Do Software Companies Spread Cyber Risk?

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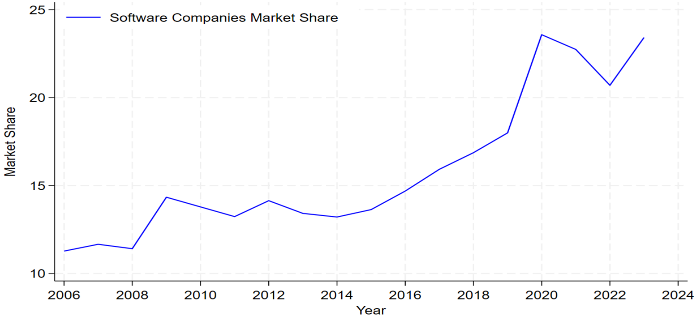
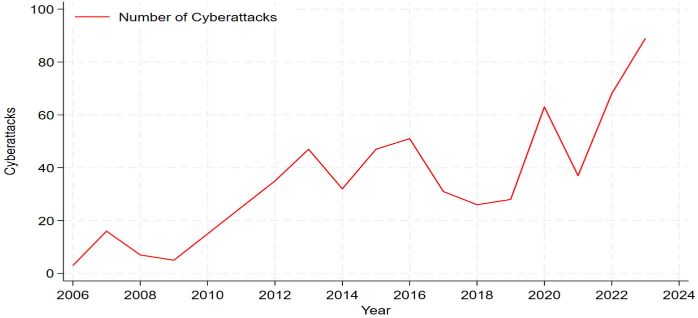
2025 State-of-the-Field Conference on Cyber Risk to Financial Stability

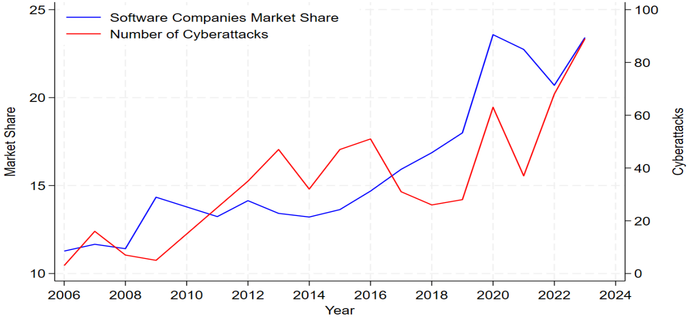


- Software companies provided in 2020 15.8 million U.S. jobs and contributed $933 billion in direct value-added GDP to the U.S. economy alone. (software.org, 2021)



- Global damages from cyber crime expected to be $10.5 trillion by 2025 (Cybersecurity Ventures, 2022)

Our Contribution



- We argue that the growth of software companies is a key driver of the rise in cybersecurity risk.

Our Contribution

- We identify **software vulnerabilities** as a first-order driver of cyber risk
  - Affect many firms in the economy through software companies' digital supply chain
  - Third party risk that is hard to monitor

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- We identify **software vulnerabilities** as a first-order driver of cyber risk
  - Affect many firms in the economy through software companies' digital supply chain
  - Third party risk that is hard to monitor
- Important to shape firms' policies as well as regulatory actions aimed at mitigating cybersecurity threats
- Implications for recognizing cyber risk as a systematic source of risk

- **What we do**:
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  - Identify the effect of vulnerabilities discovery on firms and study the market reaction

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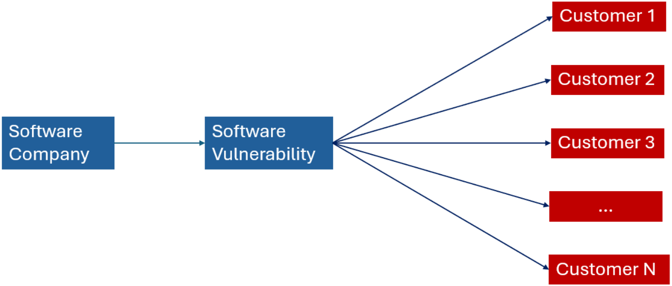
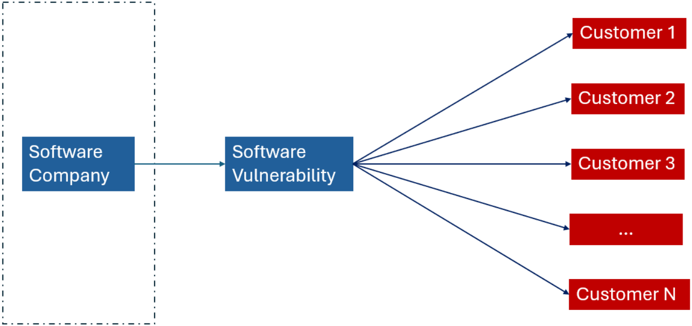
    - Frictions likely due to investors struggling to incorporate customer-supplier linkages
  - Additional tests support the view that software companies growth and increase in cyber risk are connected

Our Setting

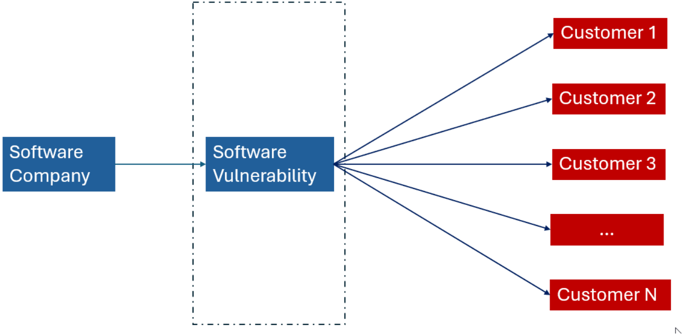

Software Company
Software Vulnerability
Customer 1
Customer 2
Customer 3
...
Customer N

Our Setting



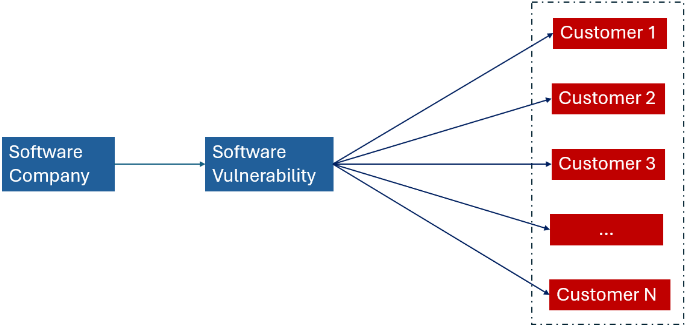
- From the vulnerabilities data, we manually identify 66 software companies that distribute vulnerable software.

Our Setting



- 1,947 software vulnerabilities; 466 vulnerabilities manually linked to cyberattacks.

Our Setting



- 3,875 unique customer companies; 1,431 customer firms every year, on average.

$$CyberAttacks_{c,t+1} = \alpha + \beta_1\,Vulnerability_{c,t} + \gamma X_{c,t} + \epsilon_{c,t+1}$$

	All Attacks$_{c,t+1}$ (1)	Vulnerability Attacks$_{c,t+1}$ (2)	Other Attacks$_{c,t+1}$ (3)
Vulnerability$_{c,t}$	0.106***	0.187***	0.029
	(4.41)	(5.75)	(1.43)
Customer Controls$_{c,t}$	Yes	Yes	Yes
Customer FE	Yes	Yes	Yes
Time FE	Yes	Yes	Yes
Observations	81,125	81,125	81,125
Adjusted r^2	0.016	0.004	0.013

- A vulnerability discovery increases the number of hacking attacks by 0.11 standard deviations.
- Dynamic effects on cyberattack probability Graphs

- Absence of effects on non vulnerability-related attacks is already informative
  - Addresses alternative explanations where suppliers and customers are matched on similar characteristics, such as poor internal cybersecurity policies
- We perform two additional falsification tests:
  - Focus on minor vulnerabilities ▸ Table
  - Placebo based on Chetty, Looney, and Kroft (2009) block permutation test ▸ Graphs

$$Risk\ Var_{c,t+1} = \alpha + \beta_1\, Vulnerability_{c,t} + \gamma X_{c,t} + \epsilon_{c,t+1}$$

	$\text{RetVol}_{c,t+1}$ (1)	$\text{Ivol}_{c,t+1}$ (2)	Var $95\%_{c,t+1}$ (3)	$\text{LPSD}_{c,t+1}$ (4)
$\text{Vulnerability}_{c,t}$	0.046***	0.035***	-0.062***	0.053***
	(3.39)	(2.62)	(-4.66)	(3.87)
Customer $\text{Controls}_{c,t}$	Yes	Yes	Yes	Yes
Customer FE	Yes	Yes	Yes	Yes
Time FE	Yes	Yes	Yes	Yes
Observations	81,125	81,125	81,125	81,125
Adjusted r^2	0.560	0.577	0.541	0.438

- A vulnerability discovery increases the return vol. by 0.046 standard deviations
- Dynamic effects on risk variables ▸ Graphs

$$Real\ Var_{c,t+1} = \alpha + \beta_1\, Vulnerability_{c,t} + \gamma X_{c,t} + \epsilon_{c,t+1}$$

	$I_{c,t+1}/K_{c,t}$ (1)	$R_{c,t+1}/G_{c,t}$ (2)	Sale Growth$_{c,t+1}$ (3)	Cybersecurity Rel.n$_{c,t+1}$ (4)
Vulnerability$_{c,t}$	-0.044** (-2.38)	-0.043*** (-2.68)	-0.037*** (-2.89)	0.111*** (3.36)
Customer Controls$_{c,t}$	Yes	Yes	Yes	Yes
Customer FE	Yes	Yes	Yes	Yes
Time FE	Yes	Yes	Yes	Yes
Observations	70,069	70,069	70,069	70,069
Adjusted r^2	0.202	0.756	0.025	0.652

- Literature linking increases in firm risk with decreases in investments (see, e.g., Bloom, 2009, Hassan et al., 2019)
- A vulnerability discovery decreases firm investments by 0.044 standard deviations
- Dynamic effects on real variables Graphs

Market Reaction

- Stock market prices do not seem to react in the short-term
- We show that market slowly incorporates the information

Market Reaction

- Stock market prices do not seem to react in the short-term
- We show that market slowly incorporates the information
- We document that investors overlook supply chain links between software companies and their customers (see e.g., Cohen and Frazzini (2008))
  - Significant reaction when knowledge of customer–supplier links is not needed

$$CAR_c = \alpha_t + \beta\, Vulnerability_c + \gamma X_c + \epsilon_c$$

	Market-Adjusted CAR_c (1)	CAPM CAR_c (2)	5-factor CAR_c (3)
Vulnerability_c	-0.008	0.001	-0.011
	(-0.23)	(0.03)	(-0.43)
$\text{Customer Controls}_c$	Yes	Yes	Yes
Time FE	Yes	Yes	Yes
Observations	645,846	645,846	645,846
Adjusted r^2	0.039	0.042	0.015

- Stock market prices do not seem to react in the short-term

- Three potential explanation for the absence of reaction in the short-run:

    1. Vulnerabilities are inconsequential to the firm
        - Unlikely given previous results on cyberattacks and investments
    2. Market may be unaware of the consequences
        - Again unlikely given previous results on market-based risk variables
    3. Market only slowly incorporates the information
        - We should be able to observe the reaction over a longer window

Long-Term Price Reaction

$$R_{c,t+1} = \alpha_t + \alpha_c + \beta_1\, Vulnerability_{c,t} + \gamma X_{c,t} + \epsilon_{c,t+1}$$

	Market-Adjusted$_{c,t+1}$ (1)	CAPM$_{c,t+1}$ (2)	5-factor Model$_{c,t+1}$ (3)
Vulnerability$_{c,t}$	-0.008**	-0.007***	-0.006**
	(-2.45)	(-2.86)	(-2.08)
Customer Controls$_{c,t}$	Yes	Yes	Yes
Customer FE	Yes	Yes	Yes
Time FE	Yes	Yes	Yes
Observations	77,357	77,357	77,357
Adjusted r^2	0.062	0.062	0.040

- A vulnerability discovery decreases next quarter risk-adjusted stock returns by 0.6%-0.8%

- Investors may overlook supply chain links between software companies and their customers (see e.g., Cohen and Frazzini (2008))
- To assess this conjecture, we perform two tests where knowledge of customer–supplier links is not needed:
  1. Software company's stock price reaction to the discovery of a vulnerability
  2. Market reaction to the occurrence of a cyberattack due to a vulnerability

$$CAR_s = \alpha_t + \beta\, Vulnerability_s + \gamma X_s + \epsilon_s$$

	Market-Adjusted CAR_s (1)	CAPM CAR_s (2)	5-factor CAR_s (3)
$Vulnerability_s$	-0.221***	-0.247***	-0.277***
	(-2.80)	(-2.73)	(-2.97)
Supplier $Controls_s$	Yes	Yes	Yes
Time FE	Yes	Yes	Yes
Observations	213,024	213,024	213,024
Adjusted r^2	0.012	0.012	0.012

- On average, one vulnerability decreases 3-day CAR by 0.22%-0.27%

Market Reaction to Cyberattacks

$$CAR_c = \alpha_t + \beta Attack_c + \gamma X_c + \epsilon_c$$

	Market-Adjusted CAR_c (1)	CAPM CAR_c (2)	5-factor CAR_c (3)
Attack_c	-1.280***	-1.081***	-1.125***
	(-3.59)	(-2.97)	(-2.91)
Customer Controls_c	Yes	Yes	Yes
Time FE	Yes	Yes	Yes
Observations	49,407	49,407	49,407
Adjusted r^2	0.016	0.025	0.010

- On average, one attack decreases 3-day CAR by 1.1%-1.3%

Link with Software Companies' Growth

- Ongoing regulatory debate on software companies as Systemically Important Entities (Welburn, 2024)
- We study whether the growth of software companies increases cybersecurity risk
  - → We explore heterogeneity based on software supplier market share
- If software companies were a systemic source of cyber risk, the effect of vulnerabilities should have aggregate implications
  - → We move the analysis at the industry-level Table

$$CyberAttacks_{s,t+1} = \alpha + \beta_1 Vuln._{s,t} + \beta_2 Mktshare_{s,t} + \beta_3 Vuln._{s,t} \times Mktshare_{s,t} + \gamma X_{s,t} + \epsilon_{s,t+1}$$

	All Attacks$_{s,t+1}$ (1)	Vulnerability Attacks$_{s,t+1}$ (2)	Other Attacks$_{s,t+1}$ (3)
MktShare$_{s,t}$	0.165***	0.071**	0.157***
	(4.29)	(2.11)	(3.94)
Vulnerability$_{s,t}$	0.028**	0.030	0.011
	(2.36)	(1.60)	(1.04)
MktShare$_{s,t}$ × Vuln.$_{s,t}$	0.015***	0.015***	0.003
	(2.67)	(2.93)	(0.47)
Supplier Controls$_{s,t}$	Yes	Yes	Yes
Supplier FE	Yes	Yes	Yes
Time FE	Yes	Yes	Yes
Observations	26,627	26,627	26,627
Adjusted r^2	0.336	0.175	0.262

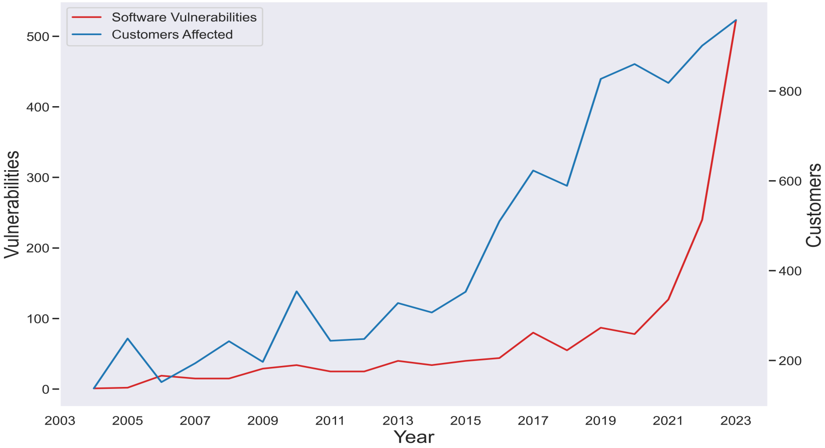
- Dependent variable is the number of cyberattacks among the customers of the software company
- Results on firm risk, investments, and quarterly returns

Conclusion

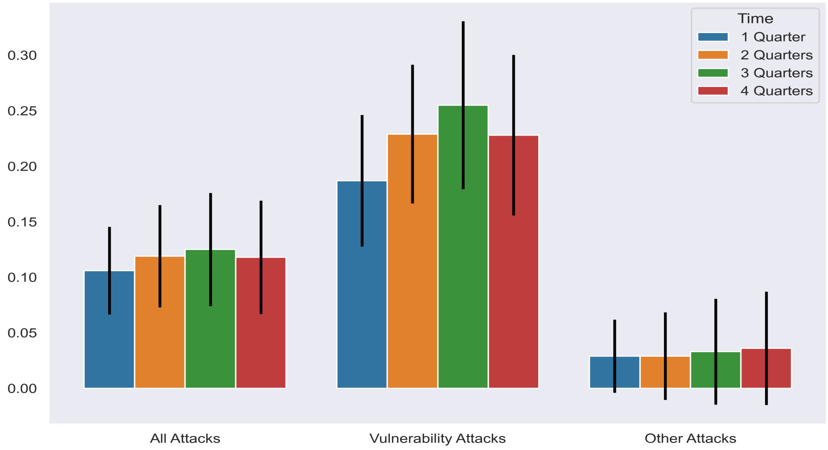
- Expansion and concentration of software companies is a significant driver of cybersecurity risk
- Software vulnerabilities spread through digital supply chains, and:
  - Increase probability of cyberattacks for affected customers
  - Increase customer risk
  - Decrease customer investments and sale growth
- Strong link with the growth of software companies:
  - Worse consequences when software supplier has a larger market share
  - All results aggregate at the industry-level

Trends of Vulnerabilities and Affected Customers

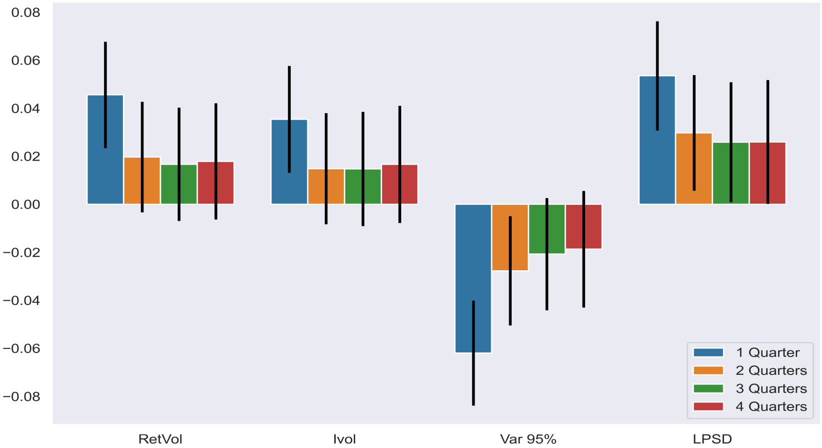
Back



Dynamic Effects on CyberAttacks ▸ Back

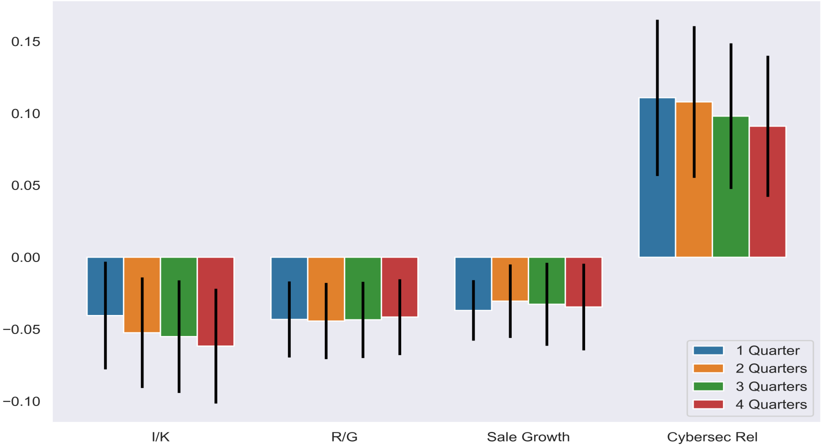


Dynamic Effects on Risk Variables ▸ Back



Dynamic Effects on Real Variables

Back



Minor Vulnerabilities and CyberAttacks ▸ Back

$$CyberAttacks_{c,t+1} = \alpha + \beta_1 Minor\ Vulnerability_{c,t} + \gamma X_{c,t} + \epsilon_{c,t+1}$$

	All Attacks$_{c,t+1}$ (1)	Vulnerability Attacks$_{c,t+1}$ (2)	Other Attacks$_{c,t+1}$ (3)
Minor Vulnerability$_{c,t}$	0.011	-0.003	0.014
	(1.24)	(-0.44)	(1.53)
Customer Controls$_{c,t}$	Yes	Yes	Yes
Customer FE	Yes	Yes	Yes
Time FE	Yes	Yes	Yes
Observations	81,125	81,125	81,125
Adjusted r^2	0.017	0.006	0.013

Block Permutation Test ▸ Back

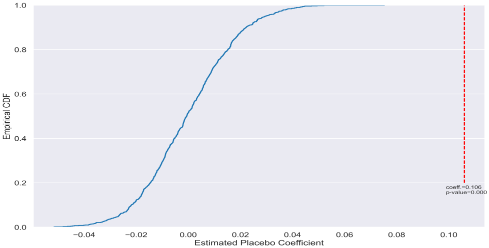


Figure A: All Attacks

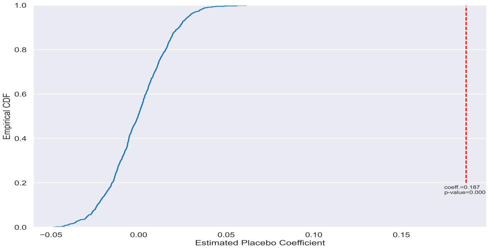


Figure B: Vulnerability Attacks

Long-Term Price Reaction ▸ Back

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Software Companies Price Reaction

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Market Reaction to Cyberattacks
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Firm Risk and Market Share ‣ Back

$$Risk\ Var_{s,t+1} = \alpha + \beta_1 Vuln._{s,t} + \beta_2 Mktshare_{s,t} + \beta_3 Vuln._{s,t} \times Mktshare_{s,t} + \gamma X_{s,t} + \epsilon_{s,t+1}$$

	$\text{RetVol}_{s,t+1}$ (1)	$\text{Ivol}_{s,t+1}$ (2)	Var $95\%_{s,t+1}$ (3)	$\text{LPSD}_{s,t+1}$ (4)
$\text{MktShare}_{s,t}$	-0.075***	-0.091***	0.061***	-0.063***
	(-5.50)	(-6.09)	(4.86)	(-4.63)
$\text{Vulnerability}_{s,t}$	0.010***	0.009***	-0.009***	0.011***
	(3.83)	(3.76)	(-3.75)	(4.53)
$\text{MktShare}_{s,t} \times \text{Vuln.}_{s,t}$	0.003**	0.003**	-0.004**	0.003**
	(2.19)	(1.99)	(-2.41)	(2.05)
Supplier $\text{Controls}_{s,t}$	Yes	Yes	Yes	Yes
Supplier FE	Yes	Yes	Yes	Yes
Time FE	Yes	Yes	Yes	Yes
Observations	26,627	26,627	26,627	26,627
Adjusted r^2	0.530	0.538	0.507	0.460

$$
\begin{aligned}
Real\ \ Var_{s,t+1} = \alpha + \beta_1\, Vuln._{s,t} + \beta_2 Mktshare_{s,t} \\
+ \beta_3\, Vuln._{s,t} \times Mktshare_{s,t} + \gamma X_{s,t} + \epsilon_{s,t+1}
\end{aligned}
$$

	$I_{s,t+1}/K_{s,t}$ (1)	$R_{s,t+1}/G_{s,t}$ (2)	Sale Growth$_{s,t+1}$ (3)	Cybersecurity Rel.$_{s,t+1}$ (4)
MktShare$_{s,t}$	0.568**	1.304***	-0.066	-0.080
	(2.38)	(3.65)	(-0.43)	(-1.33)
Vulnerability$_{s,t}$	-0.002	0.002	-0.001	0.014*
	(-0.74)	(0.43)	(-0.28)	(1.96)
MktShare$_{s,t}$ × Vuln.$_{s,t}$	-0.155***	-0.115**	-0.091**	-0.042
	(-2.84)	(-2.01)	(-2.30)	(-0.38)
Supplier Controls$_{s,t}$	Yes	Yes	Yes	Yes
Supplier FE	Yes	Yes	Yes	Yes
Time FE	Yes	Yes	Yes	Yes
Observations	23,337	23,337	23,337	23,337
Adjusted r^2	0.141	0.395	-0.001	0.492

Long-Term Returns and Market Share

Back

$$R_{s,t+1} = \alpha + \beta_1 \, Vuln._{s,t} + \beta_2 Mktshare_{s,t} + \beta_3 \, Vuln._{s,t} \times Mktshare_{s,t} + \gamma X_{s,t} + \epsilon_{s,t+1}$$

	Market-Adjusted$_{s,t+1}$ (1)	CAPM$_{s,t+1}$ (2)	5-factor Model$_{s,t+1}$ (3)
MktShare$_{s,t}$	-0.003	0.002	0.046***
	(-0.45)	(0.26)	(4.76)
Vulnerability$_{s,t}$	-0.001	-0.004	-0.007**
	(-0.51)	(-1.26)	(-2.16)
MktShare$_{s,t}$ × Vuln.$_{s,t}$	-0.006***	-0.006**	-0.003**
	(-3.42)	(-2.09)	(-2.15)
Supplier Controls$_{s,t}$	Yes	Yes	Yes
Supplier FE	Yes	Yes	Yes
Time FE	Yes	Yes	Yes
Observations	25,112	25,112	25,112
Adjusted r^2	0.621	0.167	0.069

Industry CyberAttacks ▸ Back

$$CyberAttacks_{i,t+1} = \alpha + \beta_1\, Vulnerabilities_{i,t} + \epsilon_{i,t+1}$$

	All Attacks$_{i,t+1}$ (1)	Vulnerability Attacks$_{i,t+1}$ (2)	Other Attacks$_{i,t+1}$ (3)
Vulnerabilities$_{i,t}$	0.091***	0.104***	0.004
	(5.56)	(11.09)	(0.23)
Industry FE	Yes	Yes	Yes
Observations	3,381	3,381	3,381
Adjusted r^2	0.130	0.209	0.074

- Dependent variable is the number of cyberattacks in each of the Fama-French 49 industries

Industry Risk ▸ Back

$$Risk\ Var_{i,t+1} = \alpha + \beta_1\, Vulnerabilities_{i,t} + \epsilon_{i,t+1}$$

	$\text{RetVol}_{i,t+1}$ (1)	$\text{Ivol}_{i,t+1}$ (2)	$\text{Var 95\%}_{i,t+1}$ (3)	$\text{LPSD}_{i,t+1}$ (4)
$\text{Vulnerabilities}_{i,t}$	0.026^{***} (3.73)	0.037^{***} (4.62)	-0.016^{**} (-2.38)	0.016^{**} (2.38)
Industry FE	Yes	Yes	Yes	Yes
Observations	3,381	3,381	3,381	3,381
Adjusted r^2	0.180	0.293	0.143	0.139

Industry Real Effects

▸ Back

$$Real\ \ Var_{i,t+1} = \alpha + \beta_1\, Vulnerabilities_{i,t} + \epsilon_{i,t+1}$$

	$I_{i,t+1}/K_{i,t}$ (1)	$R_{i,t+1}/G_{c,t}$ (2)	Sales Growth$_{i,t+1}$ (3)	Cybersecurity Relation$_{i,t+1}$ (4)
Vulnerabilities$_{i,t}$	-0.104*	-0.098*	0.013	0.148***
	(-1.78)	(-1.78)	(0.38)	(6.63)
Industry FE	Yes	Yes	Yes	Yes
Observations	3,228	3,228	3,228	3,228
Adjusted r^2	0.049	0.050	0.024	0.800

$$Real\ Var_{i,t+1} = \alpha + \beta_1\, Vulnerabilities_{i,t} + \epsilon_{i,t+1}$$

	Market-Adjusted$_{i,t+1}$ (1)	CAPM$_{i,t+1}$ (2)	5-factor Model$_{i,t+1}$ (3)
Vulnerabilities$_{i,t}$	-0.003**	-0.004**	-0.001*
	(-2.39)	(-2.57)	(-1.71)
Industry FE	Yes	Yes	Yes
Observations	3,381	3,381	3,381
Adjusted r^2	-0.003	0.012	0.006