The Implied Volatility Smirk of Pharmaceutical Options during the COVID-19 Pandemic

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Abstract

This study is the first to document the impact of COVID-19-induced uncertainty in major pharmaceutical options in the United States of America. We focus on Johnson & Johnson, Pfizer and Moderna, three pharmaceutical companies that have developed an effective COVID-19 vaccine. Using the methodology of Zhang and Xiang, we examine the dynamics of the level, slope and curvature of implied volatility (IV) curves of these options during the COVID-19 pandemic. We show that, on average, the level and curvature are mostly positive, while the slope is mostly negative. As time to maturity increases, the IV curves flatten out and become less convex. In addition, these curves become significantly steeper and more convex, with increased trading volume, when the pandemic is first announced. We present evidence of a significant positive relationship between the IV slope and the daily number of new COVID-19 cases and deaths for SPX, Johnson & Johnson and Pfizer options, with a negative relationship reported for Moderna options. Finally, we show that options' traders induce a bullish reaction in these IV curves when the pandemic is announced by the World Health Organisation in March 2020 but disregard the approval of the Pfizer vaccine towards the end of the year.

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1 Introduction

This is the first study to document the shape and dynamics of the implied volatility (IV) curves of options written on three pharmaceutical companies, Johnson & Johnson (Ticker: JNJ), Pfizer (Ticker: PFE), and Moderna (Ticker: MRNA), during the coronavirus disease of 2019 (COVID-19) pandemic. Given the wide-ranging effects of this disease on financial markets, the applied approach investigates if and how COVID-19-induced uncertainty was priced into the pharmaceutical options market in the United States of America (U.S.).

We decide to focus on the pharmaceutical industry because we believe it has particular relevance in the context of the COVID-19 pandemic. As the pandemic has had severely negative consequences on economies and markets around the world, affected countries have likely been trying to develop solutions that would ultimately allow them to return to some form of normality. A key consideration has been the development of an effective vaccine against the virus that would provide welcome relief from harsh COVID-19 restrictions and policies implemented by different governments. Pharmaceutical companies with the capabilities of developing and producing such a vaccine have thus been an important factor in this potential solution. The biggest pharmaceutical companies in the world are based in the U.S., and with sufficient public funding provided by the U.S. government, were tasked with the rapid development of a COVID-19 vaccine. Johnson & Johnson, Pfizer and Moderna are all U.S.-based pharmaceutical companies that proved to be at the forefront of this race throughout 2020, with all three managing to successfully develop and distribute their vaccines around the world. Thus, in this study we aim to investigate whether options traders imbued these companies with a sense of importance and made active bets on whether the potential solution of a vaccine would allay wide-spread COVID-19-induced uncertainty.

Using the methodology developed in Zhang and Xiang (2008), we quantify and visualise the pharmaceutical IV curves prior to and during the pandemic. By fitting a

quadratic function, the level, slope and curvature of these curves are obtained and provide information on options traders' expectations of future return moments. Thus, these factors give insight into whether COVID-19-induced uncertainty had any effect on these expectations. We further extend this methodology, according to prior literature, by developing the constant maturity IV curve factors that allow more precise study of the term structure and time-series dynamics of these options (Li, Gehricke, and Zhang, 2019; Yue et al., 2019; Aschakulporn and Zhang, 2021; Stuart et al., 2021). In addition, the sensitivity of these factors to the COVID-19 pandemic as a whole, as well as surrounding certain key events of the pandemic within the U.S., is assessed through regression-based techniques.

Overall, we find a characteristic smirk shape in the IV curves of Johnson & Johnson and Pfizer options, with these curves becoming steeper and more convex compared to before the pandemic. Moderna options, however, display a right-skewed smirk shape in their IV curves, particularly in the earliest maturities. As maturity increases, the IV smirks of all options flatten out and become less convex. In addition, we find statistically significant, positive relationships between the IV slope for the S&P 500, Johnson & Johnson and Pfizer and the daily number of new COVID-19 cases and deaths in the U.S. However, Moderna shows a relationship in the opposite direction. We also find evidence that the announcement of the pandemic in March 2020 was associated with bullish reactions in all options except for those of Moderna, and no reaction whatsoever was seen in response to the approval of the Pfizer vaccine in December 2020.

Implied volatility is different to historical volatility in that it is the volatility that equates the Black and Scholes (1973) option price to the market price of an option and is linked to the wider market's expectation of the underlying asset's volatility. Black and Scholes assume that the price of the underlying asset follows a lognormal diffusion process with a known constant volatility. However, this approach is unreliable and produces a conflict when having to deal with the more realistic, stochastic nature of volatility (Canina

and Figlewski, 1993).

Implied volatility can be depicted through the so-called implied volatility surface, which is a curve of the implied volatility on a particular day at different strike prices for certain maturities. Due to the stochastic nature of volatility in reality, the implied volatility surface is not flat as the Black-Scholes model might assume, but rather displays a near symmetric curve, colloquially known as a 'smile', and indicates that implied volatility varies across strike prices for U.S. equity index options prior to 1987 (Rubinstein, 1985). This phenomenon quickly morphed into an asymmetric, left-skewed 'smirk' following the market crash of 11 October 1987 which seemed to alter the views of market participants towards index options, thereby changing the pricing of these options (Rubinstein, 1994; Corrado and Su, 1997; Skiadopoulos, Hodges, and Clewlow, 2000; Cont and Da Fonseca, 2002; Carr and Wu, 2003; Yan, 2011). This change in shape has been well documented in the literature for the U.S. and the equity index options of various other countries around the world (Pena, Rubio, and Serna, 1999; Foresi and Wu, 2005; Shiu et al., 2010; Tanha and Dempsey, 2015; Li, Gehricke, and Zhang, 2019; Yue et al., 2019).

Since this alteration, various factors that influence the shape and dynamics of the implied volatility surface have been studied for major indices and equity markets. Bollen and Whaley (2004) look into the effect of a supply and demand imbalance on S&P 500 index options, while Garleanu, Pedersen, and Poteshman (2008) show the importance of end-user demand pressures in explaining the expensiveness and skew patterns of index options. Xing, Zhang, and Zhao (2010), as well as An et al. (2014), emphasise the role of informed options trading in the development of the IV curve shape. These studies, amongst many others, have contributed to the rapid growth of this strand of literature exploring these potential causal factors (Pan, 2002; Hentschel, 2003; Han, 2008; Larkin et al., 2012; DeMiguel et al., 2013).

Since the acknowledgement of the unrealistic assumptions made by the Black and Scholes (1973) option pricing model, many studies have proposed extensions and developed

alternate models that capture the behaviour of option prices to a far more accurate degree. Some important extensions involve the incorporation of stochastic volatility and jumps into option pricing models which have helped explain the observation that IVs vary across strike prices that characterises the IV smirk phenomenon (Merton, 1973; Stein and Stein, 1991; Heston, 1993; Bates, 1996; Duffie, Pan, and Singleton, 2000; Carr and Wu, 2004).

A large body of research surrounding financial market reactions to the COVID-19 pandemic and how investor sentiment has been priced-in have recently been published in the literature with a particular focus on equity returns. Baig et al. (2021) investigate the effect of confirmed COVID-19 case and death reports, as well as government restrictions at the individual stock level in the U.S. They find that all of these factors have negative impacts on market liquidity and stability, while severely bolstering volatility. Consistent with these findings, Albulescu (2021) show that the realised volatility of the S&P 500 increases significantly with reports of COVID-19 cases and deaths but find that this effect is stronger for global pandemic reports compared to local reports in the U.S. Baek, Mohanty, and Glambosky (2020) take a different approach by investigating the impact on different industry sectors within the U.S. They show that total and idiosyncratic risk increased significantly and that industries such as natural gas and petroleum, hotels and accommodation, and restaurants were most severely affected. Finally, Baker et al. (2020) compare the reaction of U.S. stock markets to COVID-19 with other pandemics dating back to 1918. They find that government restrictions on economic activity and social distancing were the drivers of the severe market reaction and that these factors were the main contributors towards the reaction to COVID-19 being so much more severe compared to other pandemics.

The severe impact of COVID-19 on financial markets in the U.S. is very clear, however this pandemic has proved to be a wide-reaching phenomenon, affecting economies around the world. Topcu and Gulal (2020) focus on emerging markets and find that the pandemic had significant negative effects on stock market indices initially in March

2020, before dropping off in the following month. In addition, they show that emerging markets in Asia were most severely affected, while Europe only saw a limited reaction in comparison. Zhang, Hu, and Ji (2020) investigate stock market volatility in six different countries severely affected by COVID-19, and find a significant increase in systematic risk, as well as general uncertainty produced by measures aimed at containing the pandemic. Continuing from this study, Zaremba et al. (2020) ask the question of whether government interventions and policies targeting the spread of COVID-19 had an impact on volatility in financial markets. From the investigation of 67 countries, they conclude that these measures showed robust, positive effects on market volatility, with particularly significant effects coming from wide-scale event cancellations and campaigns aimed at increasing awareness of the pandemic. In addition, Pandey and Kumari (2021) investigate the impact of COVID-19 on developed and emerging markets by focusing on 49 different stock market indices. Overall, significant, negative reactions are seen in global stock markets, however they show that over the long-term, developed markets were more severely affected than emerging markets. The above stream of literature has provided ample evidence for the significant adverse impact of COVID-19 on financial markets around the world and forms the basis for investigating these effects on volatility.

Very few studies have been published examining the pandemic's effects specifically through derivative prices. Hanke, Kosolapova, and Weissensteiner (2020) extract the risk-neutral densities from options written on six different stock market indices. They find that the initial reaction to COVID-19 across all of these markets was delayed and that country specific case and death numbers have some power in explaining market expectations. Gormsen and Koijen (2020) take a different approach by examining the pandemic's expected impact on the economy through dividend futures. They confirm the effective use of these futures by showing differences in investor expectations of short- and long-term growth in stock prices and Gross Domestic Product (GDP) due to COVID-19. Cheng (2020) finds an initial underreaction to COVID-19 in the VIX futures market

and that this produces profitable trading strategies with the increasing volatility in the market. Jackwerth (2020) provides a comprehensive investigation into the S&P 500's reaction to COVID-19 by constructing risk-neutral distributions from options written on the index. The main finding shows that the index did not reflect the full impact of the pandemic until two months after the first news was reported, and that there seemed to be a dichotomy between the timing of institutional and retail investors' reactions to the pandemic. Additionally, Li et al. (2021) use Shanghai Shenzhen CSI 300 Index options to measure changing investor expectations in the Chinese option market as a result of the COVID-19 pandemic. They construct an implied volatility slope measure that showed an increase in the cost of hedging downside tail risk, which was positively related to the severity of the pandemic during the lockdown period in China.

So far, there has not been any published literature looking at the impact of COVID-19 on market volatility through the use of pharmaceutical derivatives. Thus, this study proposes to be the first to contribute to this field of literature by investigating the IV smirks of options written on three U.S.-based pharmaceutical companies, Johnson & Johnson, Pfizer, and Moderna. These three companies received the most public funding from the U.S. government to develop a COVID-19 vaccine and became early leaders in this race. The end result was that Pfizer and Moderna were the first companies to successfully develop and distribute an effective vaccine by the end of 2020, while the Johnson & Johnson vaccine only received approval early in 2021.

We contribute towards the literature in several ways. Firstly, we provide the first study to investigate the option contracts of major pharmaceutical companies in the U.S. Secondly, we document the shape and dynamics of the IV curves of these options during the immensely volatile period of COVID-19, giving unique insight into the behaviour of this market during a global health and economic crisis. In addition, we document the term structures and dynamics of the quantified IV factors, the level, slope and curvature, which provide a starting point for the potential development and calibration of a pharmaceutical

option pricing model. Finally, we explore the relationship between these IV curve factors and the COVID-19 pandemic in the U.S. The daily new confirmed cases and deaths are used as a proxy for the severity of pandemic and we examine whether their evolution had any significant impact on the level, slope and curvature, throughout 2020 and during specific events of the pandemic.

The remainder of this study is organised as follows. Section 2 gives a summary of the hypotheses tested in the COVID-19 regression analysis. Section 3 provides background information on the COVID-19 pandemic, as well as the investigated pharmaceutical companies. Section 4 introduces the data used in the analysis, while Section 5 discusses the methodology applied in quantifying the shape and dynamics of the IV curves, as well as explanatory regressions. Section 6 provides a thorough analysis of the empirical results, and Section 7 summarizes the study in a brief conclusion.

2 Hypotheses

In order to examine the relationship between the COVID-19 pandemic in the U.S. and the behaviour of options' traders in the context of these three pharmaceutical companies, we develop two hypotheses surrounding two important events in the pandemic. The first event falls on the 12 March 2020, when the World Health Organisation (WHO) officially announced COVID-19 as a pandemic, and the second on the 11 December 2020, when the Pfizer COVID-19 vaccine received its emergency use authorisation from the U.S. Food and Drug Administration (FDA), being the very first vaccine in the world to do so.

At the beginning of 2020, when the virus had only spread to a few countries, very limited information was available on how severe this disease would become and how rapidly it would spread to overwhelm the health care systems of most economies. This lack of information going forward allowed COVID-19-induced uncertainty to affect the behaviour of investors, particularly options' traders that cast bets according to their expectations of the future. Thus, this uncertainty may have allowed these options' traders to have pre-

dominantly pessimistic expectations of the future, causing them to hedge any downside risk using out-of-the-money (OTM) put options. However, when the WHO announced COVID-19 as a pandemic, this event may have signalled to these traders that governments and regulatory organisations around the world were fully aware of the potential negative consequences of this disease. Therefore, knowing the relevant authorities were aware of and actively working on potential solutions to this global pandemic, options' traders may have developed a more optimistic expectation of the future. This would mean that the broader market would react in a more bullish way, regardless of the number of COVID-19 cases or deaths. In particular, the major, well-established pharmaceutical companies such as Johnson & Johnson and Pfizer, because of their prominence within the market, would also experience similar bullish reactions. Moderna is a smaller and less well-known company, but its specialisation in the development of vaccines may also provide a promising sign to these options traders. This leads us to our first hypothesis:

Hypothesis 1. *The pandemic announcement will induce a bullish reaction in the options written on the S&P 500, Johnson & Johnson, Pfizer and Moderna.*

In addition, the prospect of a vaccine against COVID-19 would serve as a positive signal to the general market by providing a means by which economies around the world may be able to control the continued spread and negative health effects of the virus. Thus, options' traders would likely develop a more optimistic expectation of the future and behave accordingly. Therefore, we would again expect a bullish reaction in the broader market, proxied here by the S&P 500, to the approval of a COVID-19 vaccine. As Johnson & Johnson and Pfizer are composed of different business segments and owing to their size and prominence, they would again show a similar bullish reaction. In comparison, Moderna solely focuses on the development of mRNA-based technology that would allow the rapid development of a COVID-19 vaccine. Thus, the approval of the Pfizer vaccine would likely motivate Moderna to also get their vaccine candidate approved as quickly as

possible, thereby leading to a bullish reaction from investors. This leads us to our second hypothesis:

Hypothesis 2. *The approval of the Pfizer vaccine will induce a bullish reaction in the options written on the S&P 500, Johnson & Johnson, Pfizer and Moderna.*

In this study we analyse the level, slope and curvature of IV smirks of the options written on the S&P 500 and all three investigated pharmaceutical companies. In addition, we regress the daily number of new COVID-19 cases and deaths against these factors to assess their relationship during the pandemic. Thus, in examining these particular pandemic events, we take a bullish reaction to specifically represent an increase in the IV curve slope of an option. This increase would suggest higher volatility in the call options of a particular underlying, meaning that more investors are buying these call options. This response has the effect of increasing the prices of these call options, as well as decreasing the price of put options, thereby causing an increase in the IV curve slope. Overall, a positive covid signal to investors would result in a bullish reaction in the market and particular stocks, reflected in an increase in the IV curve slope of their corresponding options.

3 Background

3.1 A COVID-19 Pandemic Timeline

The month of November 2019 marks the official starting point for the global COVID-19 pandemic, however, at this stage the disease did not have a name, and no one knew how far-reaching and severe events would later turn out to be. In the city of Wuhan, China, health officials first noticed sporadic, individual cases of a novel viral pneumonia of unknown cause. As the virus starts spreading throughout December and the incidence of new cases becomes more frequent in hospitals and infectious disease centres around

the city, a large cluster of patients begins to develop that becomes a cause for concern. On 31 December 2019, the country office of the WHO in China is notified of this rapidly spreading disease and prompts an investigation into its cause.[1] A few weeks later, in January 2020, the genome of the virus is decoded and made publicly available, identifying it as a novel coronavirus which is then officially termed severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), otherwise known as COVID-19.

The rest of January 2020 brings multiple travel warnings issued by the WHO and the U.S. Centers for Disease Control and Prevention (CDC), however it soon becomes apparent that the virus has spread to other countries outside of China, with the first case in the U.S. confirmed on 20 January 2020.[1] New cases are reported on multiple continents, with the number of infections and deaths becoming particularly severe in countries such as Italy, South Korea, and Iran.[2] As the rest of the world comes to the realisation that this disease may manifest itself as a global health and economic crisis, the WHO finally declares COVID-19 a full-scale pandemic on 11 March 2020.[1]

Throughout the rest of March 2020, an increasing number of countries start resorting to strict measures to prevent the continuing spread of the disease, such as implementing wide-scale lockdowns for local populations, restrictions on gatherings and border closures.[2] These developments have the effect of disrupting global supply chains and dramatically increasing expectations of market volatility (Choi, 2020). Financial markets in the U.S. were particularly volatile, with the Volatility Index (VIX), listed on the Chicago Board Options Exchange (CBOE), reaching an all-time high of 82.7% on 16 March 2020.[3] This increase in general market uncertainty was accompanied by large drops in major equity indices, with the S&P 500, NASDAQ, and Dow Jones Industrial Average (DJIA) indices falling by more than 12% at the height of the reaction to the pandemic in March 2020.[4]

[1] https://www.cdc.gov/museum/timeline/covid19.html

[2] https://www.who.int/emergencies/diseases/novel-coronavirus-2019/interactive-timeline

[3] https://www.cnbc.com/2020/03/16/wall-streets-fear-gauge-hits-highest-level-ever.html

[4] https://www.cnbc.com/2020/03/15/traders-await-futures-open-after-fed-cuts-rates-

By mid-April 2020, most states in the U.S. report an increasing number of cases, with the country becoming the global leader in the number of deaths, far surpassing Italy. These developments prompted President Trump to initiate 'Operation Warp Speed', a COVID-19 relief program aimed at producing an effective vaccine against the virus as quickly as possible.[1] The next few months of 2020 are marked by different economies going in and out of lockdowns as the virus continues to spread and death tolls continue to climb. By September 2020, the total number of deaths due to COVID-19 exceed 200,000 in the U.S. and 1 million worldwide.[2]

As the pandemic continued to rage throughout 2020, major pharmaceutical companies tasked themselves with the rapid development of an effective COVID-19 vaccine, with the general aim to start delivering doses by the end of the year. Amongst the initial companies to start human clinical trials with their vaccine candidates, Moderna, Johnsen & Johnsen, and Pfizer were considered to be the frontrunners with the most promising efforts.[5] Moderna and Pfizer (in collaboration with German biotechnology company, BioNTech) had initial advantages in terms of speed of development due to the specific nature of their vaccine candidates, however Johnson & Johnson quickly caught up, and towards the end of 2020, published clinical data showed promise.

Finally, on the 11 December 2020, the U.S. FDA issued an Emergency Use Authorisation (EUA) for the first commercially available COVID-19 vaccine from the Pfizer/BioNTech collaboration. Not long afterwards, on 18 December 2020, the FDA issued another EUA but this time for the Moderna vaccine.[1] With effective COVID-19 vaccines now available, mass vaccination efforts begin in the U.S., as well as other countries that have finally received their first shipments of pre-ordered doses. By the end of December 2020, more than 1 million people have been vaccinated against COVID-19 in the U.S. alone, with more than 7 million worldwide.[6] Only on the 27 February 2021 does the Johnson &

launches-easing-program.html

[5] https://www.forbes.com/sites/moneyshow/2020/06/16/9-pharmaceutical-companies-racing-for-a-covid-19-vaccine

[6] https://ourworldindata.org/coronavirus

Johnson vaccine receive its EUA and starts being distributed to the rest of the world.[1]

As of January 2022, the COVID-19 pandemic continues to plague economies around the globe, with case numbers exceeding 300 million and deaths exceeding 5 million in total.[6] However, at least half of the entire world population has been fully vaccinated against the disease, allowing many countries to finally stabilise their economies and control the continued spread of COVID-19.

3.2 Overview of Johnson & Johnson, Pfizer and Moderna

The U.S. pharmaceutical industry is the largest in world, recently having generated around 530 billion USD in revenue in 2020, capturing nearly half (46%) of the global pharmaceutical market.[7] This dominance by the U.S. is largely owed to the fact that some of the largest pharmaceutical companies in the world are based there, with Johnson & Johnson and Pfizer ranking fourth and sixth amongst the top ten.[7]

According to Thomson Reuters Datastream, Johnson & Johnson is the largest pharmaceutical company in the U.S. by market capitalisation (441.86 billion USD) as of 2021. Unlike more traditional companies in this industry that specialise purely in the development and production of pharmaceutical products, Johnson & Johnson have expanded their operations to offer a more diverse range of products. The company is composed of three business segments that specialise in pharmaceuticals, medical devices, and consumer health products, contributing 55.14%, 27.81% and 17.05% to total revenues, respectively.[8] This business structure has allowed them to generate revenues far beyond the capability of any of their competitors, with an annual revenue of 82.6 billion USD in 2020.[8]

A key focus for Johnson & Johnson in 2020 was the development of an effective COVID-19 vaccine as the pandemic was raging around the world. Their major industry leading position allowed them to secure around 910.6 million USD in public funding provided by the U.S. government for COVID-19 vaccine research and development

[7] https://www.statista.com/topics/1719/pharmaceutical-industry/dossierKeyfigures
[8] https://www.investor.jnj.com/annual-meeting-materials/2020-annual-report

(R&D).[9] With this major investment, the company quickly became one of the frontrunners in the race to develop a vaccine, but certain health complications that arose during their late-stage clinical trial soon produced unforeseen setbacks.[10] Delays due to these complications meant that Johnson & Johnson were only able to produce a commercially available COVID-19 vaccine by the start of 2021, only receiving their EUA from the U.S. FDA on the 27 February 2021. Thus, they were only able to start delivering doses of their vaccine a few months after their competitors, Pfizer and Moderna, meaning that they did not generate any revenue from the vaccine in 2020. However, as part of 'Operation Warp Speed' by the U.S. government, they did manage to secure an agreement to receive 500 million USD upon the successful delivery of several million doses of the vaccine in 2021.[11]

Figure 1 shows the hypothetical performance of a $100 investment in the S&P500, Johnson & Johnson, Pfizer and Moderna over the sample period of 2 January 2019 to 31 December 2020. The investment in the S&P 500 increases slowly to a height of around $137 at the beginning of 2020, before plunging dramatically going into March. On the 12 March 2020, the investment is worth around $109, but continues to decrease throughout the month, reaching a low-point of $88. However, the performance then rebounds and increases to a high of $149 by the end of the sample period. In comparison, the investment in Johnson & Johnson shows a similar trend, increasing slowly initially towards the beginning of 2020, but still lags the performance of the S&P 500 throughout this period. An identical plunge in value is seen as the pandemic escalates in March 2020, with the investment bottoming out at around $85. However, this also rebounds, with the performance eventually fluctuating around a mean level for the rest of the year to finish at around $121, substantially underperforming the S&P 500 during the COVID-19 pandemic. In addition, the performance of a $100 investment in Johnson & Johnson seems to

[9] https://www.forbes.com/sites/niallmccarthy/2021/05/06/which-companies-received-the-most-covid-19-vaccine-rd-funding-infographic/

[10] https://www.pharmaceutical-technology.com/comment/johnson-johnsons-covid-19/

[11] https://www.forbes.com/sites/forbesdigitalcovers/2021/05/14/virus-book-excerpt-nina-burleigh-how-the-covid-19-vaccine-injected-billions-into-big-pharma-albert-bourla-moncef-slaoui/?sh=20e57a297d80

follow the S&P 500 relatively closely when the sample period is changed to 1 January to 31 December 2020 (Figure 2). A similar dramatic decrease in value is seen during March 2020, before rebounding and finishing the year at $107, underperforming the S&P 500 by about $11.

With a market capitalisation of 308.43 billion USD, the second largest pharmaceutical company in the U.S. is Pfizer, which unlike Johnson & Johnson, has a sole focus on developing and producing pharmaceutical products. This specialisation allowed them to become a major competitor within this area of the market and led to the generation of 41.91 billion USD in revenue in 2020.[12] However, this narrower focus meant that Pfizer alone did not have the full capacity to develop an effective vaccine against COVID-19 once the severity of the pandemic became apparent. Pfizer were well aware of their deficiencies in the development of vaccines against various diseases prior to 2020, and so in response they entered into a multi-year R&D arrangement with a German biotechnology company, BioNTech, in 2018.

This collaboration proved to be a major advantage by the time the COVID-19 pandemic rolled around, because it meant that Pfizer already had the infrastructure in place to start immediate development of a COVID-19 vaccine. So, in addition to 800 million USD in public funding from the U.S. government, an official agreement was entered into with BioNTech to develop an effective vaccine against the virus in April 2020.[9] This rapid development pipeline meant that the Pfizer/BioNTech COVID-19 vaccine was successfully produced by the end of 2020 and the very first vaccine to receive an EUA from the U.S. FDA on 11 December, making it the first vaccine to be used in the U.S. The success of this effort allowed Pfizer to generate 154 million USD in revenue from their vaccine by the very end of 2020, however only contributing around 0.37% to total revenue for the year.[12] Pfizer were also successful in entering into an agreement with the U.S. government to deliver 100 million doses of its vaccine for an estimated 1.95 billion USD in 2020.[11]

[12] https://investors.pfizer.com/Investors/Financials/Annual-Reports/default.aspx

The performance of Pfizer from 2019 to 2020 is not very favourable, as captured by the decreasing value of a $100 investment in Figure 1. A dramatic plunge is also seen in the perfomance of Pfizer in March 2020, with the investment dropping to a value of around $65 soon after the announcement of the pandemic by the WHO on 12 March 2020, but manages to regain some of the loss and performs poorly for the rest of the year. However, a sharp increase is seen in the lead up to the Pfizer vaccine receiving its emergency use authorisation on 11 December 2020, with the value of the investment peaking just before the announcement date. The performance then begins to drop again, resulting in a final value of $89, $60 below the value of the S&P 500 investment. In Figure 2, the perfomance of Pfizer matches the S&P 500 and Johnson & Johnson very closely, but begins to underperfom significantly towards the end of 2020, to finish at a value $1 below the initial investment. A similar pattern of an extreme plunge and sharp increase in value are seen around the 12 March and 11 December 2020, respectively.

Moderna is a comparatively young U.S.-based company, having only been in business since 2010, and has a much narrower focus than either Johnson & Johnson or Pfizer. They have a particular focus on the development of mRNA-based technology and have worked on the clinical development of mRNA-based antiviral vaccines since 2015.[13] The specialised nature of their business has allowed them to generate around 803.4 million USD in revenue in 2020, with a market capitalisation of 83 billion USD as of 2021.[14] This extensive focus on vaccine development allowed Moderna to become the first company to begin human clinical trials with their COVID-19 vaccine candidate in March 2020, becoming one of the major competitors for larger companies such as Johnson & Johnson and Pfizer.

In addition to this advantage, Moderna also received the largest amount of public funding from the U.S. government of 956.3 million USD, which allowed them to success-

[13] https://www.cnbc.com/2021/07/03/how-moderna-made-its-mrna-covid-vaccine-so-quickly-noubar-afeyan.html

[14] https://investors.modernatx.com/financials/annual-reports/default.aspx

fully develop their vaccine by the end of 2020, receiving their EUA a few days after Pfizer, on the 18 December.[9] This early authorisation allowed them to generate vaccine revenue of 199.87 million USD, accounting for around 24.88% of total revenue in 2020.[14] In addition, Moderna signed an agreement under 'Operation Warp Speed' to receive 2.5 billion USD from the U.S. government upon successful delivery of their COVID-19 vaccine.[11]

The performance of Moderna is not particularly strong leading up to the start of 2020, as seen by the value of a $100 investment in Figure 1. The announcement of the pandemic on the 12 March 2020 is associated with a very small decrease, before the value rebounds and begins to increase exponentially for the rest of 2020. Sharp positive and negative spikes are observed in the value during this time, but it still increases overall, spiking dramatically in the lead up to the Pfizer vaccine approval in December 2020. This sharp increase in value is likely due to the fact that the Moderna vaccine received its emergency use authorisation on 18 December 2020, a week following Pfizer. The value of the investment then falls, dropping to a value of around $728 at the end of 2020. These observations show that Moderna dramatically outperformed the S&P 500, Johnson & Johnson and Pfizer. This outperformance is again seen in Figure 2, with the value of the Moderna investment outpacing the others significantly throughout 2020. A steep increase is again seen before the approval of the Pfizer vaccine, before a sharp fall to finish at a value of around $568, indicating that most of Moderna's outperformance was experienced during 2020.

4 Data

All Johnson & Johnson, Pfizer, Moderna and S&P 500 Index (SPX) options data are retrieved from the OptionMetrics Ivy DB. The daily IV, maturity date, best ask price, best bid price, strike price, trading volume and open interest are obtained for call and put options for the sample period of 2 January 2019 to 31 December 2020. All option contracts are traded on the CBOE, with the pharmaceutical stock options being physically settled

American options, while the SPX options are European options. Other stock data and underlying index data are obtained from Thomson Reuters Datastream and the Center for Research in Security Prices (CRSP) databases. In accordance with Li, Gehricke, and Zhang (2019), we clean the options data through the following steps:

1. Options with a zero bid price, and zero or missing IV are removed.

2. Options with less than 6 days to maturity are removed.

Table 1 presents a summary of the various options data following this cleaning procedure. Generally, we observe a decreasing trend with increasing maturity for all measures across all sets of options. However, this is particularly evident for the mean daily trading volume and open interest, which indicates that earlier dated contracts are far more liquid than those with a longer dated maturity. Overall, SPX options show the largest values across all measures, likely owing to their popularity and the fact that these options are written on the S&P 500 Index. Johnson & Johnson are the next most active and popular options, followed by Pfizer and then Moderna.

A proxy for the risk-free rate is calculated by linearly interpolating and extrapolating the U.S. Treasury yield curve rates to match the interest rate maturity to the option maturities. This Treasury yield data was directly retrieved from the website of the United States Department of the Treasury. The daily number of new confirmed COVID-19 cases and deaths within the U.S. are obtained from the Our World in Data database, a comprehensive project of the Global Change Data Lab charity based in the United Kingdom (U.K.). Table 2 presents descriptive statistics for the COVID-19 case and death measures, before and after a transformation in accordance with Li et al. (2021).

[Insert Table 1 about here.]

[Insert Table 2 about here.]

5 Methodology

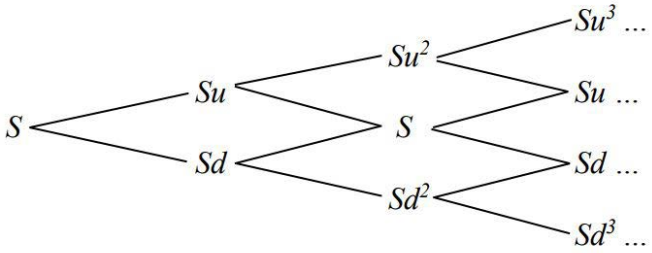
The method used in this study to quantify the implied volatility (IV) smirk is set out in Zhang and Xiang (2008). Using SPX options and the Black and Scholes (1973) model, they provide a means of relating the level, slope and curvature of the IV smirk to the risk-neutral moments of variance, skewness and excess kurtosis through the use of a second-order polynomial function. The SPX options are European, whereas the Johnson & Johnson, Pfizer, and Moderna options are American and therefore cannot be priced using the Black and Scholes model.

Alternatively, the OptionMetrics database uses a pricing algorithm based on the industry-standard Cox, Ross, and Rubinstein (1979) binomial tree model to price American options. This binomial tree model allows the pricing of an option by assuming that the underlying asset follows a binomial distribution, meaning that the asset price can only move up or down by a specified amount. Here, the interval between current time and option expiration is divided into N sub-periods, with the size of the asset price move being dependent on the size of the sub-period and the implied volatility, as given by the formulae:

$$S_{up} : S_t u \equiv S_t e^{\sigma\sqrt{h}} \tag{1}$$

$$S_{down} : S_t d \equiv S_t e^{-\sigma\sqrt{h}} \tag{2}$$

In the above formulae, $h \equiv T/N$, where T is the option expiration date, and S_t is the asset price at time t, the beginning of the sub-period. Using the current asset price (S), a tree of possible underlying asset prices can be constructed at the end of each sub-period out to T as follows:



The price for a call and put option at the beginning of each sub-period is then given by:

$$C = \max(S - K, e^{-rh}[p^* c_u + (1 - p^*)c_d]) \tag{3}$$

$$P = \max(K - S, e^{-rh}[p^* p_u + (1 - p^*)p_d]) \tag{4}$$

where c_u/p_u and c_d/p_d are the call and put option prices at the end of each sub-period, dependent on whether the underlying asset price moves up or down. The interest rate is given by r, the option strike price by K, the continuously compounded dividend yield by δ and the 'risk-neutral' probability p^* by:

$$p^* = \frac{e^{(r-\delta)h} - d}{u - d} \qquad u = e^{(r-\delta)h+\sigma\sqrt{h}} \qquad d = e^{(r-\delta)h-\sigma\sqrt{h}} \tag{5}$$

The price of the option at the beginning of each sub-period is dependent on its prices at the end of the sub-period, and therefore working backwards using the formulae above will calculate the option price at initial time 0, which represents the theoretical model price for the option.

The implied volatility is determined in a similar manner, with the model being recalculated for each sub-period with new volatility (σ) values until the model price converges to the market price of the option. The final value of σ is then known as the implied volatility of the option. The price of the underlying, S_t, together with the continuously compounded dividend yield, δ, are linked to the forward price F_t^T, at time t with expiration day T,

and the risk-free rate, r, through the formula:

$$F_t^T = S_t e^{(r-\delta)(T-t)} \tag{6}$$

Assuming the dividend is reinvested, the dividend yield is approximated over the sample period through the equation:

$$\prod_{i=1}^{n} \left(1 + \frac{D_1}{S_1}\right) \left(1 + \frac{D_2}{S_2}\right) ... \left(1 + \frac{D_n}{S_n}\right) = e^{\delta(T-t)} \tag{7}$$

where D_i is the ith time that the dividend is paid and S_i is the price of the underlying asset in the payment date of D_i. The left-hand side and middle of the equation represent the actual growth of one share of the underlying asset according to discrete dividends, whereas the right-hand side represents growth according to continuously compounded dividends. This entire equation can be used to calculate the average continuously compounded dividend yield, which is then used in the forward price calculation.

To calculate the at-the-money (ATM) strike price, K, we select out-of-the-money (OTM) options which are more liquid and model-sensitive than ATM options, in accordance with the calculation of the VIX index by the CBOE (Carr and Wu, 2003). Thus, the strike price that minimises the absolute difference between put and call prices is determined by selecting puts with $K < F_t^T$, and calls with $K > F_t^T$. Thus, using this K, the implied forward price, F_t^T, is then calculated by using the equation:

$$F_t^T = K + e^{r(T-t)}(c_t - p_t) \tag{8}$$

We assume the early exercise premium of American options is negligible to allow us to use the put-call parity. The risk-free rate, r, corresponding to option maturity is calculated through linear interpolation and extrapolation of the U.S. Treasury yield curve, in accordance with Li, Gehricke, and Zhang (2019). This is given by the following:

$$r_\tau = r_{\tau_1} + \frac{\tau - \tau_1}{\tau_2 - \tau_1} \left(r_{\tau_2} - r_{\tau_1}\right) \tag{9}$$

where r_τ is the risk-free rate for the desired maturity τ. The two Treasury yield rates closest in maturity to the desired maturity are represented by r_{τ_1} and r_{τ_2} for the maturities τ_1 and τ_2.

Moneyness, ξ, can be defined by:

$$\xi \equiv \frac{\ln\left(K/F_t^T\right)}{\bar{\sigma}\sqrt{T-t}} \tag{10}$$

By plotting moneyness versus implied volatility, an implied volatility curve can be constructed by fitting the quadratic IV function through the minimisation of volume-weighted mean square error (VWMSE):

$$VWMSE = \frac{\sum_\xi Volume \times [IV_{market} - IV(\xi)]^2}{\sum_\xi Volume} \tag{11}$$

In order to ensure the best quality of for we employ a median volume filter, as in Li, Gehricke, and Zhang (2019). Thus, if a particular maturity contract has a median volume of less than 10, we employ ordinary least squares (OLS) regression to fit the market IVs, otherwise we use the volume-weighted least squares (VWLS) approach.

Once the IV curve is fit, the at-the-money volatility (γ_0), the slope (γ_1) and curvature (γ_2) can be determined through the equation Zhang and Xiang (2008):

$$IV(\xi) = \gamma_0(1 + \gamma_1\xi + \gamma_2\xi^2) \tag{12}$$

However, the implied volatility curve is not calculated directly but rather indirectly using standard regression techniques through the equation:

$$IV(\xi) = \hat{\beta}_0 + \hat{\beta}_1\xi + \hat{\beta}_2\xi^2 \tag{13}$$

Once the implied volatility curve has been calculated, the individual curve factors are determined as followed:

$$\gamma_0 = \hat{\beta}_0 \qquad \gamma_1 = \frac{\hat{\beta}_1}{\hat{\beta}_0} \qquad \gamma_2 = \frac{\hat{\beta}_2}{\hat{\beta}_0} \tag{14}$$

These curve factors are then grouped by maturity before analysis. This method is less

accurate, however, because it could lead to cases where multiple different maturities are sorted into one maturity category on a given day. Thus, to study the term structures and time-series dynamics of these factors more precisely, the constant maturity factors for the 30, 60, 90, 120, 150, 180, and 360 days maturities are determined through interpolation and extrapolation.

In order to examine the effect of COVID-19 severity on the level, slope and curvature IV factors during the pandemic we estimate the following regression model:

$$Y_t = \alpha + \beta X_{t-1} + \gamma Y_{t-1} + \varepsilon_t \tag{15}$$

Here, Y_t is the 30-day constant maturity level (γ_0), slope (γ_1) and curvature (γ_2) at time t. X_{t-1} represents the daily number of new COVID-19 cases and deaths at time $t-1$. We take the log transformation of these daily figures and because the initial period in the pandemic did not see many COVID-19 infections or deaths, we further transform this into $\ln(Cases + 1)$ or $\ln(Deaths + 1)$ to obtain valid variable numbers (Li et al., 2021). We also include Y_{t-1} as a control, which represents the one-day lagged form of the dependent variable to account for any autocorrelation effects.

In addition, we construct interaction regressor terms to examine whether specific events during the COVID-19 pandemic in 2020 had any influence on the relationship between daily COVID-19 case or death numbers and the level, slope and curvature IV factors. Adjusting Jaccard, Turrisi, and Jaccard (2003), we implement the following regression model:

$$Y_t = \alpha + \beta X_{t-1} + \gamma ED_{t-1} + \delta \left(X \cdot ED\right)_{t-1} + \lambda Y_{t-1} + \varepsilon_t \tag{16}$$

Here, Y_t again represents the 30-day constant maturity level (γ_0), slope (γ_1) and curvature (γ_2) at time t. X_{t-1} represents the daily number of new COVID-19 cases or deaths, transformed according to Li et al. (2021), at time $t-1$. ED_{t-1} is a dummy variable at time $t-1$ corresponding to the date of a specific event in the pandemic and is equal to

zero on all the days prior to the event, and one on all the days including and after the event. We investigate a total of two major events, as follows:

- 12 March 2020 – WHO declares COVID-19 a global pandemic
- 11 December 2020 – U.S. FDA issues emergency use authorisation for the first effective COVID-19 vaccine (Pfizer)

Moderna received its emergency use authorisation on the 18 December 2020, and as this is only a week after the Pfizer vaccine approval, we only investigate the first date to capture the influence of vaccine approval. Thus, a dummy variable is generated only for each of the above events. Finally, $(X \cdot ED)_{t-1}$ represents an interaction term between the number of new daily COVID-19 cases or deaths and each dummy variable. The full regression model incorporating all of these variables is then estimated for each event for each company. This procedure generates regression coefficients that should give an indication of whether the number of new COVID-19 cases or deaths had any significant effect on the IV curve factors during those specific events. The lagged form of the dependent variable, Y_{t-1}, is again included as a control for autocorrelation.

6 Empirical Results

In this section, we present a thorough analysis of the results of quantifying the shape and dynamics of the IV curves of the options for Johnson & Johnson, Pfizer and Moderna. To examine the IV curve factors, the level, slope and curvature, fitted IV curves are plotted each day over the entire sample period for every available maturity. Following which, in order to study the term structure and time-series dynamics of these IV curves, we calculate the constant maturity factors and report the empirical results in several different ways. Finally, to gain insight into the relationship between the IV curve factors of these options and the COVID-19 pandemic, we run a series of multivariate regressions against the daily number of new COVID-19 cases and deaths in the U.S., ultimately focusing on this relation on key dates of the pandemic.

6.1 IV curve dynamics for pharmaceutical options

As a visual representation of the information contained within the options of Johnson & Johnson, Pfizer and Moderna, we first show that fitted IV curves approximate market IVs reasonably well across all sets of options. As mentioned in Section 5, we apply a similar median volume filter as in Li et al. (2019) to ensure best quality of fit. This filter essentially decides whether to use OLS or VWLS when fitting IV curves based on the median volume of a particular maturity contract. Figure 3a-i and Figure 4a-i, show the market IVs, fitted IV curves and trading volumes for Johnson & Johnson options for available maturities on 12 September 2019 and 12 March 2020, respectively. It is evident that a smirk shape is observed in most of these graphs, with the shape being more prominent in the earlier maturities on both dates. In addition, it is observed that as maturity increases, the IV curves become less convex and flatten out, with the highest trading volumes seen in earlier maturities, particularly a maturity of 8 days. Comparing the IV curves between these dates, there seems to be a noticeable difference in the steepness and convexity of the curves. The IV curves on 12 March 2020, the day

the WHO officially announced COVID-19 as a pandemic, are significantly steeper and sit at a higher level than on the 12 September 2019, displaying a more pronounced smirked shape. This observation is particularly striking in the earliest maturities where most of the trading volume accumulates.

[Insert Figure 3 about here.]

[Insert Figure 4 about here.]

Table 3 provides a summary of these IV curves by showing their resulting forward prices, IV parameters and factors, all grouped by maturity. As an initial examination of the term structure of the IV curve factors, the option contracts are grouped into the following maturity categories: less than 30, 30-90, 90-180, 180-360, and more than 360 days. Overall, the level (ATM IV - γ_0) of these curves is positive, with a highly negative slope (γ_1) and positive curvature (γ_2). This confirms the left-skewed smirk shape seen in the IV curve graphs of Johnson & Johnson and is consistent with the smirk shape observed for SPX options (Carr and Wu, 2003; Foresi and Wu, 2005; Fajardo, 2017). The values of the overall level, slope and curvature are 0.2154, -0.6831 and 1.2712, respectively, with accompanying standard deviations of 0.0641, 0.3515 and 1.3049. The average term structure of the forward price (F_t^T) shows a weak downward trend, becoming more prominent towards later maturities. The term structure of the level is relatively flat on average, while the term structure of the slope increases, with a noticeable downward spike within the 30-90 day maturity group. The term structure of the curvature decreases exponentially on average. The standard deviations for the forward price and all IV curve factors seem to decrease with maturity, however once maturity is greater than 360 days, they spike upwards for the slope and curvature factors. The magnitude of the proportion of significant coefficients and R-squared (R^2) values are all above 90%, thereby indicating the reliable quantification and approximation of these IV curves. Finally, mean daily trading volume of these option contracts is highest in the earliest maturity category of less than 30 days, before decreasing substantially as maturity increases.

[Insert Table 3 about here.]

Figure 5a-i and Figure 6a-i, show the same IV curves for Pfizer options on those particular dates for each available maturity. Again, a smirk shape is observed in most of these graphs, being more pronounced in the earlier maturities. With increasing maturity, these IV curves become less convex and flatten out substantially but maintain their left-skewed characteristic. As before, the IV curves on 12 March 2020 are far steeper and sit at a much higher level compared to those on 12 September 2019, with a clear increase in trading volume, particularly in earlier dated option contracts, however this increase in volume is also observed for some later maturities.

[Insert Figure 5 about here.]

[Insert Figure 6 about here.]

Table 4 provides a summary of IV curve parameters and factors for Pfizer. Overall, these curves display a positive level factor, with a negative slope and strong, positive curvature. These results are similar to those of Johnson & Johnson, and again confirm the left-skewed IV smirks seen in the graphs for Pfizer. The value of the level, slope and curvature are 0.2497, -0.4545 and 1.4795, respectively, with standard deviations of 0.0880, 0.7305 and 5.7046. The average term structure of the forward price shows a weakly decreasing trend, while that of the level remains relatively flat. The term structure of the slope increases with increasing maturity, but similar to Johnson & Johnson, shows a downward spike in the 30-90 day maturity group. The term structure of the curvature also decreases exponentially on average. Reliable quantification and approximation of these IV curves is shown in the high proportion of significant coefficients and R^2 values. The mean daily trading volume of these option contracts (4015.90) is substantially higher than for Johnson & Johnson (913.71), with the majority of volume concentrated in contracts with maturity dates less than 30 days. However, large trading volumes are also seen in contracts within the 30-90 and 90-180 day maturity groups.

[Insert Table 4 about here.]

Finally, Figure 7a-d and Figure 8a-i, show the IV curves for each available maturity for Moderna options on 12 September 2019 and 12 March 2020, respectively. As observed, a characteristic left-skewed smirk shape is not evident in any of the graphs and fitted IV curves do not approximate market IVs as well as for Johnson & Johnson and Pfizer. In addition, as maturity increases there does not seem to be a clear pattern of behaviour, although the IV curves do tend to flatten out substantially after a maturity of 180 days. On the 12 September 2019, there is a lack of trading volume, with only a few contracts traded at each maturity. However, on the 12 March 2020, trading volume increases substantially, particularly in earlier maturities, with the IV curve for a maturity of 8 days displaying a steep, right-skewed smirk shape contrary to what we would expect. This right-skewed characteristic is maintained up to higher maturities, before flattening out completely. A possible explanation for this phenomenon is that, given the nature of Moderna's specialisation in anti-viral vaccine development, options' traders are betting that this company might have a significant advantage in the potential development of a COVID-19 vaccine, and so are willing to pay more for OTM call options, thereby increasing the slope of the IV curve.

[Insert Figure 7 about here.]

[Insert Figure 8 about here.]

Table 5 also provides a summary of quantified IV curves for Moderna. Overall, the level of these curves is extremely positive, with a weak, negative slope and strong, positive curvature. The values of the level, slope and curvature are 0.9005, -0.0553 and 1.6357, respectively, with standard deviations of 0.2209, 0.4600 and 3.0356. The average term structure of the forward price decreases dramatically, before showing an upward spike in the longest maturity category (more than 360). Both the term structures of the level

and the curvature decrease with increasing maturity, however the curvature does so exponentially. The average term structure of the slope is actually positive in the earliest maturity category, before decreasing to the 90-180 maturities and then increasing towards the longest maturities. These results are consistent with the right-skewed IV smirk shape seen in the graphs of the earliest-dated option contracts for Moderna. The proportion of significant coefficients for the level parameter is very high, however is substantially lower for the slope and curvature parameters. In addition, the R^2 values are lower and show a decreasing trend with increasing maturity. This suggests that the quantification and approximation of the slope and curvature IV factors are not entirely reliable. Finally, as for the previous two pharmaceutical companies, the trading volume of Moderna option contracts is highest in the earliest maturities, less than 30 days, before decreasing with increasing maturity.

[Insert Table 5 about here.]

6.2 Constant maturity IV curve dynamics

In order to study the term structure and time-series dynamics of the IV level, slope and curvature factors more precisely, we also calculate the corresponding constant maturity factors for Johnson & Johnson, Pfizer and Moderna. These are obtained through interpolation and extrapolation, yielding the following maturity categories: 30, 60, 90, 120, 150, 180 and more than 360 days.

Table 6 presents summary statistics for the constant maturity IV factors for Johnson & Johnson. Overall, the level is positive, the slope is highly negative, and the curvature is highly positive, consistent with the results discussed previously. The value of the level, slope and curvature are 0.2127, -0.8053 and 2.3240, respectively, with standard deviations of 0.0782, 0.3951 and 1.1519. Here, it is evident that the overall level of the slope and curvature are greater in magnitude than those reported in Table 3. The term structure of the constant maturity forward price also shows a weak, decreasing trend,

but spikes upwards in the last maturity category (more than 360 days), while the level remains relatively flat. The term structure of slope increases with increasing maturity, but spikes downward in the last maturity category. Similar behaviour is seen in the term structure of the curvature, with a decreasing trend before an upward spike in the last maturity category. These spikes in the opposite direction to the overall trend in the term structures are not observed in previous results. The standard deviations of the forward price and all IV curve factors seem to decrease with increasing maturity, before briefly increasing again towards the longest maturity categories. The predicted IV curves for each constant maturity are presented in Figure 9. Overall, a distinct, left-skewed smirk shape can be observed, providing a visual representation of the results in Table 6. As maturity increases, these IV curves become less convex and start to flatten out as the slope becomes more positive.

[Insert Table 6 about here.]

[Insert Figure 9 about here.]

In addition, the time series of the 30- and 180-day constant maturity IV factors over the entire sample period are presented in panels a, c and e of Figure 10, respectively. Generally, the level is always positive, the slope is mostly negative and the curvature is always positive, which is consistent with the previous results. In Figure 10a, it can be observed that the 30- and 180-day constant maturity level mean-reverts prior to 2020, with a short period of extreme volatility seen during the first half of 2020, particularly in March when the pandemic was officially announced. After this peak, the level falls back down to a slightly higher mean level with prolonged volatility towards the end of the year. The constant maturity slope in Figure 10c is highly negative throughout most of the sample period, with the 30-day factors fluctuating substantially more than the 180-day factors. Again, a significant reaction is seen during March 2020, with large, negative spike before recovering back to a mean level. However, towards the end of the year, the slope

increases and eventually becomes positive. Similar to the slope, the constant maturity curvature in Figure 10e is highly positive, with far greater fluctuations and spikes seen in the 30-day factors all throughout. Both maturity factors show a large positive reaction in March 2020, however this is far more pronounced for the 30-day factors. Panels b, d and f in Figure 10 show the difference between the 180- and 30-day constant maturity factors. Here, it is evident that the term structure of the level is mostly flat, with the exception of a few negative spikes and a large downward move during March 2020. The term structures of the slope and curvature are generally upward sloping and downward sloping, respectively, with both showing extreme reactions during March 2020 as well.

[Insert Figure 10 about here.]

Table 7 presents a summary of the constant maturity IV factors for Pfizer. As seen in the previous results, the overall level is positive, the slope is negative, and the curvature is highly positive. The values of the constant maturity level, slope and curvature are 0.2540, -0.5619 and 2.2249, respectively, with standard deviations of 0.1036, 0.5453 and 1.5642. The average term structure of the forward price and the curvature is decreasing with increasing maturity, however both experience positive spikes in the longest maturity category. The level displays a relatively flat term structure on average, while the slope increases up to the longest maturity category, before experiencing a small downward spike. The standard deviations of the forward price show an increasing trend, while those of the all the IV factors decrease with increasing maturity. These results are visualised in Figure 11, showing the predicted constant maturity IV curves for each maturity. A clear smirk shape is seen across all maturities, with the IV curves becoming less convex and flatter as the slope increases.

[Insert Table 7 about here.]

[Insert Figure 11 about here.]

Panels a, c and e of Figure 12 display the time series of the constant maturity level, slope and curvature over the entire sample period. In general, the level is always positive, the slope is mostly negative, and the curvature is mostly positive. Looking at Figure 12a, the level seems to mean-revert around 0.20 prior to 2020, however during March 2020 we see an extreme, positive reaction which is very similar to that of Johnson & Johnson. The level does fall back down but to a higher mean level, following which it shows a prolonged period of high volatility for the rest of the year. Figure 12c shows the slope, and here we can see a fairly stable trend, with the 30-day factors displaying far more fluctuations than the 180-day factors. During March 2020, a severe, negative reaction is seen in the slope, before it recovers and displays an increasing trend, eventually becoming positive towards the end of the year. The constant maturity curvature shown in Figure 12e is almost always positive, with the 30-day factors sitting at a higher mean level than the 180-day factors, and fluctuate substantially more. At the announcement of the pandemic in March 2020, we see large, consecutive positive and negative spikes for a prolonged period of time. These extreme fluctuations, mainly in the 30-day curvature factors, are different to those seen for Johnson & Johnson and far more short-lived. After this volatile period, the curvature stabilises back to its previous mean level.

Moving to the difference between the 180- and 30-day constant maturity factors, we see a relatively flat term structure in the level, with the exception of the extreme negative reaction during March 2020 and the subsequent negative trend for the rest of the year. The term structure of slope is largely increasing with an upward spike in reaction to the pandemic, before showing a negative trend towards the end of the year. Finally, the term structure of the curvature is almost always a negative trend, except for during and immediately following March 2020, where we see a large negative and positive spike.

Table 8 presents the summary statistics for the constant maturity IV factors for Moderna. Overall, the level is highly positive, with a slightly negative slope and highly positive curvature. Here, the values of the level, slope and curvature are 0.8523, -0.0942 and

1.9622, respectively, with standard deviations of 0.2263, 0.4873 and 2.5407. The term structure of the constant maturity forward price stays relatively flat before increasing dramatically in the 150- and 180-maturities, and then falls back down in the longest maturity category. The average term structure of the level and curvature seem to decrease before displaying a positive spike in the longest maturity category. The term structure of the slope is similar in that it shows an increasing trend at first, before reversing with a negative spike in the longest maturity category. The distinct trend of slope and curvature are identical to the results in the previous table for Moderna IV curve factors (Table 5). The standard deviations of all constant maturity factors seem to decrease with increasing maturity at first, before increasing again in the longer maturity categories.

[Insert Figure 12 about here.]

[Insert Table 8 about here.]

Figure 13 displays the predicted constant maturity IV curves. A subtle smirk shape can be seen overall, however this is not very prominent. As maturity increases, these curves begin to lose convexity and flatten out, similar to Johnson & Johnson and Pfizer. Panels a, c and e of Figure 14 show the time series of the constant maturity level, slope and curvature, respectively. In general, the level is always positive, the slope fluctuates around zero, and the curvature fluctuates around zero as well before moving to a slightly higher mean level. Specifically, the level in Figure 14a sits at a very high mean value with prolonged periods of increased volatility and occasional extreme spikes. In March 2020, we see a large positive reaction before it settles back down to a higher mean value, in addition to increased volatility. In Figure 14c, the slope seems to largely fluctuate around zero, with a large negative spike seen in the first half of 2019. A comparatively small positive reaction is seen in March 2020, mostly in the 30-day factors, before the slope fluctuates around zero again for the rest of the year. The curvature in Figure 14e also fluctuates around zero, however a large positive spike is seen around the same time as the

spike in the slope in 2019. At the announcement of the pandemic in March 2020, we see a muted positive reaction, after which the 30- and 180-day factors settle at higher mean values for the rest of the year. Moving to the difference between the 180- and 30-day factors in panels b, d and f of Figure 14, we see a very volatile but mostly negative term structure in the level, and a term structure that fluctuates around zero for the slope. The term structure of the curvature, however, fluctuates around zero prior to 2020, before showing a negative trend for the rest of the year.

[Insert Figure 13 about here.]

[Insert Figure 14 about here.]

Johnson & Johnson, Pfizer and Moderna are all pharmaceutical companies, which represent a very small proportion of the overall financial market in the U.S., and so the behaviour of their IV curve factors may be very unique in this regard. Thus, to compare their behaviour to that of the broader market, we also calculate the constant maturity IV curve factors for SPX options. Table 9 presents the summary statistics of these constant maturity IV factors. Overall, these IV curves display a positive level, with a highly negative slope, and a curvature close to zero. The values of the level, slope and curvature are 0.2003, -2.5623 and 0.0709, respectively, with standard deviations of 0.1009, 0.4297 and 0.9391. Comparing these values for the SPX options and those of the three pharmaceuticals, we see that the constant maturity level is very similar to that of Johnson & Johnson and Pfizer, however the value of the level for Moderna is far greater. In addition, the biggest difference is seen in the constant maturity slope and curvature, where these values are substantially more negative and hugely less positive, respectively, for SPX options. This difference is emphasised in the predicted constant maturity IV curves in Figure 15. Here, a smirk shape is completely absent, however, there is still strong negative sloping. The curves are very flat, and the only change seen with increasing maturity is a decrease in the slope.

Finally, panels a, c and e of Figure 14 show the time series of the constant maturity IV factors for SPX options over the entire sample period. In general, the level is always positive, the slope is always negative, and the curvature fluctuates around zero. In Figure 14a, the level shows an extreme positive reaction during March 2020, before settling down to higher mean level with prolonged volatility for the rest of the year. The constant maturity slope, in Figure 14c, is highly volatile throughout the entire sample period for both the 30- and 180-day factors, with a brief, negative spike seen during March 2020. The curvature, Figure 14e, fluctuates mostly around zero, however, when the pandemic is announced, we see a large negative spike before stabilising around zero for the rest of the year. Moving to the difference between the 180- and 30-day factors in panels b, d and f of Figure 14. The average term structure of the level is mostly positive, with the exception of a large negative trend during March 2020. The term structure of the slope is highly volatile but almost always positive on average. The curvature shows an average term structure that fluctuates around zero, however a large positive spike is seen in March 2020.

[Insert Table 9 about here.]

[Insert Figure 15 about here.]

To summarise, for Johnson & Johnson, the overall level is always positive with a relatively flat term structure. The slope is mostly negative and has an increasing term structure, while the curvature is always positive and shows a decreasing term structure. For Pfizer, the overall level is always positive with a relatively flat term structure as well. The slope is mostly negative and an increasing term structure, while the curvature is mostly positive with a decreasing term structure. For Moderna, the overall level is always positive with a downward-sloping term structure. The slope fluctuates around zero with an increasing term structure, while the curvature also fluctuates around zero and has a decreasing term structure. All three companies show significant reactions to the

announcement of the COVID-19 pandemic in March 2020 in all their constant maturity IV factors, however these reactions vary in their intensity. In addition, following this initial reaction, the level of all companies seems to experience prolonged volatility for the rest of 2020. For SPX options, the overall level is always positive with a relatively flat term structure. The slope is always highly negative and has an increasing term structure, while the curvature fluctuates around zero with a decreasing term structure. The biggest difference seen between these options and those of the three pharmaceuticals, is that the slope is far more negative, and the curvature is closer to zero. However, similar extreme reactions were seen in all of the constant maturity factors in response to the announcement of the pandemic.

[Insert Figure 14 about here.]

6.3 COVID-19 Pandemic Regression Analysis

This section provides an analysis of the relationship between the COVID-19 pandemic in the U.S. and the constant maturity IV curve factors of SPX, Johnson & Johnson, Pfizer and Moderna options. We initially carry out regressions of the daily number of new confirmed COVID-19 cases and deaths against the 30-day constant maturity level, slope and curvature factors. We then extend this analysis to test the hypotheses proposed in Section 2, by carrying out multivariate regressions of the same variables but include an interaction term that aims to capture the additional influence on this relationship of specific events during the pandemic. We examine two events that fall on separate dates, 12 March 2020, the day the WHO announced the COVID-19 as a pandemic, and 11 December 2020, the day that Pfizer received its emergency use authorisation from the U.S. FDA.

6.3.1 Impact of the COVID-19 Pandemic

Table 10 and Table 11 summarise the results of the first set of regressions for SPX, Johnson & Johnson, Pfizer and Moderna options. In these regressions, because the COVID-19 case and death measures are logged, their regression coefficients represent semi-elasticity. Thus, these regression coefficients must be divided by 100 for interpretation and represent the change in the dependent variable (IV factors) when the cases and deaths change by $\sim$1%.[15] Moving to panel A of Table 10, when the daily number of new COVID-19 cases is regressed against the IV curve factors of SPX options, we find statistically significant regression coefficients for the slope (0.0241) and the curvature (0.0472) at the 1% and 5% level, respectively. Additionally, the intercept and the coefficient for the lagged dependent variable control are statistically significant for both the slope and curvature. The R^2 values are below 50% for both factors, indicating a weak model fit. These results show a positive relationship, indicating that as the daily number of cases increases by 1%, the value of the slope increases by 0.000241, and the value of the curvature increases by 0.000472. The slope provides a more informative measure of the behaviour of options' traders by giving an indication of the cost of call or put option protection, particularly during the COVID-19 pandemic, as shown in Li et al. (2021). Therefore, we mainly focus on the direction and magnitude of the slope in these regressions to assess traders' reactions to COVID-19-induced uncertainty. The significant, positive coefficient for the slope suggests that as the number of new cases increases, options' traders become more optimistic in their expectations for the S&P 500, which induces a decrease in the cost of put option protection. Traders might see the increasing case numbers as a sign that the government may be forced to act to curb the further spread of the virus, thereby inducing a positive reaction in these options.

The daily number of new COVID-19 deaths showed statistically significant coefficients at the 1% level for the level (-0.0056), slope (0.0638) and curvature (0.2018) of SPX

[15] More precisely, a 1% change in $Cases + 1$ and $Deaths + 1$.

options. Additionally, the intercept and the coefficient of the lagged dependent variable are statistically significant for all factors, consistent with the results for the number of cases. The R^2 values are slightly higher for the slope and the curvature compared to the results for the number of cases, but still indicate weak model fit. As the number of deaths increases by 1%, the level is expected to decrease by 0.000056, and the slope and curvature are expected to increase by 0.000638 and 0.002018, respectively. These results again suggest that options' traders become more optimistic about the S&P 500 as the number of deaths increases, which is reflected in the decreasing ATM IV (level) and cost of put option protection (slope).

Panel B in Table 10 shows the regression results for Johnson & Johnson options. Looking at the number of new COVID-19 cases, we find that the coefficient for the slope (0.0145) is statistically significant at the 5% level. Additionally, the intercept and the coefficient for the lagged dependent variable are statistically significant across all three factors. The R^2 values are above 60% for the slope regression, indicating an adequate model fit. These results are similar to those for SPX options, with a positive relationship indicating that as the number of new cases increases by 1%, the value of the slope increases by 0.00145.

[Insert Table 10 about here.]

Moving to the number of new COVID-19 deaths, we find statistically significant coefficients for the level (-0.0046) and the slope (0.0470) at the 10% and 1% levels, respectively. In addition, the intercept and coefficient for the lagged dependent variable are statistically significant for all both factors. The level and the slope regressions show relatively high R^2 values, indicating good model fit. These results show a negative relationship for the level, and so as the number of deaths increases by 1%, the level decreases 0.000046. The positive relationship reported for the slope suggests that as the number of deaths increase by 1%, the value of the slope increases by 0.000470. Overall, these results for the number of cases and deaths are consistent with those seen in SPX options. Thus, as

the number of new COVID-19 cases and deaths increase, options' traders become more optimistic about the future of Johnson & Johnson, and so their behaviour is associated with a small decrease in the ATM IV and the cost of put option protection.

Panel A in Table 11 summarises the regression results for Pfizer options. We find that the coefficient for the slope (0.0255) is statistically significant at the 1% level for the number of new COVID-19 cases. Additionally, the coefficients for the level (−0.0051) and the slope (0.0564) are statistically significant at the 5% level for the number of new deaths. The intercept and coefficient of the lagged dependent variable are statistically significant across all factors for both the number of new cases and deaths. The R^2 values for the significant level and slope coefficients are reasonably high and indicate good model fit. These results show that as the number of new cases increases by 1%, the slope increases by 0.000255 for Pfizer IV smirks. Also, as the number of new deaths increases by 1%, the value of the level decreases slightly by 0.000051 and the value of the slope increases by 0.000564. Overall, these results are similar and consistent to those of SPX and Johnson & Johnson options. Options' traders seem to take the increasing number of COVID-19 cases and deaths as a positive sign, thereby inducing a decrease in the ATM IV and the cost of put option protection for the S&P 500, Johnson & Johnson and Pfizer. The prominent and well-established position of both Johnson & Johnson and Pfizer within the U.S. pharmaceutical industry, as well as their constituency in the S&P 500, are likely strong contributors to the similarity in their behaviour to the broader U.S. market in response to COVID-19.

[Insert Table 11 about here.]

Finally, moving to panel B in Table 11, we show the regression results for Moderna options. Here, we find that the coefficients for the slope (−0.0226) and the curvature (0.1093) are statistically significant at the 1% level for the number of new COVID-19 cases. Additionally, the coefficients for the slope (−0.0350) and the curvature (0.1921) are statistically significant at the 5% level for the number of new COVID-19 deaths.

The intercept and coefficient for the lagged dependent variable are statistically significant across all factors, except for the curvature in the context of the number of new deaths. The R^2 values of the significant slope and curvature coefficients are all below 50%, indicating poor model fit. These results show that as the number of new cases increases by 1%, the value of the slope of Moderna IV smirks decreases by 0.000226, while the curvature increases by 0.00‘093. Very similar relationships are seen as the number of new deaths increases by 1%, where the slope decreases by 0.000350 and curvature increases by 0.001921. Moderna options therefore show opposite relationships in their IV smirk factors compared to SPX, Johnson & Johnson and Pfizer options. This suggests that as the number of new COVID-19 cases and deaths increase, options' traders become more pessimistic about the future of Moderna, thereby inducing an increase in the cost of put option protection. Moderna is a much smaller and less well-established than Johnson & Johnson and Pfizer, as well as likely not being in as strong a position to endure through the pandemic. These factors may explain why Moderna options show different results to those of the other options.

Table 12 presents the correlations between the 30-day constant maturity level, slope and curvature for SPX, Johnson & Johnson, Pfizer and Moderna IV curves and the COVID-19 case and death measures. Here, the sign of the correlations between the number of new cases and deaths are all positive for SPX, Johnson & Johnson and Pfizer options. However, these same correlations are negative for Moderna options. These findings further confirm the direction of the relationships established between these IV curve factors and the number of new cases and deaths for the investigated options in Table 10 and Table 11.

[Insert Table 12 about here.]

6.3.2 COVID-19 Pandemic Event Study

To investigate the influence of the announcement of the COVID-19 pandemic by the WHO and the approval of the Pfizer vaccine on the IV curve factors of SPX options and the options of the three pharmaceutical companies, we test two hypotheses proposed in Section 2. Both propose that all investigated options will experience bullish reactions in response to the pandemic announcement and vaccine approval, respectively. Having already established the baseline relationships between the number of new cases and deaths and the IV factors of all options in the previous results section, we aim to examine the influence of these pandemic events on these relationships. Thus, we mainly focus on the regression coefficient for this interaction term, between the number of new cases or deaths and the event dummy variable. In these multivariate regression models, this coefficient represents the marginal effect of the paricular pandemic event on the size of the coefficient for the number of new cases or deaths.

The first half of both panels A and B in Table 13, test the first hypothesis and summarise the regression results for SPX options during the first event, on 12 March 2020. Here, in the first half of panel A, we find that the coefficient of the interaction term is statistically significant for the level (-0.0202) and the curvature (0.3754) at the 1% level, and at the 10% level for the slope (0.0918), for the number of new COVID-19 cases. Additionally, the intercept and coefficient for the lagged dependent variable are statistically significant across all factors, except for the curvature in the context of the number of new cases. The sign of the intercept values indicate that the level has a positive baseline (0.0291), while the slope has a negative baseline (-1.2235). These results suggest that as the number of new cases increases by 1%, the pandemic announcement is associated with a decrease in the level by 0.000202, and an increase in the slope and curvature by 0.000918 and 0.003754, respectively. Thus, the announcement of the pandemic by the WHO decreases the ATM IV and the cost of put option protection for SPX options, which represents a bullish reaction and supports our first hypothesis.

[Insert Table 13 about here.]

The first half of panel B in Table 13, only shows a statistically significant coefficient for the interaction term of the level (0.0523), at the 10% level. In addition, both the intercept and the coefficient for the lagged dependent variable are statistically significant. Therefore, as the number of new COVID-19 deaths increases by 1%, the pandemic announcement increases the level of SPX options by 0.000523. This increase in the ATM IV, in addition to the absence of any significant effect on the slope of these SPX IV curves, does not support our first hypothesis. This result may suggest that options' traders might not have reacted in any particular direction in response to this announcement, when taking the number of deaths into account. It is also worth noting, that this early on in the pandemic, there were very few confirmed deaths due to COVID-19 and so this might have contributed to the muted reaction by these traders.

In the second half of panel A in Table 13, on the day the Pfizer vaccine was approved, we do not find any statistically significant interaction terms across all three factors for the number of new COVID-19 cases. This does not support our second hypothesis and suggests that options' traders did not find the news of vaccine approval particularly important for the future of SPX options during COVID-19. However, in the second half of panel B in Table 13, we find a statistically significant coefficient for the interaction term of the level (-0.2609) at the 5% level, for the number of new deaths. In addition, the intercept and coefficient for the lagged dependent variable were statistically significant. This result indicates that as the number of new COVID-19 deaths increases by 1%, vaccine approval has the effect of decreasing the ATM IV of SPX options by 0.002609. This finding does not support our second hypothesis of a bullish reaction in response to vaccine approval.

Table 14 provides a summary of the event regressions for Johnson & Johnson options. In the first half of panel A in Table 14, we find statistically significant coefficients for the interaction terms for both the level (-0.0153) and the slope (0.2244) at the 1% level,

for the number of new cases. In addition, the intercept and coefficient for the lagged dependent variable are statistically significant. These results indicate that as the number of new COVID-19 cases increases by 1%, the pandemic announcement is associated with a decrease in the level of 0.000153 and an increase in the slope of 0.002244. These findings are consistent with those for SPX options and support our first hypothesis of a bullish reaction in Johnson & Johnson options in response to the pandemic announcement. However, the first half of panel B in Table 14, does not show any statically significant interaction term coefficients for the number of new COVID-19 deaths. This does not support our first hypothesis, and similar to SPX options, suggests that options' traders did not react to this event in the context of COVID-19 deaths. However, as mentioned previously, this is likely due to the absence of significant deaths due to the disease so early on in the pandemic.

[Insert Table 14 about here.]

In the second half of panels A and B in Table 14, we do not find any statistically significant interaction term coefficients across all IV curve factors. This suggests a complete lack of significant action by options' traders when the Pfizer vaccine was approved when taking the number of new COVID-19 cases and deaths into account. These results are mostly consistent with the results for SPX options, but do not support our second hypothesis.

Table 15 presents the event regressions for Pfizer options. In the first half of panel A in Table 15, we observe statistically significant coefficients for the interaction terms of the level (-0.0127) and the slope (0.2657) at the 5% and 1% level, respectively, for the number of new cases. Additionally, the intercept and coefficient for the lagged dependent variable are statistically significant as well. These results indicate that as the number of new COVID-19 cases increases by 1%, the pandemic announcement was associated with a decrease in the level of 0.000127 and an increase in the slope of 0.002657. This represents a bullish reaction and supports our first hypothesis, in that the ATM IV and the cost of put

option protection are reduced for Pfizer options as a result of the announcement, in the context of the number of COVID-19 cases. In contrast, we do not find any statistically significant interaction term coefficients in the first half of panel B in Table 15 for the number of new COVID-19 deaths. Thus, consistent with Johnson & Johnson and SPX options, the announcement of the pandemic by the WHO was not of particular importance to options traders in the context of the number of new COVID-19 deaths.

[Insert Table 15 about here.]

Moving to the second half of panels A and B in Table 15, we do not find any statistically significant interaction term coefficients for both the number of new COVID-19 cases and deaths on the day the Pfizer vaccine was approved. However, these results are again consistent with Johnson & Johnson and SPX options, in that options' traders do not act in response to this event and do not support our second hypothesis. This suggests that vaccine approval does not necessarily change their expectations of the future for Pfizer in the context of the COVID-19 pandemic.

Finally, Table 16 summarises the event regressions for Moderna options. In the first half of both panels A and B in Table 16, we do not find a single statistically significant interaction term coefficient for the number of new COVID-19 cases and deaths. These findings are only consistent with those of the other options with regards to the number of new deaths, and do not support our first hypothesis. The differing characteristics of Moderna and its less well-established status might explain why options traders do not necessarily show any reaction to the announcement of the pandemic in their options. The second half of panels A and B in Table 16 are identical to the results of Johnson & Johnson and Pfizer, in that no statistically significant interaction term coefficients were found across all IV factors. These results again do not support our second hypothesis that news of vaccine approval would induce a bullish reaction in these options.

[Insert Table 16 about here.]

To summarise, we find a statistically significant, positive relationship between the slope of SPX, Johnson & Johnson and Pfizer IV curves and the daily number of new COVID-19 cases and deaths in the U.S. In addition, we find significant bullish reactions to the announcement of the pandemic by the WHO for SPX, Johnson & Johnson and Pfizer, particularly in the context of the number of new COVID-19 cases. The very low number of COVID-19 deaths at this early stage of the pandemic may explain why options' traders did not react to this event to any significant degree. Overall, these results suggest that as the number of new cases and deaths increase, options' traders become more optimistic and reduce the cost of put option protection against downside tail risk, reflected in the increase of the IV curve slope. The announcement of the pandemic also seems to bolster this effect, but only in the context of the number of new cases. These effects are likely due to the acknowledgment by governments and regulatory agencies of the importance and potential scope of COVID-19, thereby pushing them into action to do something against it. Options' traders take this as a positive sign and trade accordingly to improve their future expectations of the broader market and these major pharmaceutical companies. In contrast, Moderna showed a significant relationship with the slope in the opposite direction for both the number of new COVID-19 cases and deaths. In addition, both the announcement of the pandemic and news of vaccine approval did not affect the IV curve factors of Moderna at all. These results may be due to the smaller size and reduced prominence of Moderna in the pharmaceutical industry in the U.S., causing options' traders to have more pessimistic future expectations of their business during COVID-19. Overall, we provide evidence supporting our first hypothesis that the announcement of the pandemic on 12 March 2020 was associated with bullish reactions in SPX, Johnson & Johnson and Pfizer options, while no reaction was seen in the Moderna options. However, we do not find any support for our second hypothesis, which suggests that news of the approval of the Pfizer vaccine was not particularly important to the future expectations of options' traders in the context of the COVID-19 pandemic.

7 Conclusion

This study investigates the IV smirks and their dynamics of Johnson & Johnson, Pfizer, and Moderna options during the COVID-19 Pandemic. By following the methodology in Zhang and Xiang (2008) and Li, Gehricke, and Zhang (2019), we quantify these IV curves over a complete sample period of two years, from 2 January 2019 to 31 December 2020. This analysis yields three factors, the level, slope and curvature, for each day and every available maturity. We then analyse the dynamics of these factors, comparing them to the shape of corresponding IV curves, and further examine their term structure by grouping them by maturity. To study the term structure and time-series dynamics more accurately we calculate the constant maturity IV curve factors by interpolation and extrapolation, in accordance with prior studies using the same methodology. Finally, to investigate the impact of the COVID-19 pandemic on these options, we regress the daily number of new COVID-19 cases and deaths against the constant maturity IV curve factors to establish a baseline relationship. Following which, we study these relationships in the context of two pandemic events, the announcement of the pandemic by the WHO and the approval of the Pfizer vaccine against the virus.

On average, we find a similar left-skewed smirked shape in the IV curves for Johnson & Johnson and Pfizer to those of other U.S. equity options. In contrast, the IV curves for Moderna showed an uncharacteristic right-skewed smirked shape. However, the value of the IV level is usually positive, the slope is mostly negative and the curvature highly positive across all options. The IV smirks were particularly prominent in the earliest available maturities but seemed to lose convexity and flatten out with increasing maturity. In addition, we find that the IV curves of all three of these companies become much steeper with increased convexity in March 2020, compared to before the pandemic. For Johnson & Johnson and Pfizer, the average term structure of the level is relatively flat, the slope shows an increasing trend, and the curvature decreases exponentially. For Moderna, however, the term structure of the level and curvature show a decreasing trend, while that

of the slope decreases initially before increasing towards longer maturities.

In calculating the constant maturity IV curve factors, we find consistent results for all three pharmaceutical companies. The level is positive, the slope is negative, and the curvature is always highly positive. The IV curves predicted from the constant maturity factors all show distinct left-skewed smirked shapes, except for Moderna where it is less prominent but still present. The time-series dynamics of all three companies show significant reactions to the announcement of the COVID-19 pandemic in March 2020 in all of their IV curve factors. In addition, the level seems to experience prolonged volatility for the rest of 2020 following this initial reaction. To compare the behaviour of these companies to the broader market, we also calculate the constant maturity IV curve factors for SPX options. We find that the overall level is always positive with a highly negative slope and curvature that fluctuates around zero. The biggest difference seen in these options compared the pharmaceuticals is that the slope is far more negative, and the curvature is closer to zero. However, similar extreme reactions are seen in the time-series graphs for all constant maturity IV curve factors in response to the announcement of the pandemic.

With the regression analysis, we find statistically significant, positive relationships between the slope of SPX, Johnson & Johnson and Pfizer IV curves and the daily number of new confirmed COVID-19 cases and deaths. We also find significant bullish reactions to the announcement of the pandemic in these options, particularly in the context of the number of new cases but not for the number of new deaths. In contrast, Moderna showed a significant, negative relationship between its slope factor and the number of new COVID-19 cases and deaths, and the pandemic announcement did not seem to produce any reaction in its IV curves. For all the investigated options, no significant reaction was seen in the IV curve slope in response to the approval of the Pfizer vaccine in December 2020. Thus, overall, we find evidence that options' traders see the increase in the number of new COVID-19 cases and deaths as a positive sign, with their behaviour ultimately leading to an increased IV slope for SPX, Johnson & Johnson and Pfizer options. This

has the effect of increasing call option prices, while decreasing put option prices, thereby representing a bullish reaction in these options. We show that the announcement of the pandemic only increases the optimism in these options' traders and that they do not find the number of new deaths early on in the pandemic and the approval of the Pfizer vaccine particularly important.

Overall, we show that COVID-19-induced uncertainy affected the future expectations of options traders for SPX and pharmaceutical options in the U.S. These investors showed mostly bullish reactions at the beginning of the pandemic when it was first announced. However, by late 2020, even the prospect of an effective COVID-19 vaccine did not seem to change their expectations at all, even in the face of increasing cases and deaths due to COVID-19.

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Tables

Table 1: Descriptive summary for options data.

A summary presenting the mean daily number of strike prices, contracts, trading volume and open interest for Johnson & Johnson (A), Pfizer (B), Moderna (C) and SPX (D) options data for the full sample period of 2 January 2019 to 31 December 2020 and by maturity group. These data are summarised post-cleaning.

	Overall	**< 30**	**$30 - 90$**	**$90 - 180$**	**$180 - 360$**	**> 360**
(A) *JNJ Options*						
Number of Observations	378,666	103,200	85,685	43,790	63,244	83,465
Mean number of strikes	56	45	45	26	29	30
Mean number of contracts	751	205	170	87	126	166
Mean daily trading volume	21,739	11,108	6,733	1,862	1,281	768
Mean daily open interest	335,050	78,172	91,592	66,399	60,318	39,223
(B) *PFE Options*						
Number of Observations	252,796	80,667	76,490	34,041	37,496	24,504
Mean number of strikes	51	37	41	30	27	16
Mean number of contracts	502	160	152	68	74	49
Mean daily trading volume	63,609	28,446	20,107	7,877	4,715	2,490
Mean daily open interest	891,724	189,623	240,239	201,240	166,510	95,866
(C) *MRNA Options*						
Number of Observations	207,376	87,188	59,313	23,083	15,503	22,380
Mean number of strikes	50	38	35	22	15	17
Mean number of contracts	411	173	118	46	31	44
Mean daily trading volume	17,541	10,507	4,628	1,363	660	396
Mean daily open interest	119,004	39,173	35,955	25,058	9,293	9,566
(D) *SPX Options*						
Number of Observations	6,338,237	1,845,485	2,115,324	1,450,380	530,545	401,916
Mean number of strikes	356	304	327	307	150	125
Mean number of contracts	12,551	3,654	4,189	2,872	1051	796
Mean daily trading volume	790,518	360,607	276,699	89,629	48,119	16031
Mean daily open interest	13,078,485	3,439,172	4,263,155	2,393,864	1,985,540	1,016,377

Table 2: Descriptive Statistics for COVID-19 Case and Death Measures.

A summary of the descriptive statistics for the daily number of new confirmed COVID-19 cases and deaths, before and after the transformation in accordance with Li et al. (2021).

Variable	**Mean**	**Median**	**Std. Dev.**	**Max**	**Min**
$Cases$	58,608.93	38,927.50	62,730.90	258,979	0
$\ln(Cases + 1)$	9.3681	10.5695	3.5394	12.4645	0
$Deaths$	1,145.78	1,003	786.22	3,933	0
$\ln(Deaths + 1)$	6.5995	6.9117	1.4112	8.2774	0

Table 3: Quantified IV curve parameters for Johnson & Johnson.

A summary of the forward prices $\left(F_t^T\right)$, coefficients $\left(\hat{\beta}\right)$ and factors (γ) from quantifying the IV curves of Johnson & Johnson over the entire sample period of 2 January 2019 to 31 December 2020.

Maturity	**Overall**	**< 30**	**$30 - 90$**	**$90 - 180$**	**$180 - 360$**	**> 360**
			Mean			
F_t^T	139.6695	140.3469	140.2124	140.1194	139.5185	137.9969
$\hat{\beta}_0$	0.2154	0.2143	0.2144	0.2165	0.2201	0.2133
$\hat{\beta}_1$	−0.1500	−0.1551	−0.1881	−0.1510	−0.1361	−0.1071
$\hat{\beta}_2$	0.2848	0.4775	0.4361	0.1727	0.1127	0.0859
γ_0	0.2154	0.2143	0.2144	0.2165	0.2201	0.2133
γ_1	−0.6831	−0.6930	−0.8567	−0.6982	−0.6151	−0.5015
γ_2	1.2712	2.0900	1.9910	0.7590	0.4890	0.3992
			Standard Deviation			
F_t^T	7.8141	7.9627	7.9321	7.6486	7.8047	7.3472
$\hat{\beta}_0$	0.0641	0.0891	0.0708	0.0548	0.0453	0.0288
$\hat{\beta}_1$	0.1250	0.1652	0.1566	0.0836	0.0585	0.0538
$\hat{\beta}_2$	0.4337	0.6123	0.4785	0.1942	0.0720	0.1525
γ_0	0.0641	0.0891	0.0708	0.0548	0.0453	0.0288
γ_1	0.3515	0.4403	0.3780	0.2509	0.1703	0.2496
γ_2	1.3049	1.3734	1.3594	0.6969	0.2356	0.7901
			% Significant Coefficients at 5% level of significance			
$\hat{\beta}_0$	99.93	100.00	99.95	99.61	100.00	100.00
$\hat{\beta}_1$	98.67	96.32	98.51	99.52	100.00	100.00
$\hat{\beta}_2$	97.58	97.91	96.58	98.26	97.81	97.72
			R^2			
Mean $R^2(\%)$	96.71	94.38	96.39	97.78	98.03	98.08
Mean $R^2_{Adj.}(\%)$	96.39	93.84	96.01	97.54	97.86	97.92
			Daily Trading Volume			
Mean Daily Volume	913.71	2,143.00	1,264.11	329.57	151.40	37.40

Table 4: Quantified IV curve parameters for Pfizer.

A summary of the forward prices $\left(F_t^T\right)$, coefficients $\left(\hat{\beta}\right)$ and factors (γ) from quantifying the IV curves of Pfizer over the entire sample period of 2 January 2019 to 31 December 2020.

Maturity	**Overall**	$\mathbf{< 30}$	$\mathbf{30 - 90}$	$\mathbf{90 - 180}$	$\mathbf{180 - 360}$	$\mathbf{> 360}$
			Mean			
F_t^T	37.9050	38.2377	38.2002	37.7290	37.6960	36.9923
$\hat{\beta}_0$	0.2497	0.2581	0.2493	0.2457	0.2441	0.2420
$\hat{\beta}_1$	−0.1009	−0.0985	−0.1242	−0.1031	−0.0980	−0.0626
$\hat{\beta}_2$	0.3891	0.5303	0.5808	0.2512	0.1439	0.0775
γ_0	0.2497	0.2581	0.2493	0.2457	0.2441	0.2420
γ_1	−0.4545	−0.4494	−0.5628	−0.4548	−0.4279	−0.2832
γ_2	1.4795	2.0938	2.1136	0.9511	0.5544	0.3157
			Standard Deviation			
F_t^T	3.1773	3.1290	3.1249	2.9787	3.2114	3.2757
$\hat{\beta}_0$	0.0880	0.1180	0.0910	0.0608	0.0519	0.0426
$\hat{\beta}_1$	0.3769	0.2103	0.6624	0.1055	0.0731	0.0443
$\hat{\beta}_2$	3.4384	0.8458	6.3465	0.1770	0.1018	0.0736
γ_0	0.0880	0.1180	0.0910	0.0608	0.0519	0.0426
γ_1	0.7305	0.5298	1.1990	0.3356	0.2587	0.1908
γ_2	5.7046	1.5023	10.4286	0.5270	0.3203	0.2905
			% Significant Coefficients at 5% level of significance			
$\hat{\beta}_0$	99.92	100.00	99.77	100.00	100.00	99.89
$\hat{\beta}_1$	92.14	89.82	92.33	92.33	96.70	91.81
$\hat{\beta}_2$	95.05	92.52	96.78	99.08	98.07	90.91
			$\boldsymbol{R^2}$			
Mean $R^2(\%)$	94.23	92.55	95.09	97.32	96.80	91.19
Mean $R^2_{Adj.}(\%)$	93.35	91.36	94.44	97.09	96.39	89.53
			Daily Trading Volume			
Mean Daily Volume	4,015.90	6,158.48	4,495.94	4,289.94	1,749.21	775.46

Table 5: Quantified IV curve parameters for Moderna.

A summary of the forward prices $\left(F_t^T\right)$, coefficients $\left(\hat{\beta}\right)$ and factors (γ) from quantifying the IV curves of Moderna over the entire sample period of 2 January 2019 to 31 December 2020.

Maturity	**Overall**	$\mathbf{< 30}$	$\mathbf{30 - 90}$	$\mathbf{90 - 180}$	$\mathbf{180 - 360}$	$\mathbf{> 360}$
			Mean			
F_t^T	52.3261	57.8671	53.3634	42.5403	40.1885	60.8037
$\hat{\beta}_0$	0.9005	0.9677	0.9347	0.8536	0.8071	0.7984
$\hat{\beta}_1$	−0.0229	0.0714	−0.0611	−0.0768	−0.0466	−0.0593
$\hat{\beta}_2$	1.6155	2.5546	2.1124	0.6559	0.3162	0.5237
γ_0	0.9005	0.9677	0.9347	0.8536	0.8071	0.7984
γ_1	−0.0553	0.0298	−0.0947	−0.1143	−0.0677	−0.0706
γ_2	1.6357	2.5505	2.0906	0.7344	0.3641	0.6112
			Standard Deviation			
F_t^T	35.5794	34.7506	35.3868	32.3960	32.8185	38.83037
$\hat{\beta}_0$	0.2209	0.2687	0.2097	0.1911	0.1453	0.1060
$\hat{\beta}_1$	0.4693	0.4936	0.6183	0.2373	0.2005	0.3096
$\hat{\beta}_2$	3.3554	2.0506	4.8776	1.3173	0.6119	3.4405
γ_0	0.2209	0.2687	0.2097	0.1911	0.1453	0.1060
γ_1	0.4600	0.5032	0.5408	0.3140	0.3074	0.3649
γ_2	3.0356	1.8214	4.0288	1.6753	0.6863	3.9936
			% Significant Coefficients at 5% level of significance			
$\hat{\beta}_0$	95.30	88.67	96.25	99.26	99.26	100.00
$\hat{\beta}_1$	56.13	60.39	53.11	55.45	65.19	45.74
$\hat{\beta}_2$	66.00	78.03	68.04	54.34	46.91	65.21
			$\boldsymbol{R^2}$			
Mean $R^2(\%)$	75.45	83.54	74.98	74.25	69.48	64.43
Mean $R^2_{Adj.}(\%)$	68.76	79.77	67.45	66.46	61.68	57.70
			Daily Trading Volume			
Mean Daily Volume	1,631.50	3,693.49	1,358.41	508.55	272.05	86.50

Table 6: Quantified constant maturity IV curve parameters for Johnson & Johnson.

A summary of the forward prices $\left(F_t^T\right)$, coefficients $\left(\hat{\beta}\right)$ and factors (γ) from quantifying the predicted constant maturity IV curves of Johnson & Johnson over the entire sample period of 2 January 2019 to 31 December 2020.

Maturity	**Overall**	**30**	**60**	**90**	**120**	**150**	**180**	**> 360**
				Mean				
F_t^T	140.2805	140.1844	140.0228	139.8011	139.6201	139.4524	138.4425	139.6862
$\hat{\beta}_0$	0.2127	0.2160	0.2178	0.2179	0.2167	0.2161	0.2117	0.2156
$\hat{\beta}_1$	−0.1778	−0.1884	−0.1662	−0.1520	−0.1466	−0.1417	−0.1178	-0.1558
$\hat{\beta}_2$	0.5230	0.3568	0.2362	0.1870	0.1519	0.1308	0.0872	0.2390
γ_0	0.2127	0.2160	0.2178	0.2179	0.2167	0.2161	0.2117	0.2156
γ_1	−0.8053	−0.8603	−0.7646	−0.7001	−0.6802	−0.6580	−0.5579	-0.7183
γ_2	2.3240	1.6086	1.0516	0.8152	0.6649	0.5799	0.3986	1.0642
				Standard Deviation				
F_t^T	7.9399	7.9236	7.8418	7.7688	7.7574	7.7269	7.5117	7.7974
$\hat{\beta}_0$	0.0782	0.0664	0.0605	0.0547	0.0510	0.0477	0.0352	0.0577
$\hat{\beta}_1$	0.1675	0.1355	0.0959	0.0785	0.0702	0.0626	0.0388	0.1038
$\hat{\beta}_2$	0.4699	0.2439	0.2190	0.1340	0.1013	0.0797	0.0802	0.2695
γ_0	0.0782	0.0664	0.0605	0.0547	0.0510	0.0477	0.0352	0.0577
γ_1	0.3951	0.3360	0.2795	0.2390	0.2202	0.1947	0.1465	0.2860
γ_2	1.1519	0.8482	0.8074	0.3981	0.3043	0.2518	0.3848	0.9213

Table 7: Quantified constant maturity IV curve parameters for Pfizer.

A summary of the forward prices $\left(F_t^T\right)$, coefficients $\left(\hat{\beta}\right)$ and factors (γ) from quantifying the predicted constant maturity IV curves of Pfizer over the entire sample period of 2 January 2019 to 31 December 2020.

Maturity	**Overall**	**30**	**60**	**90**	**120**	**150**	**180**	**> 360**
				Mean				
F_t^T	38.2110	38.1794	38.1151	38.0428	37.9768	37.9148	37.6024	38.0060
$\hat{\beta}_0$	0.2540	0.2484	0.2440	0.2426	0.2414	0.2399	0.2370	0.2439
$\hat{\beta}_1$	-0.1341	-0.1148	-0.1126	-0.1142	-0.1115	-0.1094	-0.0906	-0.1124
$\hat{\beta}_2$	0.5585	0.7594	0.3574	0.2593	0.2024	0.1681	0.1061	0.3445
γ_0	0.2540	0.2484	0.2440	0.2426	0.2414	0.2399	0.2370	0.2439
γ_1	-0.5619	-0.5473	-0.5236	-0.5071	-0.4927	-0.4839	-0.4005	-0.5024
γ_2	2.2249	2.2194	1.3383	0.9950	0.7766	0.6518	0.4257	1.2328
				Standard Deviation				
F_t^T	3.1438	3.1391	3.1547	3.1763	3.2008	3.2271	3.3470	3.2021
$\hat{\beta}_0$	0.1036	0.0872	0.0731	0.0663	0.0616	0.0573	0.0452	0.0730
$\hat{\beta}_1$	0.2298	0.7918	0.1765	0.1117	0.0978	0.0862	0.0555	0.3258
$\hat{\beta}_2$	0.9411	6.9546	1.1605	0.1706	0.1405	0.1227	0.0724	2.6970
γ_0	0.1036	0.0872	0.0731	0.0663	0.0616	0.0573	0.0452	0.0730
γ_1	0.5453	1.4588	0.4644	0.3510	0.3154	0.2901	0.2034	0.6544
γ_2	1.5642	11.7679	2.1316	0.4709	0.4080	0.3714	0.2328	4.6105

Table 8: Quantified constant maturity IV curve parameters for Moderna.

A summary of the forward prices $\left(F_t^T\right)$, coefficients $\left(\hat{\beta}\right)$ and factors (γ) from quantifying the predicted constant maturity IV curves of Moderna over the entire sample period of 2 January 2019 to 31 December 2020.

Maturity	**Overall**	**30**	**60**	**90**	**120**	**150**	**180**	**> 360**
				Mean				
F_t^T	40.4061	40.3195	40.3040	40.3004	40.3204	43.4499	52.6849	41.9803
$\hat{\beta}_0$	0.8523	0.8511	0.8472	0.8327	0.8197	0.8168	0.7850	0.8319
$\hat{\beta}_1$	−0.0582	−0.0979	−0.1039	−0.0999	−0.0947	−0.0656	−0.0408	-0.0825
$\hat{\beta}_2$	1.8152	1.4958	1.1066	0.7170	0.5341	0.4357	0.4423	0.9704
γ_0	0.8523	0.8511	0.8472	0.8327	0.8197	0.8168	0.7850	0.8319
γ_1	−0.0942	−0.1339	−0.1454	−0.1389	−0.1305	−0.0903	−0.0489	-0.1161
γ_2	1.9622	1.5452	1.1992	0.8235	0.6163	0.4942	0.5390	1.0684
				Standard Deviation				
F_t^T	32.6710	32.6558	32.6771	32.6981	32.7151	33.7169	35.1331	33.2531
$\hat{\beta}_0$	0.2263	0.2268	0.2149	0.1971	0.1813	0.1829	0.2131	0.2077
$\hat{\beta}_1$	0.5137	0.6053	0.3437	0.2362	0.1939	0.1801	0.1545	0.3686
$\hat{\beta}_2$	2.9397	4.3507	2.2341	1.1272	0.7466	0.5630	1.2277	2.3892
γ_0	0.2263	0.2268	0.2149	0.1971	0.1813	0.1829	0.2131	0.2077
γ_1	0.4873	0.5257	0.3868	0.3102	0.2672	0.2697	0.1893	0.3773
γ_2	2.5407	3.3922	2.0863	1.4221	0.9188	0.6130	1.4144	2.0986

Table 9: Quantified constant maturity IV curve parameters for SPX options.

A summary of the forward prices $\left(F_t^T\right)$, coefficients $\left(\hat{\beta}\right)$ and factors (γ) from quantifying the predicted constant maturity IV curves of SPX options over the entire sample period of 2 January 2019 to 31 December 2020.

Maturity	**Overall**	**30**	**60**	**90**	**120**	**150**	**180**	**> 360**
				Mean				
F_t^T	3,064.6681	3,063.8387	3,063.0163	3,062.2951	3,061.3727	3,060.4358	,3054.8131	3,061.4914
$\hat{\beta}_0$	0.2003	0.2059	0.2076	0.2088	0.2078	0.2071	0.2027	0.2057
$\hat{\beta}_1$	−0.5146	−0.4698	−0.4248	−0.3891	−0.3756	−0.3655	−0.2869	-0.4038
$\hat{\beta}_2$	−0.0156	−0.0083	−0.0122	−0.0098	−0.0236	−0.0369	−0.0426	-0.0213
γ_0	0.2003	0.2059	0.2076	0.2088	0.2078	0.2071	0.2027	0.2057
γ_1	−2.5623	−2.2952	−2.0542	−1.8555	−1.7824	−1.7346	−1.3647	-1.9502
γ_2	0.0709	0.0060	−0.0318	−0.0215	−0.0690	−0.1242	−0.1471	-0.0452
				Standard Deviation				
F_t^T	292.2363	291.4310	290.3593	289.3653	288.3734	287.3127	280.3179	288.2796
$\hat{\beta}_0$	0.1009	0.0902	0.0820	0.0754	0.0700	0.0664	0.0489	0.0778
$\hat{\beta}_1$	0.3074	0.2498	0.2098	0.1837	0.1788	0.1745	0.1584	0.2251
$\hat{\beta}_2$	0.5303	0.2920	0.2060	0.1748	0.1691	0.2120	0.2575	0.2877
γ_0	0.1009	0.0902	0.0820	0.0754	0.0700	0.0664	0.0489	0.0778
γ_1	0.4297	0.3582	0.2951	0.2658	0.2672	0.2739	0.4152	0.4954
γ_2	0.9391	0.6250	0.4598	0.4422	0.4603	0.5364	0.8657	0.6499

Table 10: Impact of COVID-19 on IV curve factors I

The results of estimating ordinary least square regressions to document the relationship between daily new confirmed COVID-19 case and death measures, and the 30-day constant maturity IV curve level (γ_0), slope (γ_1) and curvature (γ_2). These results are reported for SPX (Panel A) and Johnson & Johnson (Panel B) options.

	$\gamma_{0,t}$	$\gamma_{1,t}$	$\gamma_{2,t}$	$\gamma_{0,t}$	$\gamma_{1,t}$	$\gamma_{2,t}$
(A) *SPX Options*						
Intercept	0.0265^{***}	-1.2774^{***}	-0.4567^{**}	0.0680^{***}	-1.4271^{***}	-1.3310^{***}
	(2.9626)	(−6.1905)	(−2.4821)	(3.4961)	(−5.9237)	(−3.7993)
$\ln(Cases+1)_{t-1}$	−0.0009	0.0241^{***}	0.0472^{**}			
	(−1.2695)	(2.9606)	(2.5592)			
$\ln(Deaths+1)_{t-1}$				-0.0056^{***}	0.0638^{***}	0.2018^{***}
				(−2.6079)	(3.0949)	(3.9063)
$\gamma_{X,t-1}$	0.9240^{***}	0.6057^{***}	0.6833^{***}	0.8784^{***}	0.6180^{***}	0.5962^{***}
	(40.8453)	(9.5913)	(11.7215)	(31.8471)	(9.7014)	(9.6133)
Obs.	188	188	188	168	168	168
$R^2(\%)$	90.07	43.07	47.68	89.53	43.73	51.60
$R^2_{Adj.}(\%)$	89.97	42.46	47.12	89.40	43.05	51.02
(B) *JNJ Options*						
Intercept	0.0287^{***}	-0.2521^{***}	1.2862^{***}	0.0652^{***}	-0.4351^{***}	1.3410^{***}
	(3.2347)	(−3.3689)	(4.2995)	(3.4942)	(−3.3520)	(2.8986)
$\ln(Cases+1)_{t-1}$	−0.0007	0.0145^{**}	0.0114			
	(−1.0095)	(2.4083)	(0.4376)			
$\ln(Deaths+1)_{t-1}$				-0.0046^{*}	0.0470^{***}	−0.0049
				(−2.3025)	(2.870)	(−0.0769)
$\gamma_{X,t-1}$	0.9126^{***}	0.8578^{***}	0.5245^{***}	0.8671^{***}	0.8377^{***}	0.5595^{***}
	(36.9904)	(18.3743)	(6.0446)	(28.9958)	(17.4127)	(6.6594)
Obs.	188	188	188	168	168	168
$R^2(\%)$	88.10	69.08	18.16	87.85	75.29	21.45
$R^2_{Adj.}(\%)$	87.97	68.75	17.28	87.70	74.99	20.50

*, **, *** denote significance at the 10%, 5%, and 1% levels, respectively.

Corresponding t-statistics are shown in parentheses.

Table 11: Impact of COVID-19 on IV curve factors II

The results of estimating ordinary least square regressions to document the relationship between daily new confirmed COVID-19 case and death measures, and the 30-day constant maturity IV curve level (γ_0), slope (γ_1) and curvature (γ_2). These results are reported for Pfizer (Panel A) and Moderna (Panel B) options.

	$\gamma_{0,t}$	$\gamma_{1,t}$	$\gamma_{2,t}$	$\gamma_{0,t}$	$\gamma_{1,t}$	$\gamma_{2,t}$
(A) *PFE Options*						
Intercept	0.0230^{**}	-0.3089^{***}	1.8045^{***}	0.0613^{***}	-0.4306^{***}	2.3664^{**}
	(2.2080)	(−3.6274)	(3.5573)	(2.9592)	(−2.7708)	(2.4159)
$\ln(Cases+1)_{t-1}$	−0.0008	0.0255^{***}	0.0171			
	(−0.9633)	(3.1657)	(0.3751)			
$\ln(Deaths+1)_{t-1}$				-0.0051^{**}	0.0564^{**}	−0.0504
				(−2.3037)	(2.5471)	(−0.3828)
$\gamma_{X,t-1}$	0.9585^{***}	0.7515^{***}	0.2101^{**}	0.9240^{***}	0.7492^{***}	0.1972^{**}
	(33.6483)	(18.8460)	(2.5443)	(29.4538)	(17.9455)	(2.1745)
Obs.	188	188	188	168	168	168
$R^2(\%)$	87.32	71.90	3.44	85.57	72.11	3.40
$R^2_{Adj.}(\%)$	87.19	71.60	2.39	85.39	71.77	2.22
(B) *MRNA Options*						
Intercept	0.1427^{***}	0.2526^{***}	0.8779^{**}	0.1667^{***}	0.2506^{**}	0.8882
	(4.4735)	(3.5461)	(2.5680)	(3.7222)	(2.2166)	(1.4333)
$\ln(Cases+1)_{t-1}$	−0.0007	-0.0226^{***}	0.1093^{***}			
	(−0.4207)	(−5.4323)	(2.9929)			
$\ln(Deaths+1)_{t-1}$				−0.0024	-0.0350^{**}	0.1921^{**}
				(−0.6765)	(−2.1205)	(2.1430)
$\gamma_{X,t-1}$	0.8614^{***}	0.4670^{***}	0.3852^{***}	0.8467^{***}	0.5687^{***}	0.3363^{***}
	(30.1119)	(7.2156)	(5.1721)	(30.0428)	(8.9547)	(4.3884)
Obs.	188	188	188	168	168	168
$R^2(\%)$	83.21	33.48	24.04	86.95	40.61	14.40
$R^2_{Adj.}(\%)$	83.03	32.76	23.22	86.79	39.89	13.37

*, **, *** denote significance at the 10%, 5%, and 1% levels, respectively.

Corresponding t-statistics are shown in parentheses.

Table 12: Correlation matrix of regression variables.
Correlations of the 30-day constant maturity IV curve level (γ_0), slope (γ_1) and curvature (γ_2) for each set of options, and the logged daily number of new COVID-19 cases and deaths in the U.S. These are reported for SPX (Panel A), Johnson & Johnson (Panel B), Pfizer (Panel C) and Moderna (Panel D) options.

	γ_0	γ_1	γ_2	$\ln(Cases+1)$	$\ln(Deaths+1)$
(A) *SPX Options*					
γ_0	1.0000				
γ_1	−0.1209	1.0000			
γ_2	−0.4205	0.6630	1.0000		
$\ln(Cases+1)$	−0.5456	0.3270	0.4240	1.0000	
$\ln(Deaths+1)$	−0.4825	0.3127	0.4627	0.8884	1.0000
(B) *JNJ Options*					
γ_0	1.0000				
γ_1	−0.6767	1.0000			
γ_2	0.1638	−0.0911	1.0000		
$\ln(Cases+1)$	−0.5061	0.6942	0.0861	1.0000	
$\ln(Deaths+1)$	−0.4973	0.5538	0.0845	0.8884	1.0000
(C) *PFE Options*					
γ_0	1.0000				
γ_1	−0.2856	1.0000			
γ_2	−0.1418	0.1567	1.0000		
$\ln(Cases+1)$	−0.1592	0.6129	−0.0797	1.0000	
$\ln(Deaths+1)$	−0.2842	0.3979	−0.1035	0.8884	1.0000
(D) *MRNA Options*					
γ_0	1.0000				
γ_1	0.4683	1.0000			
γ_2	−0.1920	−0.3511	1.0000		
$\ln(Cases+1)$	−0.5124	−0.3584	0.1562	1.0000	
$\ln(Deaths+1)$	−0.4216	−0.3250	0.1651	0.8884	1.0000

Table 13: Impact of COVID-19 cases and deaths on SPX IV curve factors during pandemic events.
The results of estimating ordinary least square regressions to document the influence of the pandemic announcement (E1) and vaccine approval (E2) on the relationship between daily new confirmed COVID-19 case and death measures, and the 30-day constant maturity IV curve level (γ_0), slope (γ_1) and curvature (γ_2). These results are reported for the number of new cases (Panel A) and deaths (Panel B) for SPX options.

	E1: 12/03/2020			**E2: 11/12/2020**		
	$\gamma_{0,t}$	$\gamma_{1,t}$	$\gamma_{2,t}$	$\gamma_{0,t}$	$\gamma_{1,t}$	$\gamma_{2,t}$

Table 14: Impact of COVID-19 cases and deaths on Johnson & Johnson IV curve factors during pandemic events.
The results of estimating ordinary least square regressions to document the influence of the pandemic announcement (E1) and vaccine approval (E2) on the relationship between daily new confirmed COVID-19 case and death measures, and the 30-day constant maturity IV curve level (γ_0), slope (γ_1) and curvature (γ_2). These results are reported for the number of new cases (Panel A) and deaths (Panel B) for Johnson & Johnson options.

	E1: 12/03/2020			**E2: 11/12/2020**		
	$\gamma_{0,t}$	$\gamma_{1,t}$	$\gamma_{2,t}$	$\gamma_{0,t}$	$\gamma_{1,t}$	$\gamma_{2,t}$
(A) *New Cases*						
Intercept	0.0270^{***}	-0.3447^{***}	1.4178^{***}	0.0273^{***}	-0.2623^{***}	1.3038^{***}
	(3.0167)	(−4.8250)	(4.3983)	(3.1145)	(−3.4874)	(4.3853)
ED_{t-1}	0.0684^{*}	-1.8115^{***}	1.6294	−0.1896	2.9667	2.0584
	(1.9463)	(−5.7700)	(1.5186)	(−0.1300)	(0.2332)	(0.0367)
$\ln(Cases+1)_{t-1}$	0.0097^{***}	-0.0485^{*}	−0.1442	−0.0006	0.0135^{**}	0.0131
	(2.7441)	(−1.6598)	(−1.1122)	(−0.8597)	(2.2742)	(0.4942)
$(\ln(Cases+1)\cdot ED)_{t-1}$	-0.0153^{***}	0.2244^{***}	0.0035	0.0155	−0.2317	−0.1906
	(−3.0254)	(4.9054)	(0.0220)	(0.1307)	(−0.2245)	(−0.0419)
$\gamma_{X,t-1}$	0.8647^{***}	0.6075^{***}	0.4871^{***}	0.9143^{***}	0.8371^{***}	0.5168^{***}
	(27.1714)	(9.8222)	(5.5158)	(36.9273)	(16.4404)	(5.8541)
Obs.	189	189	189	189	189	189
$R^2(\%)$	88.74	73.79	20.10	88.15	69.25	18.44
$R^2_{Adj.}(\%)$	88.50	73.22	18.36	87.89	68.58	16.67
(B) *New Deaths*						
Intercept	0.1228^{***}	−0.3610	0.1755	0.0790^{***}	-0.5167^{***}	1.2433^{**}
	(3.4341)	(−1.2434)	(0.1368)	(14.4639)	(−3.7169)	(2.5587)
ED_{t-1}	−0.0538	−0.5099	2.4910	0.1054	−4.0658	2.6755
	(−1.2074)	(−1.5604)	(1.6427)	(0.12642)	(−0.6078)	(0.0875)
$\ln(Deaths+1)_{t-1}$	-0.0448^{*}	0.0303	0.4570	-0.0062^{***}	0.0538^{***}	0.0166
	(−1.7550)	(0.1515)	(0.4944)	(−2.9581)	(3.1599)	(0.2436)
$(\ln(Deaths+1)\cdot ED)_{t-1}$	0.0396	0.0734	−0.6285	−0.0121	0.5134	−0.3629
	(1.5189)	(0.3639)	(−0.6749)	(−0.1180)	(0.6229)	(−0.0963)
$\gamma_{X,t-1}$	0.8690^{***}	0.7980^{***}	0.5127^{***}	0.8578^{***}	0.8045^{***}	0.5475^{***}
	(26.0217)	(16.1647)	(5.9567)	(28.8168)	(15.2182)	(6.3764)
Obs.	168	168	168	168	168	168
$R^2(\%)$	88.24	76.42	23.70	88.10	75.80	21.68
$R^2_{Adj.}(\%)$	87.95	75.84	21.83	87.81	75.20	19.76

*, **, *** denote significance at the 10%, 5%, and 1% levels, respectively.

Corresponding t-statistics are shown in parentheses.

Table 15: Impact of COVID-19 cases and deaths on Pfizer IV curve factors during pandemic events.
The results of estimating ordinary least square regressions to document the influence of the pandemic announcement (E1) and vaccine approval (E2) on the relationship between daily new confirmed COVID-19 case and death measures, and the 30-day constant maturity IV curve level (γ_0), slope (γ_1) and curvature (γ_2). These results are reported for the number of new cases (Panel A) and deaths (Panel B) for Pfizer options.

	E1: 12/03/2020			**E2: 11/12/2020**		
	$\gamma_{0,t}$	$\gamma_{1,t}$	$\gamma_{2,t}$	$\gamma_{0,t}$	$\gamma_{1,t}$	$\gamma_{2,t}$
(A) *New Cases*						
Intercept	0.0174^{*}	-0.2739^{***}	1.2455^{**}	0.0220^{**}	-0.3063^{***}	1.7472^{***}
	(1.6666)	(−3.3078)	(2.3942)	(2.1400)	(−3.6744)	(3.4901)
ED_{t-1}	0.0596^{*}	-1.9066^{***}	−2.9582	−0.7568	17.6511	−37.3518
	(1.6700)	(−4.82322)	(−1.5024)	(−0.4224)	(1.0658)	(−0.3702)
$\ln(Cases+1)_{t-1}$	0.0076^{*}	-0.0711^{*}	0.7222^{***}	−0.0006	0.0231^{***}	0.0279
	(1.7686)	(−1.8964)	(3.1704)	(−0.6901)	(2.9335)	(0.6115)
$(\ln(Cases+1)\cdot ED)_{t-1}$	-0.0127^{**}	0.2657^{***}	−0.3942	0.0605	−1.4129	2.9764
	(−2.3545)	(4.7391)	(−1.3622)	(0.4163)	(−1.0516)	(0.3636)
$\gamma_{X,t-1}$	0.9367^{***}	0.5906^{***}	0.2509^{***}	0.9570^{***}	0.7355^{***}	0.2052^{**}
	(31.2291)	(11.9147)	(2.9913)	(33.3898)	(18.1270)	(2.4860)
Obs.	189	189	189	189	189	189
$R^2(\%)$	87.81	75.32	10.36	87.50	72.61	4.03
$R^2_{Adj.}(\%)$	87.54	74.78	8.39	87.23	72.01	1.92
(B) *New Deaths*						
Intercept	0.0754^{*}	−0.1726	0.6704	0.0675^{***}	-0.5072^{***}	2.2000^{**}
	(1.6924)	(−0.4119)	(0.2671)	(3.1416)	(−3.1284)	(2.1316)
ED_{t-1}	0.0204	−0.4959	−2.6821	−0.0196	−6.1276	3.0206
	(0.3834)	(−1.0217)	(−0.8950)	(−0.0188)	(−0.6279)	(0.0493)
$\ln(Deaths+1)_{t-1}$	−0.0165	−0.1716	2.4567	-0.0058^{**}	0.0633^{***}	−0.0197
	(−0.5200)	(−0.5745)	(1.3669)	(−2.4749)	(2.7780)	(−0.1417)
$(\ln(Deaths+1)\cdot ED)_{t-1}$	0.0071	0.2601	−1.9239	0.0018	0.7814	−0.4461
	(0.2224)	(0.8628)	(−1.0586)	(0.0139)	(0.6499)	(−0.0591)
$\gamma_{X,t-1}$	0.9125^{***}	0.7344^{***}	0.2858^{***}	0.9228^{***}	0.7250^{***}	0.1975^{**}
	(27.5326)	(17.4408)	(3.0887)	(29.4635)	(17.0903)	(2.1776)
Obs.	168	168	168	168	168	168
$R^2(\%)$	85.84	72.76	10.69	85.73	73.13	3.74
$R^2_{Adj.}(\%)$	85.48	72.08	8.48	85.38	72.46	1.35

*, **, *** denote significance at the 10%, 5%, and 1% levels, respectively.

Corresponding t-statistics are shown in parentheses.

Table 16: Impact of COVID-19 cases and deaths on Moderna IV curve factors during pandemic events.

The results of estimating ordinary least square regressions to document the influence of the pandemic announcement (E1) and vaccine approval (E2) on the relationship between daily new confirmed COVID-19 case and death measures, and the 30-day constant maturity IV curve level (γ_0), slope (γ_1) and curvature (γ_2). These results are reported for the number of new cases (Panel A) and deaths (Panel B) for Moderna options.

	E1: 12/03/2020			**E2: 11/12/2020**		
	$\gamma_{0,t}$	$\gamma_{1,t}$	$\gamma_{2,t}$	$\gamma_{0,t}$	$\gamma_{1,t}$	$\gamma_{2,t}$
(A) *New Cases*						
Intercept	0.1442^{***}	0.1801^{**}	0.9330^{**}	0.1422^{***}	0.2373^{***}	0.8552^{**}
	(4.4367)	(2.3766)	(2.4479)	(4.5657)	(3.2962)	(2.5161)
ED_{t-1}	0.0217	0.2799	1.3312	0.0339	−8.8532	53.2621
	(0.2688)	(1.0093)	(0.9390)	(0.0092)	(−0.6076)	(0.7185)
$\ln(Cases+1)_{t-1}$	−0.0017	0.0274	−0.0193	−0.0005	-0.0217^{***}	0.1142^{***}
	(−0.1819)	(0.7927)	(−0.1115)	(−0.3101)	(−3.0286)	(3.0919)
$(\ln(Cases+1)\cdot ED)_{t-1}$	−0.0010	−0.0689	0.0061	−0.0039	0.7284	−4.3549
	(−0.0799)	(−1.5941)	(0.0284)	(−0.0133)	(0.6161)	(−0.7241)
$\gamma_{X,t-1}$	0.8595^{***}	0.4488^{***}	0.3677^{***}	0.8610^{***}	0.4612^{***}	0.3814^{***}
	(25.5507)	(6.6679)	(4.8519)	(30.1382)	(6.9858)	(5.1110)
Obs.	189	189	189	189	189	189
$R^2(\%)$	83.68	33.38	24.99	83.70	33.10	24.77
$R^2_{Adj.}(\%)$	83.32	31.94	23.36	83.34	31.65	23.13
(B) *New Deaths*						
Intercept	0.2348^{***}	0.7022^{**}	−1.6368	0.1758^{***}	0.3099^{**}	0.7044
	(3.1373)	(2.2273)	(−0.8784)	(3.7742)	(2.5116)	(1.0716)
ED_{t-1}	−0.0248	−0.4374	3.3513	0.17856	1.2499	−11.5422
	(−0.3221)	(−1.2063)	(1.6050)	(0.1142)	(0.1684)	(−0.2702)
$\ln(Deaths+1)_{t-1}$	−0.0562	-0.3890^{*}	1.7662	−0.0029	-0.0438^{**}	0.2228^{**}
	(−1.1898)	(−1.7212)	(1.3363)	(−0.7743)	(−2.4514)	(2.3380)
$(\ln(Deaths+1)\cdot ED)_{t-1}$	0.0487	0.3528	−1.6962	−0.0237	−0.1389	1.3596
	(1.0228)	(1.5486)	(−1.2761)	(−0.1229)	(−0.1518)	(0.2583)
$\gamma_{X,t-1}$	0.8402^{***}	0.5798^{***}	0.3418^{***}	0.8424^{***}	0.5467^{***}	0.3281^{***}
	(29.1756)	(8.9176)	(4.2814)	(29.5231)	(8.3394)	(4.2486)
Obs.	168	168	168	168	168	168
$R^2(\%)$	87.15	41.56	15.84	87.02	41.28	14.99
$R^2_{Adj.}(\%)$	86.84	40.12	13.77	86.70	0.3984	12.90

*, **, *** denote significance at the 10%, 5%, and 1% levels, respectively.

Corresponding t-statistics are shown in parentheses.

Figures

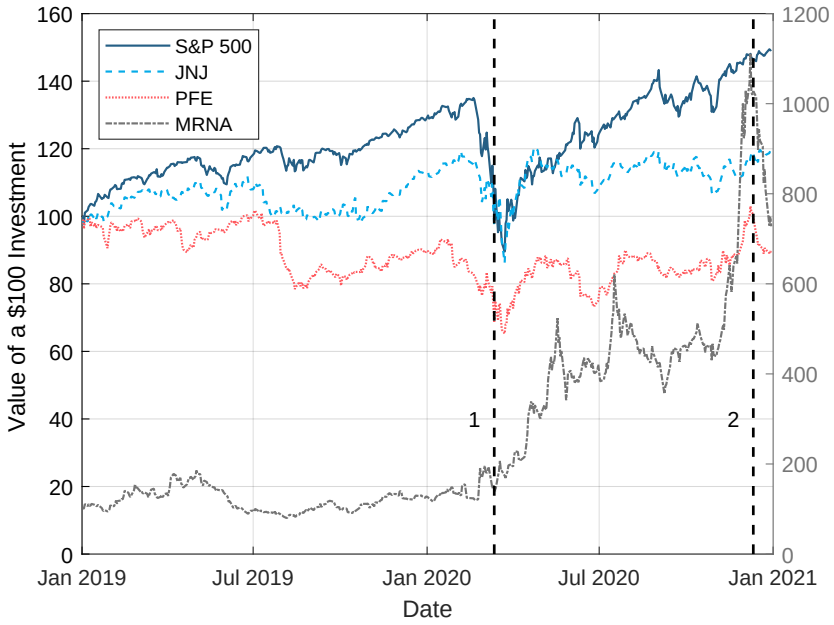


Figure 1: Performance of JNJ, PFE and MRNA compared to the S&P 500 (2019/20).
The hypothetical performance of a $100 investment in the S&P 500, Johnson & Johnson (JNJ), Pfizer (PFE) and Moderna (MRNA - right axis) from 2 January 2019 to 31 December 2020. Daily returns excluding dividends are used. (1) 12 March 2020 - The WHO announces COVID-19 as a pandemic. (2) 11 December 2020 - Pfizer vaccine receives emergency use authorisation.

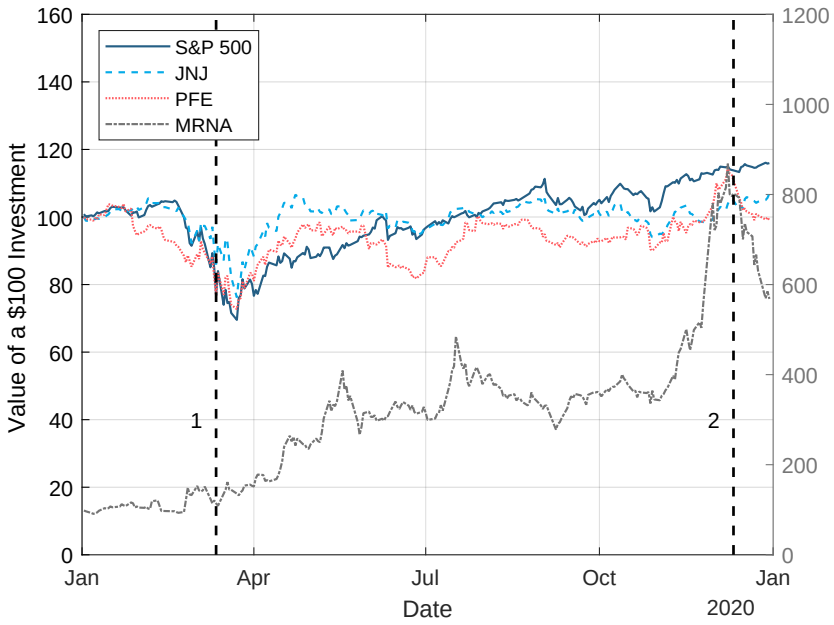
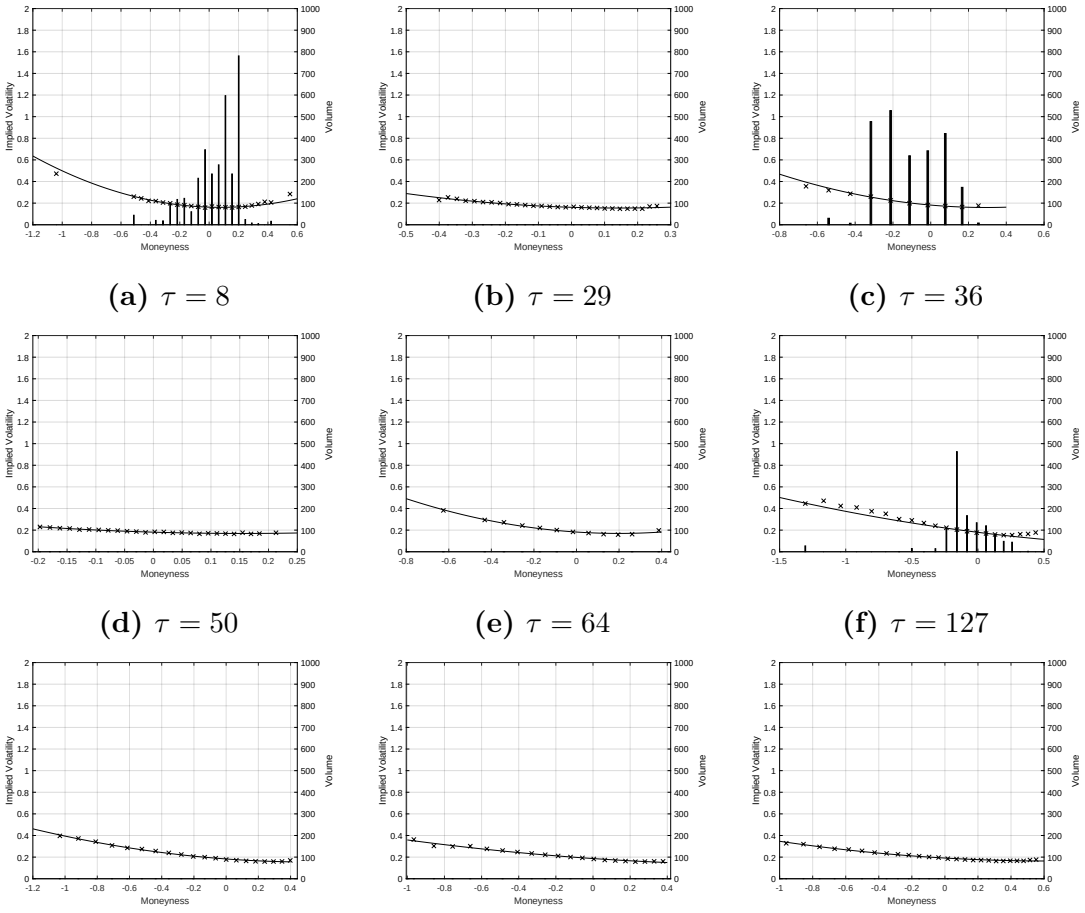


Figure 2: Performance of JNJ, PFE and MRNA compared to the S&P 500 (2020).
The hypothetical performance of a $100 investment in the S&P 500, Johnson & Johnson (JNJ), Pfizer (PFE) and Moderna (MRNA - right axis) from 1 January 2020 to 31 December 2020. Daily returns excluding dividends are used. (1) 12 March 2020 - The WHO announces COVID-19 as a pandemic. (2) 11 December 2020 - Pfizer vaccine receives emergency use authorisation.

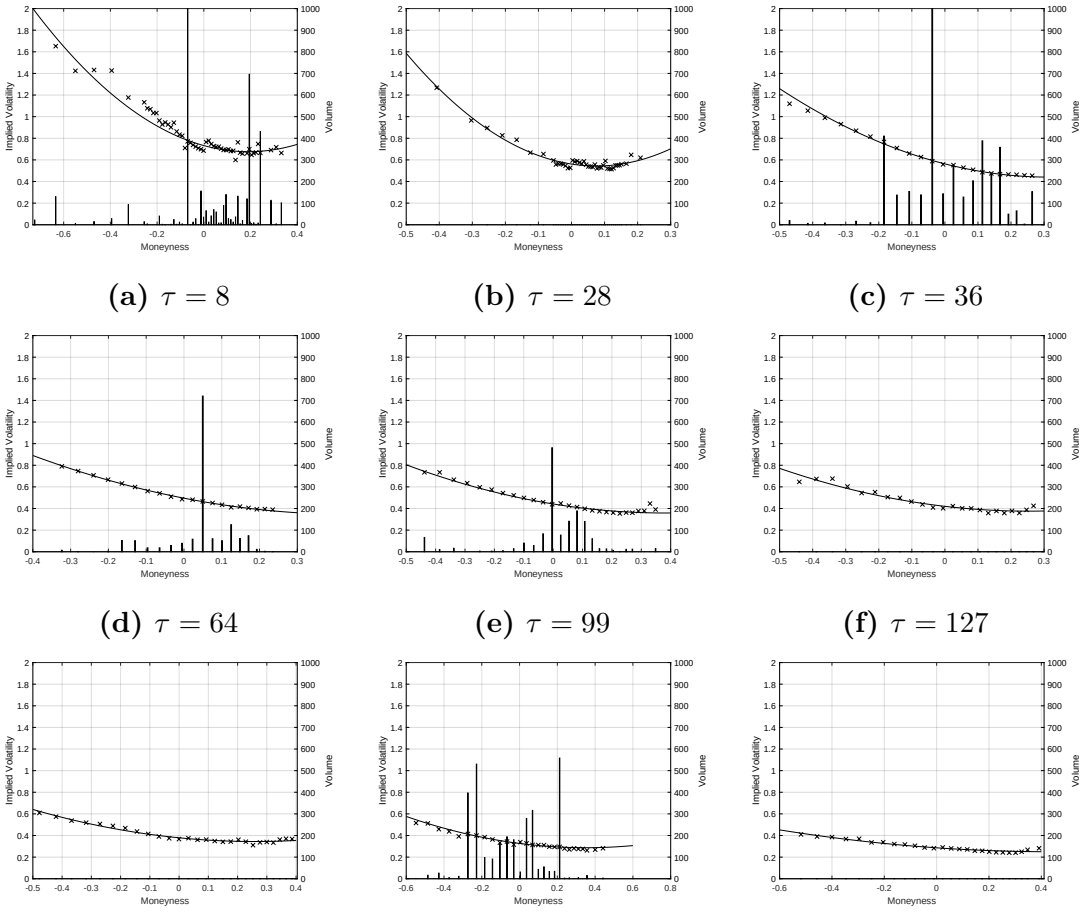


(a) $\tau = 8$ **(b)** $\tau = 29$ **(c)** $\tau = 36$

(d) $\tau = 50$ **(e)** $\tau = 64$ **(f)** $\tau = 127$

(g) $\tau = 217$ **(h)** $\tau = 280$ **(i)** $\tau = 490$

Figure 3: Johnson & Johnson IV curves on 12 September 2019.
Market and fitted IV curves are shown for the available maturities (τ) of 8, 29, 36, 50, 64, 127, 217, 280 and 490 days in panels a-i, respectively. Crosses represent market IVs, solid lines represent fitted IV curves, and bars represent trading volumes. IV – Implied Volatility

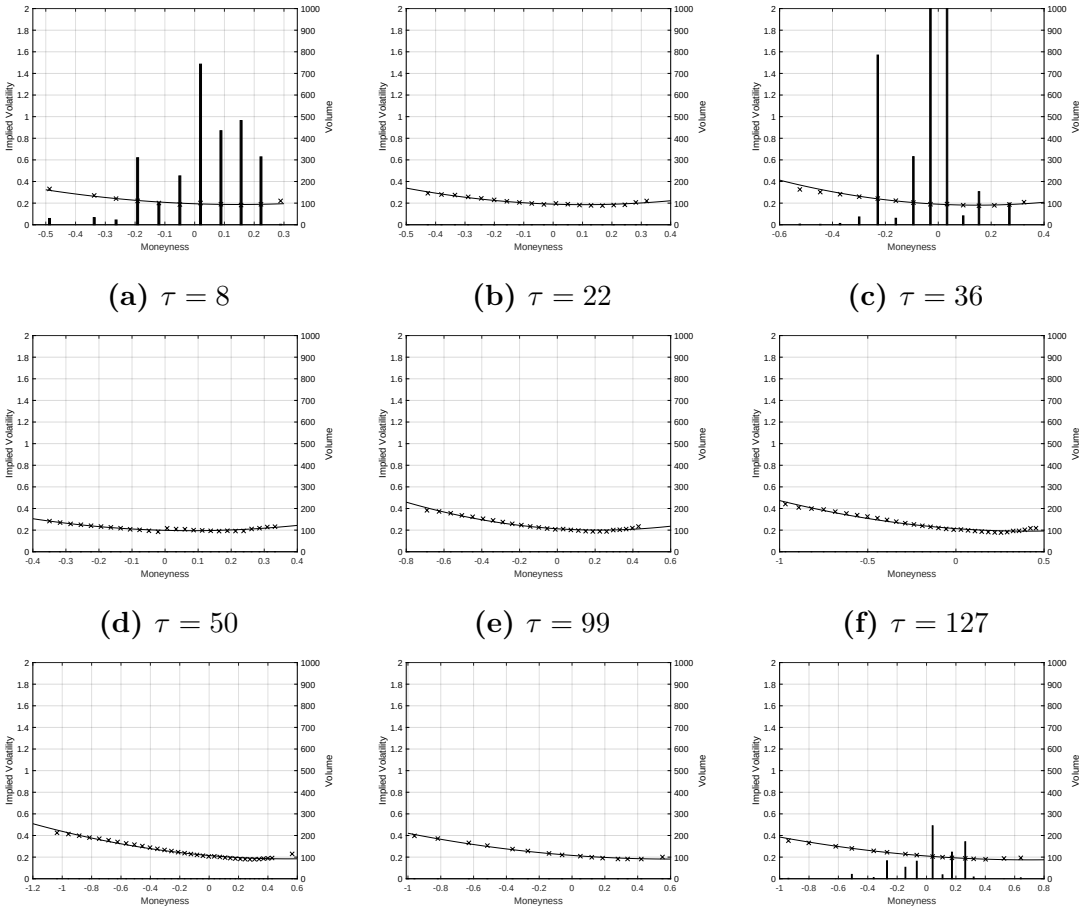


(a) $\tau = 8$ **(b)** $\tau = 28$ **(c)** $\tau = 36$

(d) $\tau = 64$ **(e)** $\tau = 99$ **(f)** $\tau = 127$

(g) $\tau = 190$ **(h)** $\tau = 309$ **(i)** $\tau = 554$

Figure 4: Johnson & Johnson IV curves on 12 March 2020.
Market and fitted IV curves are shown for the available maturities (τ) of 8, 28, 36, 64, 99, 127, 190, 309 and 554 days in panels a-i, respectively. Crosses represent market IVs, solid lines represent fitted IV curves, and bars represent trading volumes. IV – Implied Volatility

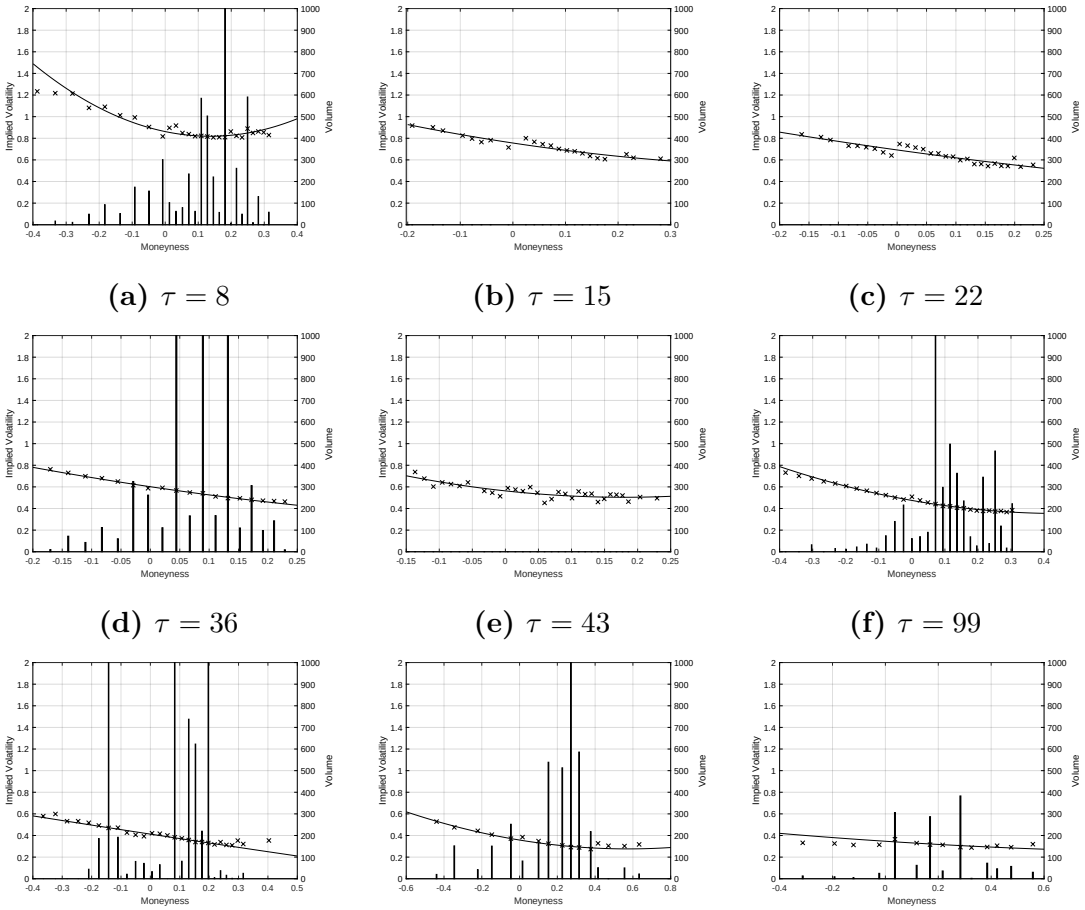


(a) $\tau = 8$ **(b)** $\tau = 22$ **(c)** $\tau = 36$

(d) $\tau = 50$ **(e)** $\tau = 99$ **(f)** $\tau = 127$

(g) $\tau = 189$ **(h)** $\tau = 280$ **(i)** $\tau = 490$

Figure 5: Pfizer IV curves on 12 September 2019.
Market and fitted IV curves are shown for the available maturities (τ) of 8, 22, 36, 50, 99, 127, 189, 280 and 490 days in panels a-i, respectively. Crosses represent market IVs, solid lines represent fitted IV curves, and bars represent trading volumes. IV – Implied Volatility

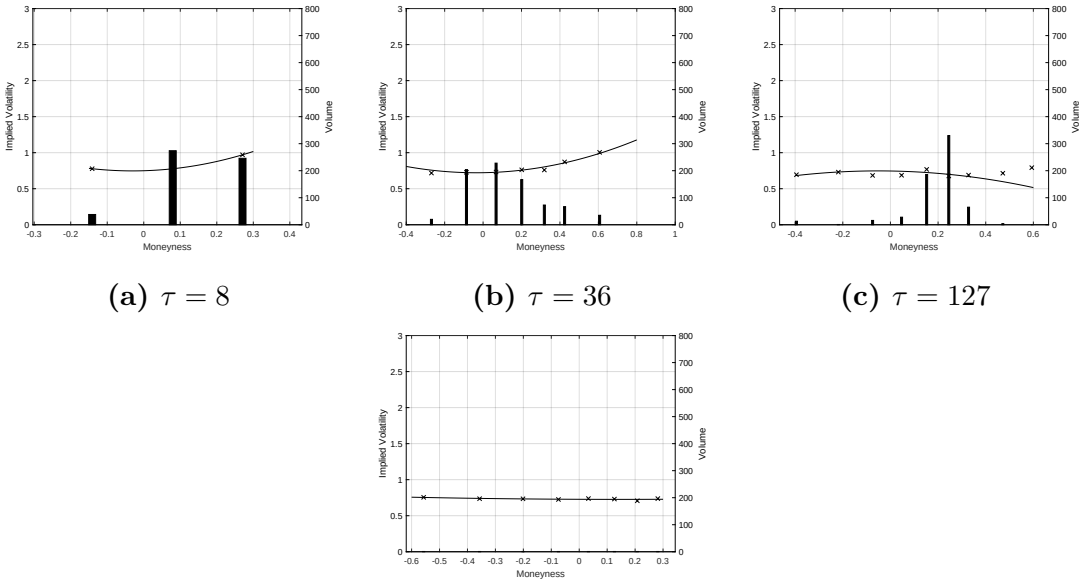


(a) $\tau = 8$ **(b)** $\tau = 15$ **(c)** $\tau = 22$

(d) $\tau = 36$ **(e)** $\tau = 43$ **(f)** $\tau = 99$

(g) $\tau = 190$ **(h)** $\tau = 309$ **(i)** $\tau = 680$

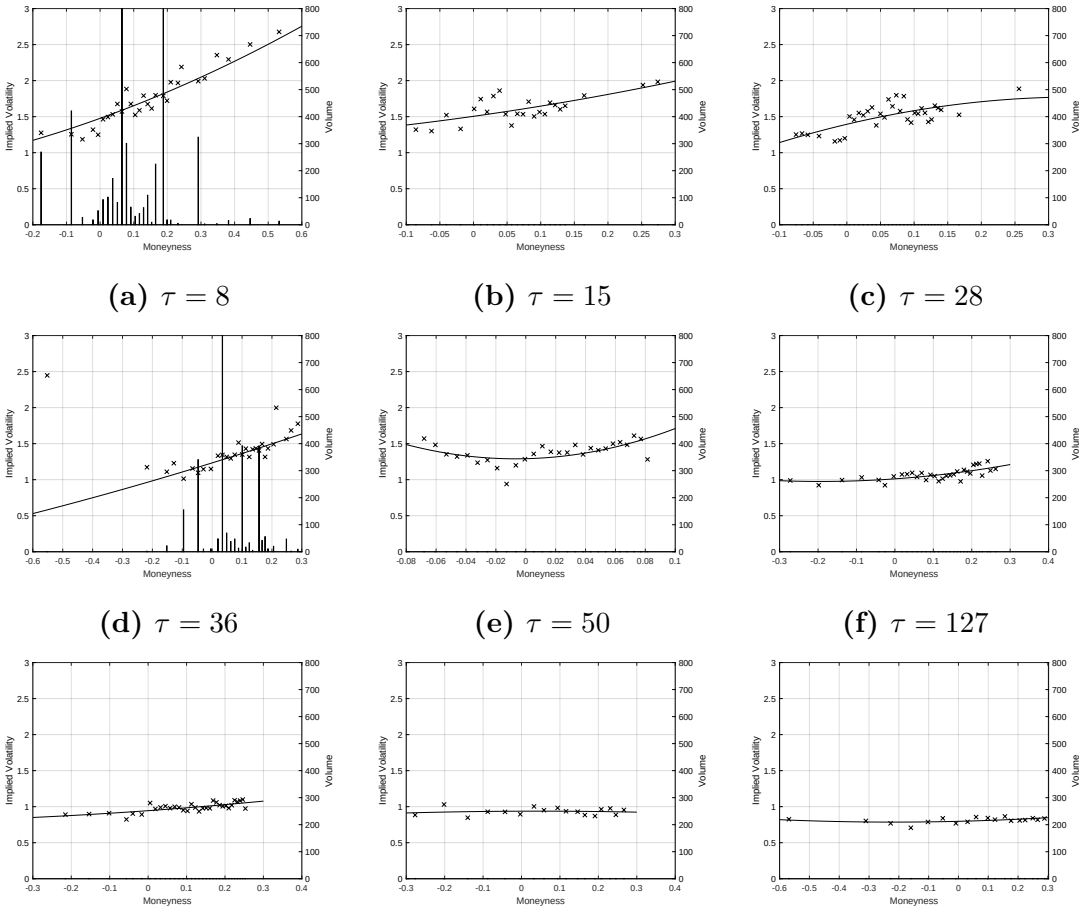
Figure 6: Pfizer IV curves on 12 March 2020.
Market and fitted IV curves are shown for the available maturities (τ) of 8, 15, 22, 36, 43, 99, 190, 309 and 680 days in panels a-i, respectively. Crosses represent market IVs, solid lines represent fitted IV curves, and bars represent trading volumes. IV – Implied Volatility



(a) $\tau = 8$ **(b)** $\tau = 36$ **(c)** $\tau = 127$

(d) $\tau = 217$

Figure 7: Moderna IV curves on 12 September 2019.
Market and fitted IV curves are shown for the available maturities (τ) of 8, 36, 127 and 217 days in panels a-d, respectively. Crosses represent market IVs, solid lines represent fitted IV curves, and bars represent trading volumes. IV – Implied Volatility



(a) $\tau = 8$ **(b)** $\tau = 15$ **(c)** $\tau = 28$

(d) $\tau = 36$ **(e)** $\tau = 50$ **(f)** $\tau = 127$

(g) $\tau = 218$ **(h)** $\tau = 309$ **(i)** $\tau = 680$

Figure 8: Moderna IV curves on 12 March 2020.
Market and fitted IV curves are shown for the available maturities (τ) of 8, 15, 28, 36, 50, 127, 218, 309 and 680 days in panels a-i, respectively. Crosses represent market IVs, solid lines represent fitted IV curves, and bars represent trading volumes. IV – Implied Volatility

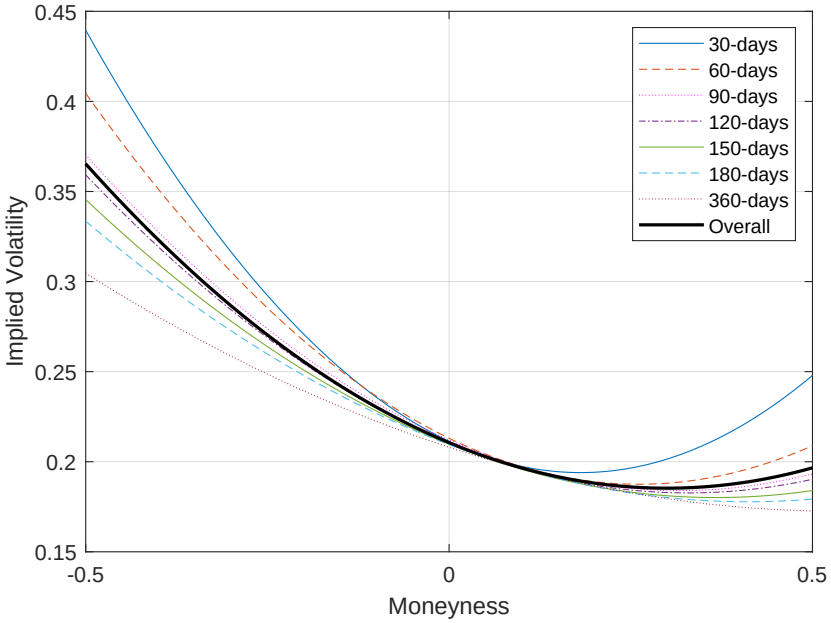
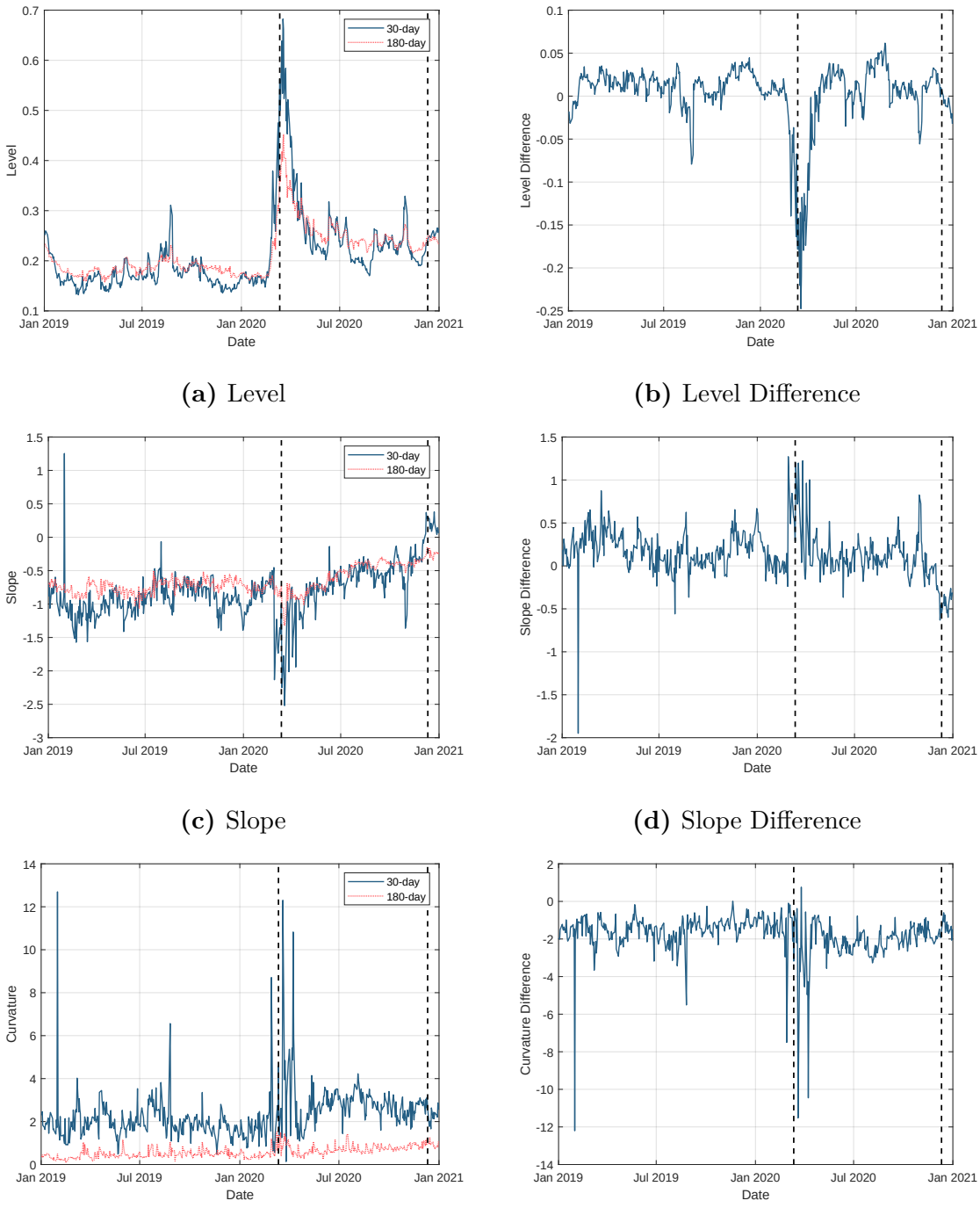


Figure 9: Constant Maturity IV curves for Johnson & Johnson.
Predicted IV curves using the mean constant maturity level, slope and curvature IV factors. IV – Implied Volatility



(a) Level **(b)** Level Difference

(c) Slope **(d)** Slope Difference

(e) Curvature **(f)** Curvature Difference

Figure 10: Constant maturity time-series dynamics for Johnson & Johnson. The 30- and 180-day constant maturity time series of the level, slope and curvature factors used to quantify the IV curves are shown in panels a, c and e, respectively. The difference between the 180- and 30-day factors are shown in panels b, d and e. The first dashed line represents the 12 March 2020, when the WHO announced COVID-19 as a pandemic. The second dashed line represents the 11 December 2020, when the Pfizer vaccine was approved. IV – Implied Volatility

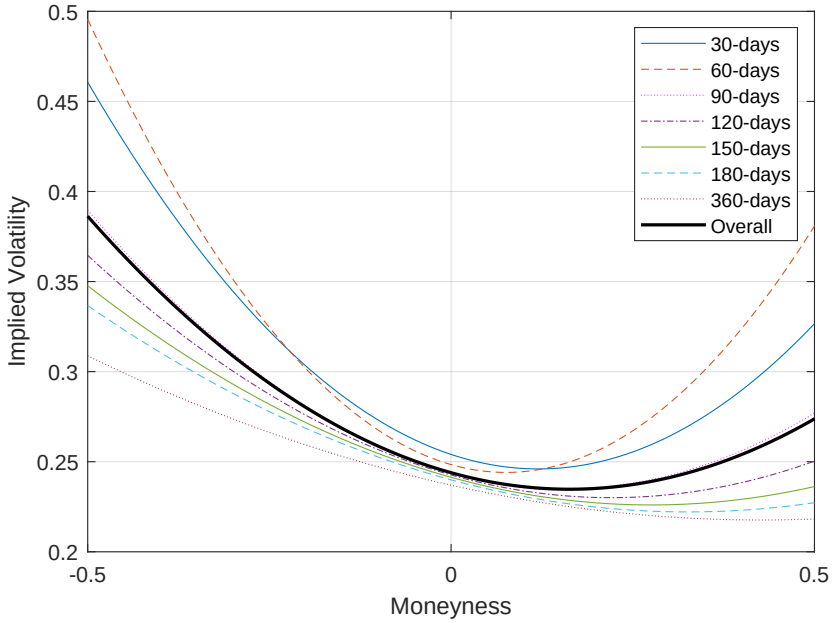
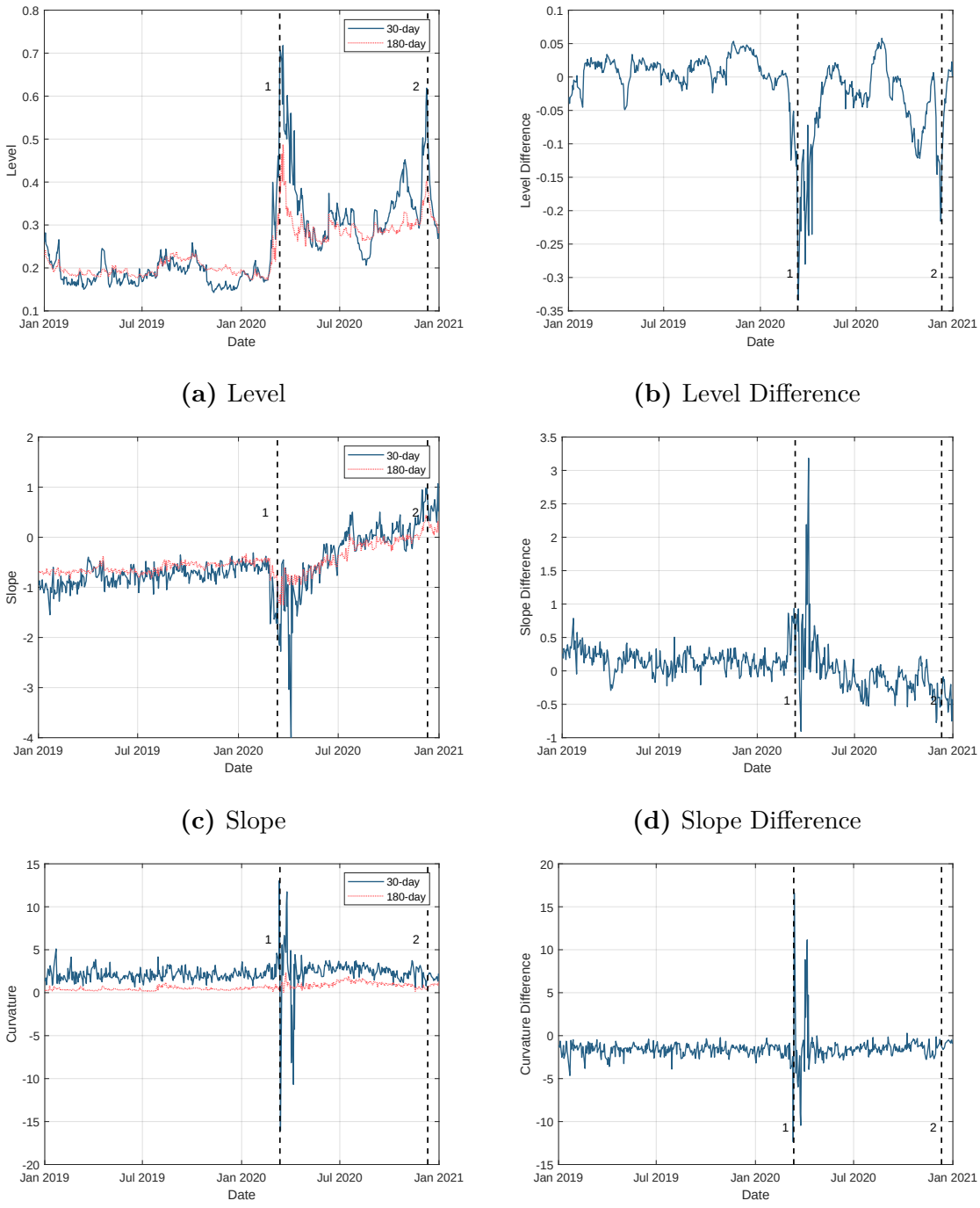


Figure 11: Constant Maturity IV curves for Pfizer.
Predicted IV curves using the mean constant maturity level, slope and curvature IV factors. IV – Implied Volatility



(a) Level **(b)** Level Difference

(c) Slope **(d)** Slope Difference

(e) Curvature **(f)** Curvature Difference

Figure 12: Constant maturity time-series dynamics for Pfizer
The 30- and 180-day constant maturity time series of the level, slope and curvature factors used to quantify the IV curves are shown in panels a, c and e, respectively. The difference between the 180- and 30-day factors are shown in panels b, d and e. (1) 12 March 2020 - The WHO announces COVID-19 as a pandemic. (2) 11 December 2020 - Pfizer vaccine receives emergency use authorisation. IV – Implied Volatility

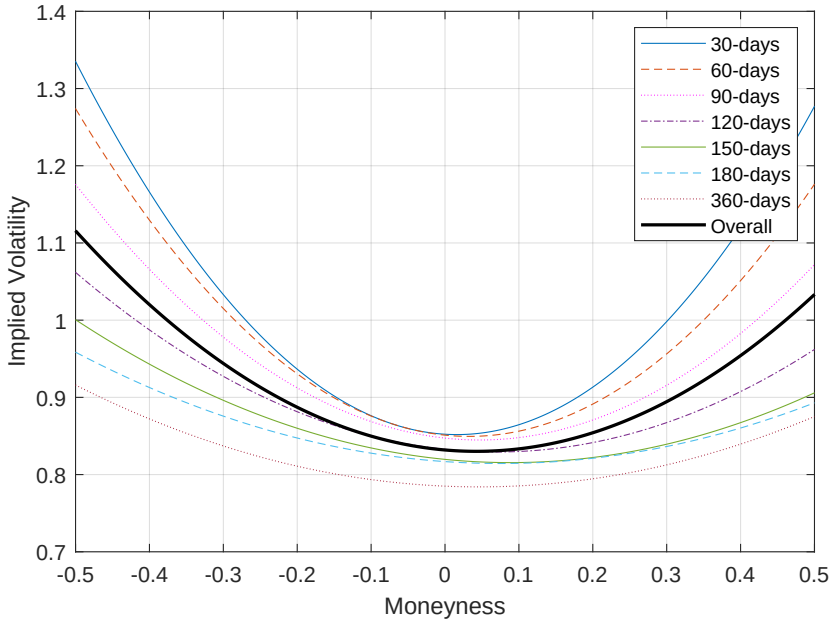
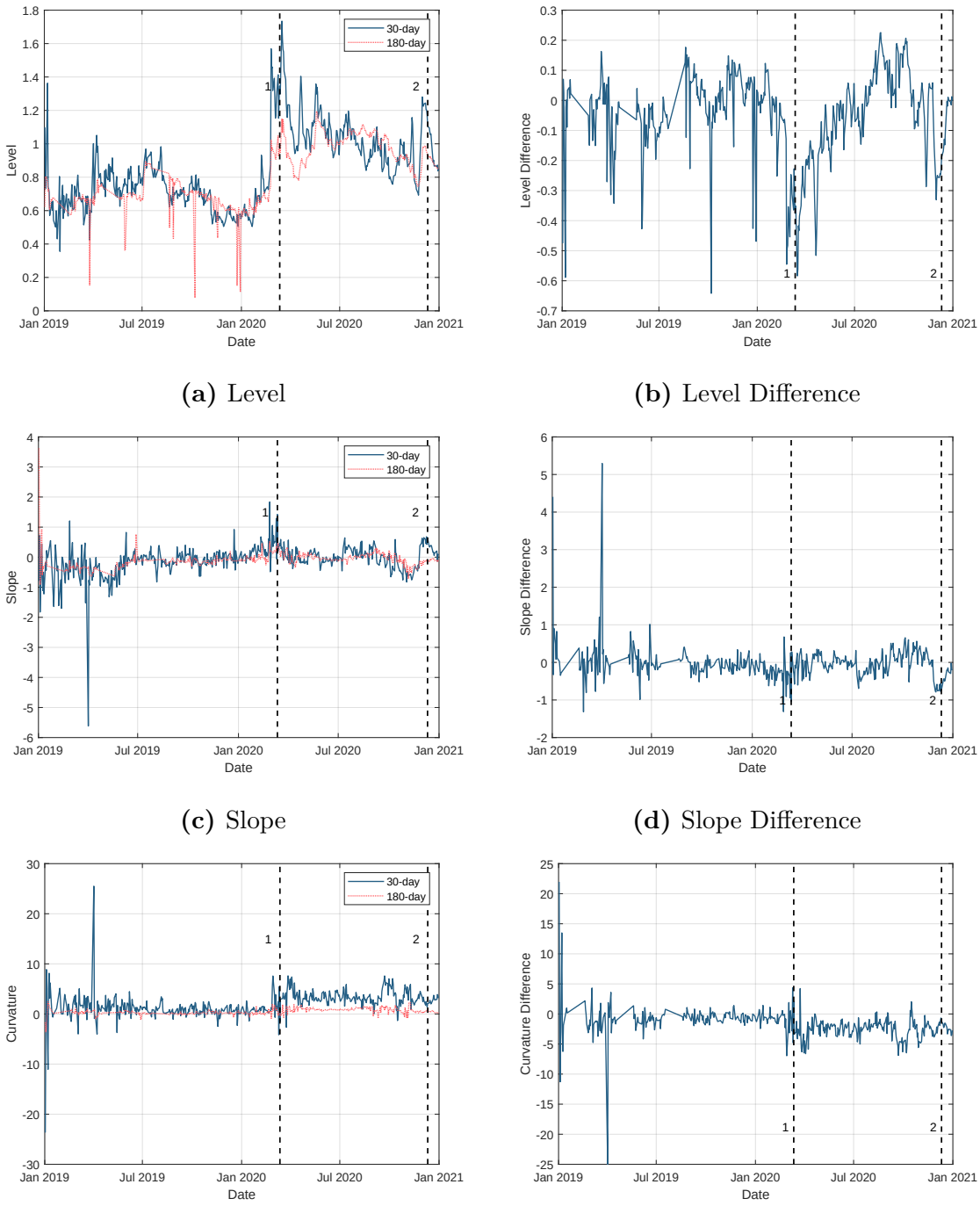


Figure 13: Constant Maturity IV curves for Moderna.
Predicted IV curves using the mean constant maturity level, slope and curvature IV factors. IV – Implied Volatility



(a) Level **(b)** Level Difference

(c) Slope **(d)** Slope Difference

(e) Curvature **(f)** Curvature Difference

Figure 14: Constant maturity time-series dynamics for Moderna
The 30- and 180-day constant maturity time series of the level, slope and curvature factors used to quantify the IV curves are shown in panels a, c and e, respectively. The difference between the 180- and 30-day factors are shown in panels b, d and e. (1) 12 March 2020 - The WHO announces COVID-19 as a pandemic. (2) 11 December 2020 - Pfizer vaccine receives emergency use authorisation. IV – Implied Volatility

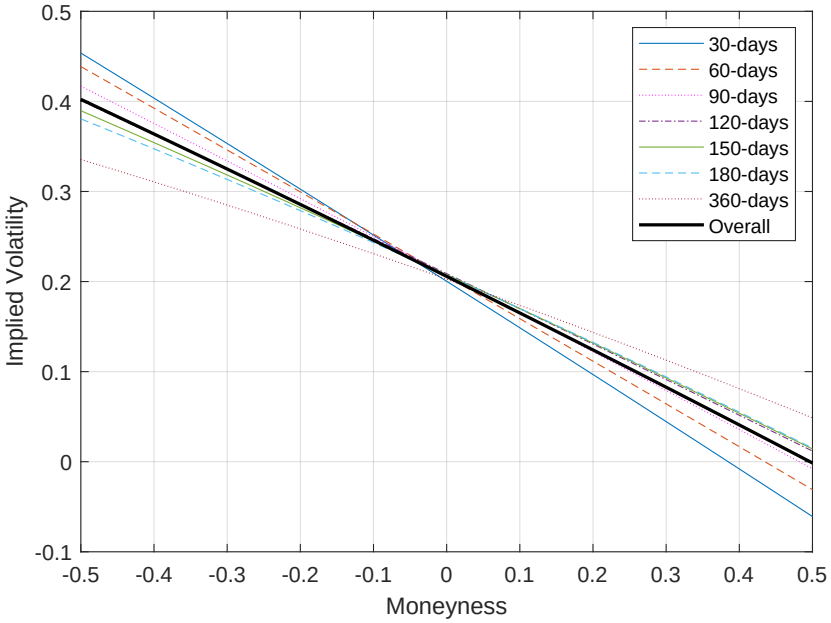
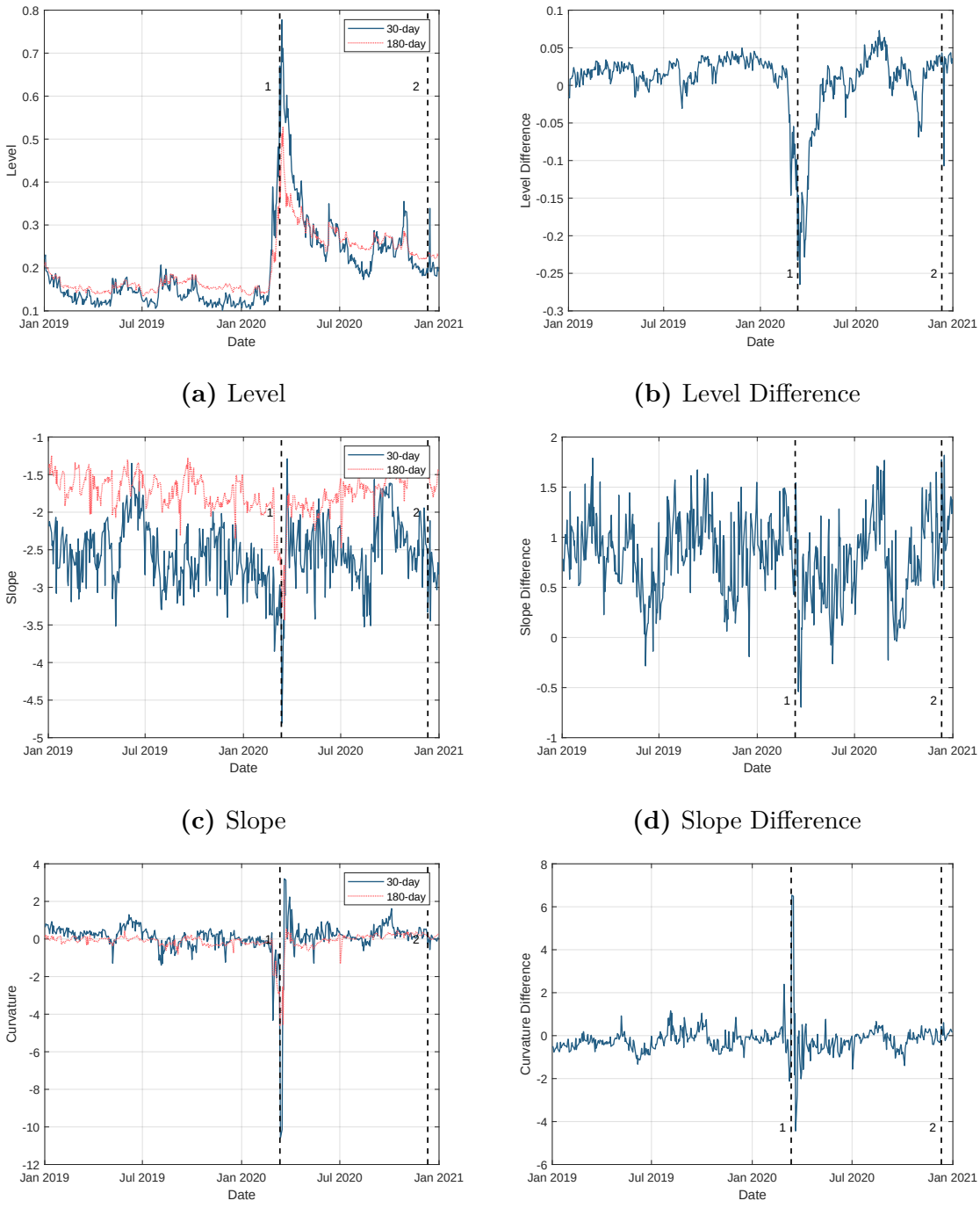


Figure 15: Constant Maturity IV curves for SPX options.
Predicted IV curves using the mean constant maturity level, slope and curvature IV factors. IV – Implied Volatility



(a) Level **(b)** Level Difference

(c) Slope **(d)** Slope Difference

(e) Curvature **(f)** Curvature Difference

Figure 16: Constant maturity time-series dynamics for SPX options
The 30- and 180-day constant maturity time series of the level, slope and curvature factors used to quantify the IV curves are shown in panels a, c and e, respectively. The difference between the 180- and 30-day factors are shown in panels b, d and e. (1) 12 March 2020 - The WHO announces COVID-19 as a pandemic. (2) 11 December 2020 - Pfizer vaccine receives emergency use authorisation. IV – Implied Volatility