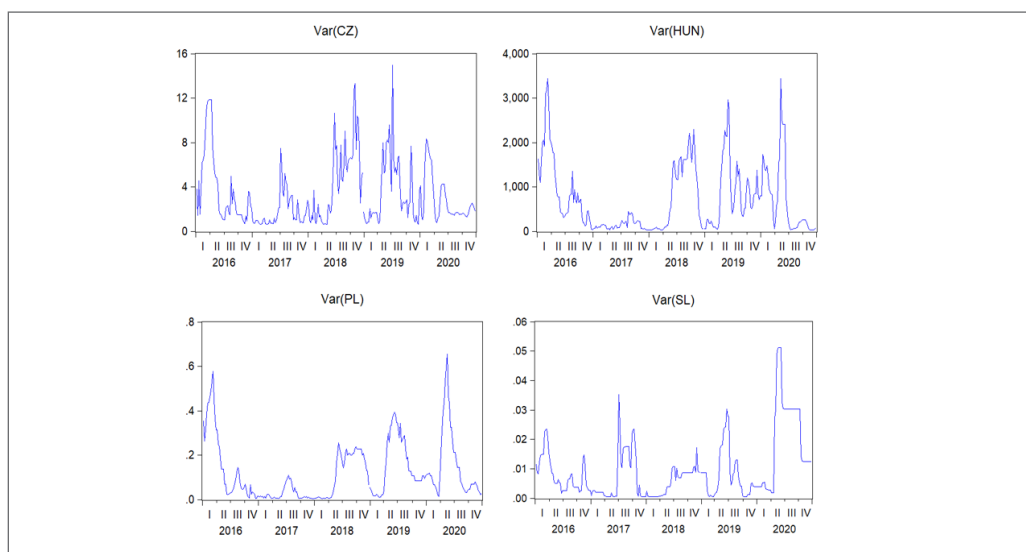
The results for price volatility in multidimensional terms confirms the previous conclusions about the greater importance of differentiating fuel prices for the internal market than their impacts of volatility on another market. The dynamics of gasoline price volatility within the market and between the analyzed markets are different (see Figures 2 and 3). In 2020, high volatility of gasoline prices occurred in Poland, Hungary, and Slovakia, while in this period gasoline price volatility in the Czech Republic was one of the lowest values in the analyzed period, comparable to the 2016-2017 period.

## 5. Conclusions

This paper investigates dynamic correlation and volatility for Visegrad Group (V4) fuel markets from 2016 through 2020. The preliminary statistical analysis of the time series, consisting of logarithmic weekly prices of Pb 95 gasoline and diesel, reveal that they exhibit negative asymmetry and kurtosis so that their distributions do not follow normal distributions. Moreover, the analysis discovers volatility clustering and non-stationarity of the time series, as well as strong correlations between gasoline and diesel prices in the V4 countries. The strongest “net” correlation, after the elimination of the impact of diesel prices, is the correlation between gasoline prices in Poland and gasoline prices in Hungary and Slovakia, which is the result of the close cooperation between these countries in both production and sale of gasoline.

The second step of research results in estimating VAR models. The best models, fulfilling the fundamental statistical criteria, appeared to be VAR (3)

**Figure 2**  
*Variances of Gasoline Prices*



Source: own calculation and elaboration using EViews 11

Table 11

*Transformed Variance Coefficients*

Transformed Variance Coefficients				
	Coefficient	Std. Error	z-Statistic	Prob.
M(1,1)	0,5265	0,1208	4,3595	0,0000
M(1,2)	1,5628	0,6437	2,4276	0,0152
M(1,3)	0,0085	0,0086	0,9926	0,3209
M(1,4)	0,0047	0,0024	1,9467	0,0516
M(2,2)	24,641	5,7778	4,2647	0,0000
M(2,3)	0,1906	0,0599	3,1825	0,0015
M(2,4)	0,0310	0,0167	1,8581	0,0632
M(3,3)	0,0044	0,0007	6,2546	0,0000
M(3,4)	0,0002	0,0002	1,1244	0,2608
M(4,4)	0,0004	0,0001	7,4587	0,0000
A1(1,1)	0,7431	0,2917	2,5478	0,0108
A1(1,2)	0,8143	0,3105	2,6229	0,0087
A1(1,3)	0,8604	0,3178	2,7072	0,0068
A1(1,4)	0,8516	0,3246	2,6235	0,0087
A1(2,2)	0,9185	0,3440	2,6704	0,0076
A1(2,3)	0,9498	0,3516	2,7010	0,0069
A1(2,4)	0,9503	0,3591	2,6464	0,0081
A1(3,3)	0,9946	0,3606	2,7577	0,0058
A1(3,4)	0,9857	0,3656	2,6958	0,0070
A1(4,4)	0,9901	0,3747	2,6423	0,0082
B1(1,1)	0,1500	0,0985	1,5223	0,1279
B1(1,2)	0,1142	0,0672	1,6997	0,0892
B1(1,3)	0,0769	0,0538	1,4291	0,1530
B1(1,4)	0,1235	0,0667	1,8515	0,0641
B1(2,2)	0,0952	0,0482	1,9724	0,0486
B1(2,3)	0,0564	0,0375	1,5056	0,1322
B1(2,4)	0,1031	0,0523	1,9706	0,0488
B1(3,3)	0,0205	0,0407	0,5031	0,6149
B1(3,4)	0,0698	0,0437	1,5985	0,1099
B1(4,4)	0,1073	0,0587	1,8266	0,0678

Note: Covariance specification: Diagonal VECH

$$\text{GARCH} = M + A1 \cdot \text{RESID}(-1) \cdot \text{RESID}(-1)' + B1 \cdot \text{GARCH}(-1)$$

M is an indefinite matrix

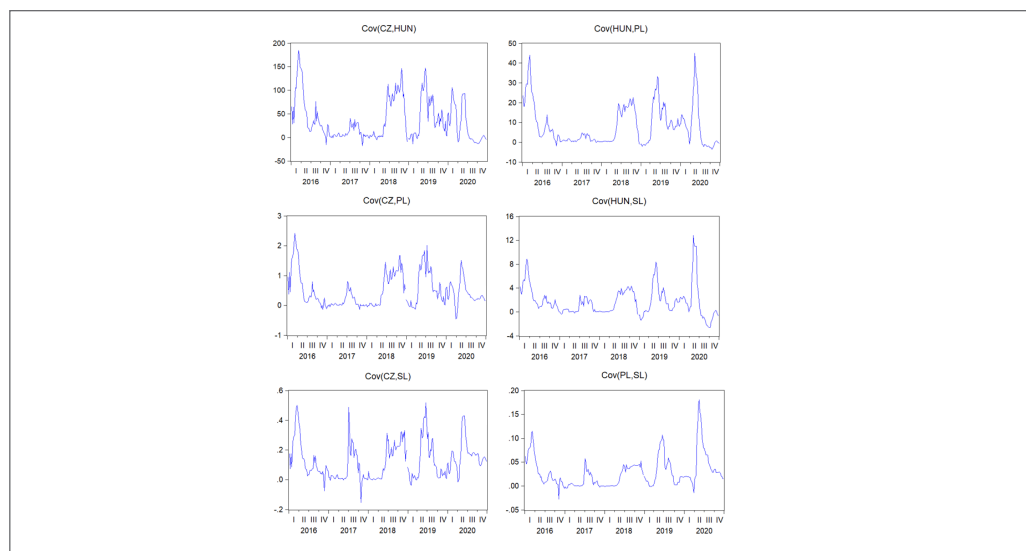
A1 is an indefinite matrix\*

B1 is an indefinite matrix\*

Source: own calculation using EViews 11



**Figure 3**  
Covariances in Gasoline Prices



Source: own calculation using EViews 11

models. They are characterized by high R-squared and F-statistic values, low estimation errors, and the lowest values of information criteria for individual equations.

Next, the analysis of cointegration through the application of Johansen procedures for multiple equation models finds no cointegrating vectors for gasoline prices in the V4 countries. Thus, there are no long-term relationships among them. In other words, only small movements in gasoline prices for each country can be attributed to movements in prices in other countries. The Czech, Hungarian, Polish and Slovakian gasoline markets seemed to be exogenous to a certain extent.

However, an investigation revealed long-term relationships between diesel prices. In the long-term, the increase in diesel prices in Poland and Slovakia resulted, on average, in a slight decrease in diesel prices in the Czech Republic. Moreover, the statistically significant relations between diesel prices in Hungary and diesel prices in Poland and Slovakia show different directions for the long-term dependencies, negative for Poland and positive for Slovakia.

Finally, the last stage of the research aimed at estimating multivariate dynamic conditional correlation GARCH models (DCC GARCH-M) to determine the reaction of variability over time and its persistence. It allows for analyzing dynamic relationships between volatilities and covariances of gasoline prices in the V4 countries. The investigation shows that the conditional mean value of gasoline prices in Hungary is the highest, whereas the lowest value is observed for Poland. The conditional variations of gasoline prices for individual countries are statistically significant. Generally, the examination of volatility in multidimensional terms confirms the previous conclusions about the greater importance of differentiating fuel prices in internal markets than their impacts on the other markets.

The findings of this paper are important to the main actors in the Visegrad Group fuel markets. Since fuel markets affect many sectors of any economy, the results of this paper are of particular significance. In the current economic instability, analyzing fuel price transmission, not only among the V4 countries, is of utmost importance.

Despite the world's aspiration for a transition from fossil fuels to clean energy, oil is still an essential commodity and a source of wealth of nations who own it. Thus, it is important to examine the dynamic of energy markets, specifically, fuel markets. This paper surprisingly finds that even though the Visegrad countries are working together to support, promote, and develop economic and cultural cooperation in many areas, the fuel market in each country behaves independently. However, it is possible that the period from January 2016 through December 2020 may be too short for the analysis and identification of long-term relationships. Thus, it seems reasonable to continue the research in the future.

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