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What fueled the illicit opioid epidemic? New evidence from a takeover of white powder heroin markets

J. Travis Donahoe
Adam Soliman

LSE The London School of Economics and Political Science

UKRI Economic and Social Research Council

Abstract
In recent years, illicitly manufactured opioids—primarily heroin and fentanyl—have overtaken prescription opioids as the leading cause of overdose deaths in the United States. We provide the first causal evidence that geographically concentrated heroin purity shocks and supply-side adulteration of heroin with fentanyl played a central role in driving this transition. Using a difference-in-differences design that exploits the fact that white powder heroin markets—but not black tar heroin markets—were exposed to supply chain shifts beginning in 2012 that increased both the variability of heroin purity and the prevalence of fentanyl adulteration, we find that exposure to these shocks increased all-cause overdose death rates by approximately 50% and account for roughly half of the rise in illicit opioid deaths through 2019. These effects cannot be explained by previously studied policy efforts aimed at restricting prescription opioids. Our findings also help reconcile unexplained patterns in the opioid epidemic, including the sharp geographic shift in overdose deaths toward eastern states and rising mortality among populations less exposed to prescription opioids.

Key words: overdose epidemic, illicit opioids, segmented market
JEL Codes: H1; I1; K4

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J. Travis Donahoe, University of Pittsburgh. Adam Soliman, Clemson University and Centre for Economic Performance at London School of Economics.

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The ongoing drug overdose epidemic now stands as one of the worst public health crises in U.S. history, taking more than one million lives in less than 25 years (CDC 2021). There have been three waves of the epidemic, each involving a different form of opioids: prescription opioids in the 1990s and early 2000s, heroin beginning in the early 2010s, and synthetic opioids, primarily illegally-produced fentanyl, ever since (see Figure A.1). Understanding the drivers of rising heroin and fentanyl mortality is crucial for designing new interventions to combat the illicit opioid waves of the epidemic, as historic investments in programs aimed at addressing the first wave—such as reducing prescription opioid use and expanding access to opioid addiction treatment (CBO 2022)—have thus far failed to significantly reduce overdose death rates.

This paper provides the first causal evidence that geographically concentrated shocks to heroin potency, stemming from shifts in heroin supply chains and fentanyl adulteration, played a key role in igniting the heroin and fentanyl waves of the epidemic. Using annual data on undercover heroin purchases by the Drug Enforcement Administration (DEA), we first show that historical illicit drug supply chains established sticky links between domestic geography, heroin source countries, and the formulations of heroin sold (Ciccarone 2009). In eastern cities, heroin was predominantly a white powder formulation produced in Colombia to mimic the Southeast Asian heroin that had gained popularity there in earlier decades. In contrast, western cities were dominated by black tar heroin, which was produced in Mexico. Then, beginning in 2012, Mexican Drug Trafficking Organizations (DTOs) assumed control over white powder heroin production from Colombian DTOs in the east. Black tar heroin production in the west remained unchanged.

Heroin supply changed in two key ways following the shift in production from Colombia to Mexico—these changes were confined to cities where white powder heroin was prevalent and did not affect those with black tar heroin markets. First, the newly produced white powder heroin from Mexico was sold at the retail level with more variable purity. Second, suppliers increasingly adulterated white powder heroin with illicitly-produced fentanyl to boost potency and reduce costs (Pardo et al. 2019). Both DEA data and ethnographic research with heroin users indicate that this supplier-driven fentanyl adulteration was largely limited to white powder heroin. The underlying reason is asymmetric information: chemical differences between white powder and black tar heroin make it more difficult for white powder users to detect whether they are purchasing heroin or fentanyl prior to use (Carroll et al. 2017; Mars et al. 2018, 2019). We refer to increased variability in heroin purity and fentanyl adulteration collectively as 'exposure to potency shocks,' a term that captures how both phenomena raise effective potency from the user's perspective. Moreover, leading with 'exposure' emphasizes the potential for lasting effects on mortality beyond the immediate shock, such as increased fentanyl addiction.

We estimate the causal effects of exposure to these potency shocks on overdose mortality, examining both their immediate impact and how they shaped the longer-term trajectory of the epidemic. To do so, we use restricted death records for all U.S. counties from 2000 to 2019 and analyze the natural experiment resulting from these shocks exclusively affecting cities with white powder heroin markets. We compare changes in overdose death rates after 2012 for commuting zones that historically had white powder heroin markets with those that had black tar heroin markets. Commuting zones supplied black tar heroin serve as an effective control

group, as there was no observed change in heroin supply chains during this period and users possessed greater information about whether they were being sold heroin or fentanyl. However, cities with black tar heroin faced other potential causes of increased death rates suggested in the literature, such as substitution to heroin and fentanyl as a result of tighter prescription opioid controls (Alpert et al. 2018; Evans et al. 2019; Kim 2021; Powell and Pacula 2021).

Consistent with the potency shocks being exogenous, we observe no differential pre-trends in overdose mortality between white powder and black tar heroin markets for over a decade. Beginning in 2012—when white powder heroin production shifted to Mexico and fentanyl entered the supply—we find significant increases in overdose mortality in commuting zones with white powder heroin markets. These increases grow over time yet evolve in nature. Initially, the shocks led to rising deaths from heroin and heroin-fentanyl combinations. Over time, however, fentanyl became the dominant driver of mortality, suggesting that its early adulteration of white powder heroin helped establish it as a standalone product. One mechanism that can explain this is thick market externalities: once heroin users were exposed to fentanyl, some would have become addicted to it, increasing demand and making standalone fentanyl markets thicker (Cutler and Donahoe 2024). In this way, an initial shock to heroin supply triggered a transformation of the illicit drug market. This pattern—where a shock to one opioid initiates long-term harm through a shift to another—echoes prior findings, such as the role of OxyContin marketing in sparking downstream increases in heroin and fentanyl deaths (Alpert et al. 2022).

We estimate that exposure to the potency shocks led to a 233% increase in heroin-related deaths and a 901% increase in fentanyl-related deaths between 2012 and 2019, translating into a 49% rise in all-cause overdose mortality. These increases cannot be explained by other factors explored in the literature, such as tighter prescription opioid controls (Alpert et al. 2018; Evans et al. 2019; Kim 2021; Powell and Pacula 2021), greater exposure to imported fentanyl via legal imports (Moore et al. 2023), or changes in enforcement. Instead, additional evidence suggests that the mortality surge was driven by an increase in the rate of death among existing heroin users. First, combining data from the National Survey on Drug Use and Health with vital records, we find that the probability of overdose death among past-year heroin users rose by approximately 232% from 2011 to 2019. Second, mortality increases were larger in white powder heroin markets with higher baseline heroin use, as proxied by pre-shock heroin death rates.

Next, we shed light on key aspects of the evolving opioid epidemic that have thus far remained unexplained. One aspect is the earlier and disproportionate impact of the fentanyl epidemic on eastern states (Zoorob 2019; Abouk et al. 2021; Moore et al. 2023), despite the prescription opioid epidemic being a nationwide phenomenon. Our analysis provides the first causal evidence linking these regional disparities to differences in heroin supply chains between the eastern and western United States. A second puzzle that we explain is the rising burden of the opioid epidemic among non-White populations. Despite lower exposure to prescription opioids, Black Americans have experienced substantial increases in illicit opioid mortality in recent years (Ruhm 2022; Mulligan 2024). While prescription opioid use has historically been lower among Black than White Americans, heroin use is comparable, and thus potency shocks have had similarly deadly effects across racial groups. These patterns underscore the need to expand public health responses beyond prescribing regulations, recognizing that the pathways

to fentanyl-related overdose differ across racial and ethnic communities.

Our main contribution to the literature is providing the first causal evidence on the role of exposure to heroin purity changes and supply-side adulteration of heroin with fentanyl in driving the heroin and fentanyl waves of the opioid epidemic. Prior work emphasizes the unintended consequences of tighter prescription opioid controls—particularly the OxyContin reformulation and state-level Prescription Drug Monitoring Programs (PDMPs)—as the primary cause of rising heroin overdoses via user substitution (Alpert et al. 2018; Mallatt 2018; Evans et al. 2019; Powell and Pacula 2021; Kim 2021; Balestra et al. 2021). We revisit these two interventions, both of which curtailed the supply of abusable prescription opioids, to assess how they and exposure to potency shocks contributed to the sharp increases in heroin and fentanyl mortality in the 2010s. Controlling for exposure to potency shocks within existing empirical specifications significantly attenuates the estimated effects of OxyContin reformulation and must-access PDMPs. Moreover, our preferred decomposition exercise attributes roughly half of the increase in illicit opioid mortality to exposure to potency shocks, with the OxyContin reformulation explaining another one-third of the rise and PDMPs not being a significant contributor.

More broadly, our findings highlight how recent shifts in the composition and structure of illicit drug supply chains represent an urgent national policy concern. We document substantial variation in heroin source countries, formulations, potency, and adulterants across cities and over time, and show that these differences have profound and lasting consequences for overdose mortality rates. Prior research emphasizes that drug quality in illicit markets is non-contractible and only verifiable after consumption, leaving buyers unable to assess product safety or quality ex ante (Galenianos et al. 2012; Galenianos and Gavazza 2017). This informational asymmetry creates moral hazard: sellers have a strong incentive to adulterate supply with more potent or cost-effective—yet more dangerous—substances (like fentanyl) to enhance potency, addictiveness, and/or profit margins. While such adverse selection might unravel most markets (Akerlof 1970), the inelastic demand for addictive substances (Becker and Murphy 1988) combined with the presence of thick market externalities (Cutler and Donahoe 2024) can weaken these corrective forces, allowing heightened supply-side risks to persist.

There is a potential role for government intervention to address these informational asymmetries, but programs that monitor illicit drug use and disseminate information about drug quality and attributes remain poorly funded in the United States. In fact, many such programs were de-funded as the opioid epidemic unfolded, such as the Arrestee Drug Abuse Monitoring Program (in 2014) and the Heroin Domestic Monitoring Program used in this study (in 2016). This leaves practitioners, policymakers, and the scientific community in the dark about shifts in illicit drug markets that could be used to inform more responsive public health interventions. Future research should also consider whether interventions that correct informational asymmetries—such as provision of drug checking kits or regulated supply for high-risk drug users—can be effective at reducing overdose mortality.

1 Data

We begin by describing our data, which plays a central role in informing the background on illicit drug markets presented in the next section. To better understand the dynamics of retail heroin supply—particularly the role of drug trafficking organizations in shaping formulations, purity, and adulterants—we draw on the DEA's Heroin Domestic Monitoring Program (HDMP), a unique source of federal surveillance intelligence that operated intermittently until 2016. The HDMP is one of the only systematic efforts to track the composition and origin of heroin at the retail level across U.S. cities. Unlike data based on large seizures or arrests, HDMP samples come from undercover DEA purchases conducted strictly for surveillance, not enforcement, purposes. This distinction matters because heroin is often adulterated and diluted as it moves down the supply chain; as a result, data based on wholesale seizures may not reflect what users actually consume (Arkes et al. 2008).

The HDMP focused on major cities and regional distribution hubs, though not all cities are represented in all years. We restrict attention to a consistent subset of 31 cities with near-continuous coverage from 2004 to 2016, excluding smaller locations and earlier "geo-probe" efforts with limited and irregular sampling. Earlier HDMP reports (e.g., from 1992 and 1993) exist but are sparse, inconsistent in coverage, and often lack systematic detail on purity or type. Moreover, several major cities included in later years are missing entirely in earlier phases. Therefore, we focus on the 2004 to 2016 period to ensure comparability and continuity.[1]

Roughly 900 heroin samples were collected nationwide each year, with most cities contributing 15 to 40 samples depending on field office capacity and local conditions. These samples are not randomly drawn; they reflect operational intelligence and agent access, making the data more akin to informed surveillance than a statistically representative sample. Nevertheless, in the absence of alternative data, the HDMP offers the most granular and direct evidence on retail heroin supply available to analyze this critical component of the opioid epidemic.

Each sample underwent chemical analysis at DEA laboratories, which measured heroin purity, type (black tar, white powder, or brown powder), and common adulterants. As new substances emerged, such as fentanyl analogs, testing protocols were updated accordingly (see Section 2). A key limitation is that data are only available at the city-year level, which likely leads us to understate local variation in purity and formulation. The HDMP was discontinued after 2016 due to shifting DEA priorities and budget reallocation, and its termination coincided with a broader strategic pivot toward synthetic opioids. We focus on HDMP data because they uniquely capture the heroin supply actually available to users, offering detail on formulation, adulterants, and potency. In contrast, other supply-side sources—such as CBP seizures—reflect upstream flows and are less informative for understanding the drugs consumed at the street level, which is the focus of this study.

Second, to measure overdose mortality, we use individual-level data from the CDC's Restricted-Use Vital Statistics Data, also known as the Multiple Cause of Death (MCOD) research files. NCHS (2021) provide comprehensive information on all recorded deaths in the United States

[1]Some later HDMP reports include backfilled data for prior years (e.g., 2006 includes data from 2004 and 2005), allowing us to construct a balanced panel for 2004–2006 and 2009–2016. The gap in 2007–2008 reflects years in which no HDMP report was released.

since 1999, including demographic details of the decedent, county and year of death, underlying cause of death, and all contributing causes listed on the death certificate. We focus on the pre-COVID-19 pandemic period and follow CDC coding guidance (CDC 2021), using both the underlying and contributing cause-of-death fields (if applicable) to classify drug overdose deaths. We construct several non-mutually exclusive indicators to capture deaths involving heroin and/or fentanyl. Specifically, we code whether a death involved any heroin, any fentanyl, only heroin (i.e., heroin without fentanyl), only fentanyl (i.e., fentanyl without heroin), both heroin and fentanyl, or either heroin or fentanyl. This approach allows us to differentiate overlapping and exclusive involvement of these substances and to track shifts in the nature of opioid mortality over time and across geographies. Appendix Figure A.1 highlights the three waves of the opioid epidemic using these data.

Third, to examine prescription opioid distribution across space and time, we use the Automation of Reports and Consolidated Orders System (ARCOS) database. These data contain the record of every controlled substance shipped in the United States from 2006 to 2019. Each record contains the DEA number, address, name, and business type for both the reporter and the buyer, as well as information on each transaction, such as the transaction date, opioid drug name, quantity, strength, and Morphine Milligram Equivalent (MME) conversion factor. This allows us to examine shipments of, for example, generic oxycodone or OxyContin, at any level of temporal or geographical aggregation. Lastly, we obtain data used in the literature, cited as they appear, to control for variables previously shown to be associated with illicit opioid deaths, such as state-level OxyContin misuse rates, state opioid policies, and trade flows.

2 Background on U.S. Heroin Supply

This section provides background information on the evolution of heroin supply chains in the U.S., with a focus on the distinct geographic division between white powder and black tar heroin markets that has persisted for decades. We document how Mexican DTOs gained control of white powder heroin production, leading to a supply that was not only higher and more variable in purity, but also increasingly adulterated with illicitly-produced fentanyl.

2.1 Changes in U.S. Heroin Supply Chains

In the early 1970s, heroin was supplied to the largest and most lucrative heroin markets in the eastern U.S. as a white powder that was sourced from the Golden Triangle of Southeast Asia (Ciccarone 2009). In the 1990s, Colombian Drug Trafficking Organizations (DTOs) developed a "mimic" white powder heroin to compete for market share (DEA 1994). Owing in part to the infrastructure they developed to distribute cocaine in the 1980s, Colombian DTOs were able to sell their heroin at a lower cost than traffickers coming from Southeast Asia and took over as the dominant suppliers in the east (Rosenblum et al. 2014). Meanwhile, Mexican DTOs established dominance in the heroin markets of the west. There, they produced different types of heroin that resembled black tar and, to a lesser extent, brown powder (DEA 1994).

The result of this is that by the early 2000s, the U.S. heroin market was geographically segmented. Figure 1 highlights this phenomenon by showing that areas further east were sup-

plied white powder heroin and those further west were supplied black tar heroin, where the dividing longitude is approximately -91 degrees; suppliers in the east were almost exclusively Colombian, while those in the west were Mexican.[2] Note that one crude marker cited in DEA reports for this division of supply is the Mississippi River, but there is no evidence this was an explicit boundary and we observe one city that straddles the river (St. Louis) receiving a mix of both types of heroin. These differences endured over time because heroin users developed sticky tastes for the types of heroin they were sold (Ciccarone 2009).

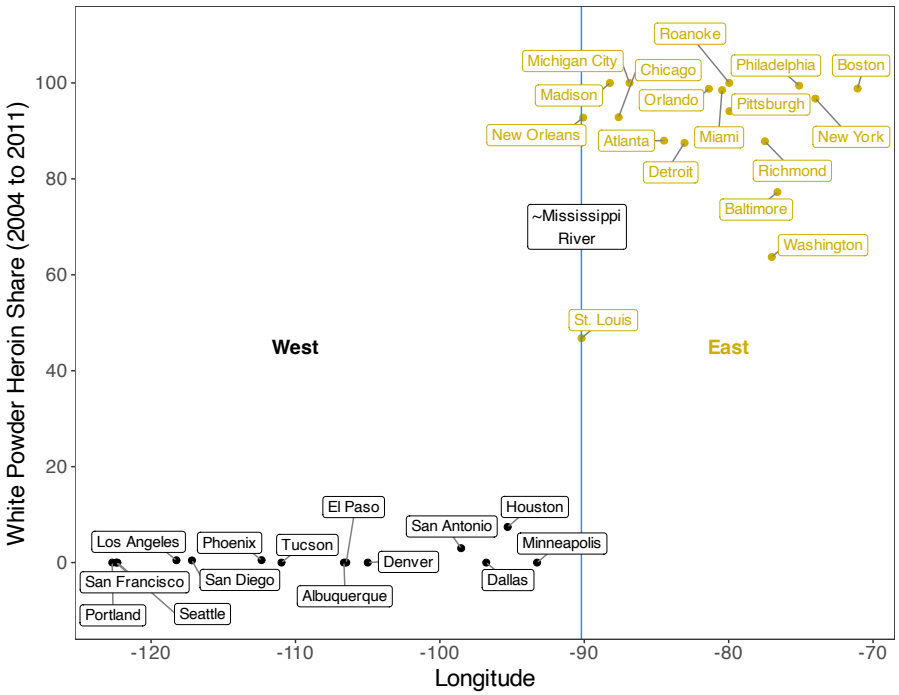


Figure 1: Geographic Segmentation of the U.S. Heroin Market

Notes: The data used to generate this figure comes from the Heroin Domestic Monitoring Program (HDMP) and each dot represents a city that is repeatedly sampled as part of this program. The share of white powder heroin in a given city is calculated by using the total number of exhibits collected by heroin type from 2004 to 2011, excluding exhibits with inconclusive testing (for which we can not confirm type) from the calculation. The centroid of the city is used to plot the longitude.

The means of trafficking heroin into the U.S. by the Colombian and Mexican groups also differed in fundamental ways. Colombian DTOs used couriers who concealed or swallowed packages of heroin and smuggled them on flights destined for the U.S., principally the John F. Kennedy (NY), Miami (FL), Newark (NJ), and San Juan (PR) international airports (DEA 2001). In contrast, Mexican DTOs smuggled heroin across the U.S.-Mexico border, primarily in San Diego, CA and El Paso, TX (DEA 2001).

Several factors pushed Colombian DTOs to abandon heroin trafficking. First, in 1997, the U.S. and Colombia re-instated a treaty that permitted narcotics traffickers to be extradited to the U.S. As a result, leaders of the most prolific Colombian cartels, such as Fabio Ochoa Vásquez (Medellin cartel) and Don Berna (AUC), were arrested, extradited, and imprisoned in the U.S.

[2]Data from the HDMP from 2004-2011 indicate 99% of white powder heroin was produced in Colombia and just 1% was produced in Southeast Asia.

throughout the early 2000s.[3] Second, the September 11, 2001 terrorist attacks led to heightened airport security, reportedly increasing the risks of smuggling drugs by air and shifting trafficking routes toward the U.S.–Mexico border, where Mexican DTOs held a geographic comparative advantage (DEA 2003).

Ultimately, Colombian DTOs scaled back their operations, focusing on wholesale production and selling heroin to Mexican DTOs, who assumed responsibility for cross-border trafficking and retail distribution in the U.S. As one DEA report notes:

> "The amount of South American heroin seized in the U.S. Arrival Zone along the Southwest Border—particularly Texas—increased significantly in 2003... Law enforcement reporting indicates that Colombian DTOs are increasingly relying on Mexican DTOs and criminal groups to transport South American heroin to the United States..." (DEA 2005, p. 68)

These events would eventually result in Mexican DTOs taking over the white powder heroin market, but this process was gradual (DEA 2001). Starting in 2005, estimates of Colombian heroin production permanently decreased and Mexican production increased.[4] Mexican DTOs increasingly sold black tar and brown powder heroin in eastern markets (DOJ 2007, p. 14), but these products never "took off."[5] Mexican DTOs even made a first attempt at introducing fentanyl in white powder heroin markets when they were a small player in these markets, allegedly to provide a product that more closely rivaled the higher potency Colombian white powder heroin (DOJ 2007, p.16). This led to the spike in fentanyl deaths in eastern cities from 2005 to 2007 seen in Appendix Figure A.2. The spike ended after the lab that manufactured the fentanyl in Toluca, Mexico was raided by the DEA in May 2006 (CDC 2008). DEA reporting indicates these efforts did not result in violence because Colombian DTOs were willing to cede market share to Mexican DTOs to reduce their exposure to interdiction (DOJ 2009, p.29).

Eventually, Mexican DTOs adopted Colombian heroin processing methods and introduced their own white powder heroin to the market. DEA data indicate that the tipping point for this shift was 2012, though some suggest it may have even began somewhat earlier and gone undetected by the agency's origin testing procedures (Ospina et al. 2018). The DEA's 2011 HDMP report notes an increase in heroin exhibits with inconclusive chemical origin analyses, possibly due to Mexican-produced white powder heroin or a mix of Colombian and Mexican heroin, but states that Colombian DTOs remained the primary producers of white powder heroin. The 2012 report was never released. However, by 2013, the market was clearly experiencing a significant shift, as indicated on the first page of the 2013 HDMP report:

[3] Colombian DTOs perceived the costs of this extradition treaty to be high. In the mid-1980s, Pablo Escobar waged a domestic terror campaign to intimidate lawmakers to oppose the treaty. Pablo Escobar's group, who referred to themselves as "Los Extraditables", had a motto of "we prefer a grave in Colombia to a prison in the United States" (Butt 2022).

[4] In total, estimates of opium cultivation, a proxy for potential heroin production, in Colombia derived from the Global Illicit Crop Monitoring Programme of the United Nations Office on Drugs and Crime declined by 93% percent from 2004 to 2017. Over the same period, opium cultivation in Mexico increased 774% percent, with the largest increases coming after 2012.

[5] DEA documents and a retired DEA Subject Matter Expert whom we spoke with, Bernie Malone, allege that this was due to users' and retail sellers' preferences for white powder heroin, which was much more potent (DOJ 2007, p.15)

> "Since the inception of the HDMP, the formal signature for Mexico has encompassed both brown and black tar Mexican produced heroin. Over the last several years however, DEA's Special Testing and Research Laboratory (SFL1) has tracked the phenomenon of alleged Mexican white powder heroin (AMW) produced from opium harvested in Mexico... Of particular interest is the fact that 57 of the 64 (89.1%) heroin exhibits classified as UNK which displayed the characteristics of alleged Mexican white heroin were purchased east of the Mississippi River, in cities identified as traditional SA [Colombian] heroin markets... This is likely an indication that the current retail heroin market in each of these cities is in transition and that Mexican drug trafficking organizations (DTOs) continue to expand their role in white heroin markets." (DEA 2016, p. 1)

The timing of the transition is summarized in Figure 2. In 2013, the DEA reports the first data on white powder heroin mimicking Colombian production methods that it suspects as coming from Mexico, accounting for 13% of all exhibits in eastern markets.[6] In 2014, 74% of exhibits in white powder markets were suspected Mexican heroin. By 2015, the DEA developed the ability to chemically identify Mexican-originating white powder heroin and half of white powder heroin exhibits were confirmed as originating in Mexico (an additional 23% were inconclusive Mexican or Colombian heroin).[7] Over the same time, Colombian DTOs exited white powder heroin markets. In 2016, 71% of white powder heroin was reported as originating in Mexico and fewer than 1% in Colombia (vs. 60% in 2011). Critically to the identification strategy that we present below, western markets were unaffected by this shift and black tar heroin from Mexico continued to comprise the vast majority of heroin sold there.

2.2 Drug Potency Changes in White Powder Heroin Markets

We next examine changes in heroin purity following the integration of heroin supply chains in Mexico. Figure 3 shows the distribution of purity exhibits across markets and years for Colombian white powder heroin just before the takeover (2010-2011), white powder heroin that the DEA suspected was from Mexico (2013-2014), and white powder heroin that the DEA reported as confirmed from Mexico (2015-2016). This figure highlights that both the alleged and confirmed Mexican white powder heroin were of higher purity on average than than the Colombian white powder heroin that came just before it. Further, the tail of the distribution and probability of very high purity heroin was much greater. This increased variability significantly raises the likelihood that a person consumes more heroin than their tolerance allows, a key factor in overdose risk (White and Irvine 1999). Appendix Figure A.3 presents yearly trends in average heroin purity and the 90th percentile of purity across black tar and white powder heroin markets, which highlights the sharp divergence between markets beginning in 2012.

The next and likely more consequential change is the increasing presence of fentanyl in white powder heroin supply. Fentanyl is a synthetic opioid that is 20 to 50 times more potent than

[6] Data from 2012 were excluded as the HDMP report was not released in that year.

[7] Developing the test for which country heroin is sourced from requires analyzing a sample that is known to be produced in the lab of a given country to compare subsequent samples to. Following entry of a new type of heroin, it would take some time for the DEA to be able to locate such a lab and obtain samples. This explains the long lag time to develop the tests.

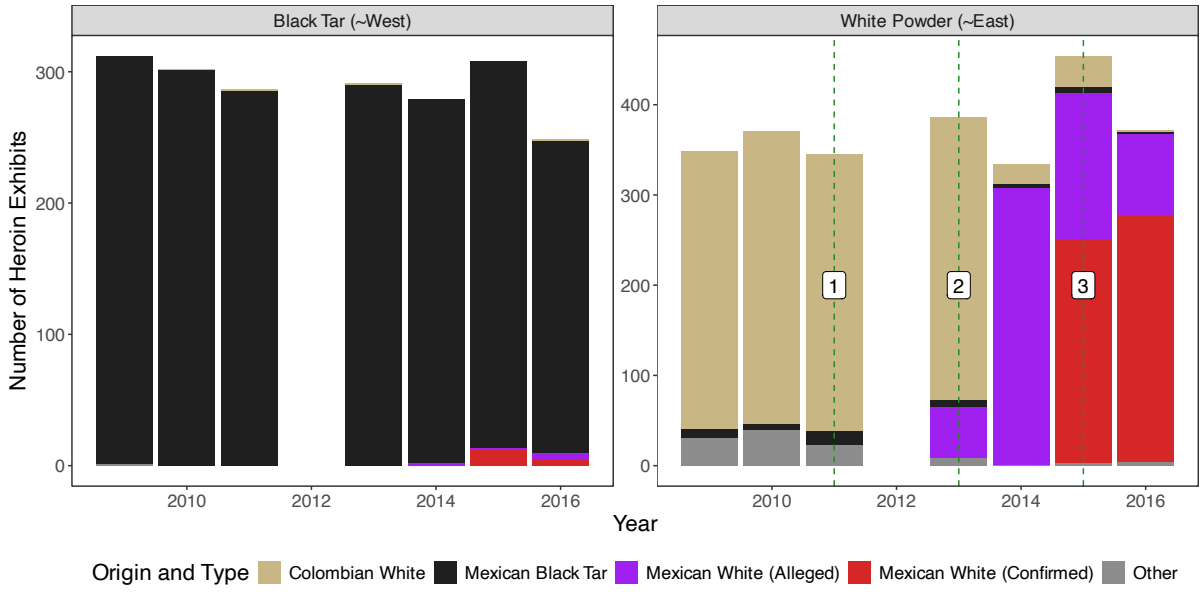


Figure 2: Trends in Heroin Origin and Type Across Markets

Notes: Data come from the Heroin Domestic Monitoring Program (HDMP). This figure presents the total exhibits by market, type, and year; 2012 is excluded due to lack of an HDMP report. In the right panel, 1. In 2011, the DEA first reports suspicions of Mexican DTOs mixing Mexican and Colombian heroin or producing white powder heroin that mimics Colombia processing methods, but that Colombian white powder remains the dominant type. 2. In 2013, the DEA first identifies suspected Mexican white powder heroin and inconclusive origin heroin that mimics Colombian heroin in the HDMP report. 3. In 2015, the DEA first implements a test to confirm Mexican white heroin.

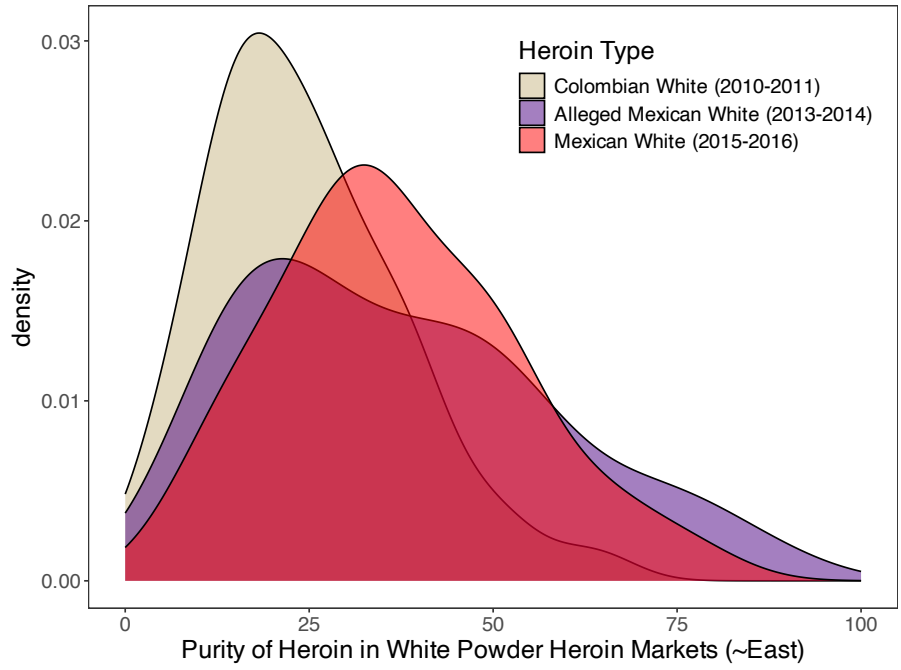


Figure 3: Purity Distributions by White Powder Heroin Type

Notes: Data come from the Heroin Domestic Monitoring Program (HDMP). This figure shows the distribution of purity of Colombian white heroin just before the Mexican DTO entry (2010-11), suspected Mexican white heroin during the first two years it is reported (2013-2014), and confirmed Mexican white heroin after testing was available (2015-2016). Appendix Figure A.3 presents yearly trends in average heroin purity and the 90th percentile of purity across black tar and white powder heroin markets.

heroin. Because of its high potency, small variations in quality, which are common in illicit drug markets, can trigger an overdose.[8] Ethnographic studies suggest that the shift to fentanyl began in the same white powder heroin markets, eastern cities like Baltimore and Boston, and at the same time that DEA data show a transition to Mexican-produced white powder heroin mimicking Colombian production methods (2012–2013) (Ciccarone et al. 2017; Mars et al. 2018, 2019). For example, one study asked a 30-year-old man who had been using heroin for 18 years about changes to heroin supply in Massachusetts (Ciccarone et al. 2017, p. 148):

> Q: So the heroin that is out there right now, how long has that been around? Have there been any changes?
>
> *A: It's been changing, like 3-1/2 years ago, maybe 4. 2012–2013, it's like that's when like the bullshit started coming in. Like mother-fucker's realized, if I got 3 grams of dope I can put 3 grams of bullshit on it.*
>
> Q: What do you mean by bullshit?
>
> *A: Like cut. Well, the fake cut or fentanyl or whatever [. . .]*

The first DEA data validating user reports of fentanyl contaminating white powder heroin supply appeared in the 2014 combined HDMP and HSP report. The report noted that 21 total heroin samples purchased through the program in 2014 contained fentanyl, and retroactively noted that 7 exhibits from 2013 contained fentanyl (DEA 2015, p. 23).[9] The report also noted that all samples containing fentanyl were purchased in eastern cities where white powder heroin was prevalent. By 2016, 40 percent of retail white powder heroin exhibits in the HDMP were adulterated with fentanyl, compared to fewer than 1 percent of black tar heroin exhibits. In terms of deaths, fentanyl-related mortality rates escalated dramatically in eastern states starting around 2013, building on a smaller epidemic from the mid-2000s; during that earlier period, Mexican DTOs were reportedly minor players in the white powder heroin market and first experimented with selling illicitly-produced fentanyl (see Appendix Figure A.2).

Ethnographic research suggests an important role for asymmetric information in driving the adoption of fentanyl-adulterated heroin in white powder markets. Heroin and other illicit drugs are classic examples of experience goods. Buyers are not able to observe the purity of drugs or what they are adulterated with until after they have consumed them, and there are no institutions to enforce quality in an illicit market. Therefore, sellers face strong incentives to rip off consumers through adulterating their products (Galenianos et al. 2012; Galenianos and Gavazza 2017). At the import level, fentanyl is approximately 99% cheaper than heroin due to its compactness, lower trafficking costs, and synthetic production, which eliminates the need for costly agricultural inputs (Pardo and Reuter 2020). As a result, it is an attractive adulterant from the perspective of heroin sellers. However, early on, many heroin users preferred heroin that did not include it because of the risk (Ciccarone et al. 2017; Mars et al. 2018, 2019).

Due to differences in the structure and physical appearance of white powder and black tar heroin (see Appendix Figure A.4), information asymmetries between buyers and sellers are

[8] A lethal dose of fentanyl for most individuals is just 2 milligrams (DEA 2024). Analyses of heroin and fentanyl samples show variation in quality of this amount is very common (Larnder et al. 2022).

[9] The lack of noting fentanyl in the 2013 report, despite it later being clarified that it was present in 2013 data, highlights the lag between changes to heroin markets and what shows up in the DEA documentation.

significantly greater in white powder heroin markets. Because fentanyl is also a white powder, it can be mixed with white powder heroin without detection prior to use. In contrast, black tar heroin is a solid, making adulteration more difficult and more visible. A quote from a heroin user illustrates this informational asymmetry (Carroll et al. 2017, p.14):

> "Black tar heroin I feel safer doing, It's harder to cut. It's not powder. Powder you can add anything to . . . Black tar heroin, in order to cut it, you have to do all this stuff to it, cook it, and it's a lot harder to cut, so I feel safer doing that. But as far as fentanyl? There's no way to know until you [use] it. Like I said, I avoid the grey dope, but there's nothing you can really do [to avoid it]."

Due to incomplete data on illicit drug supply chains, the precise mechanism behind the widespread adulteration of white powder heroin with fentanyl around 2012 remains uncertain. One possibility is that Mexican DTOs played a direct role, as suggested by their early experimentation with illicit fentanyl production (CDC 2008) and the timing of their takeover of white powder heroin markets. Supporting this view, a federal indictment of Ovidio Guzmán López, a leader of the Sinaloa Cartel, alleges that the cartel conspired to manufacture fentanyl in Mexico and import it into the U.S. beginning in at least 2014.[10] Alternatively, some evidence suggests Chinese chemical labs initially supplied fentanyl directly to retail sellers, who mixed it into heroin at the point of sale. As Chinese exports declined due to regulatory crackdowns, Mexican DTOs stepped in to sustain the supply (Dudley et al. 2019). Given limited data on these supply dynamics, we focus on the broader impact: adulteration with fentanyl was more prevalent in white powder heroin markets—where informational asymmetries were greater—regardless of whether it occurred through centralized trafficking or local mixing. This trend began around 2012, coinciding with the rise of Mexican-produced white powder heroin and disproportionately affected markets where white powder, rather than black tar, was dominant.

3 The Effects of Potency Shocks on Overdose Mortality

In this section, we describe our empirical strategy for estimating the causal effects of exposure to heroin potency shocks on mortality and present the main results. Our primary analysis focuses on commuting zones linked to the 31 cities tracked in the DEA's Heroin Domestic Monitor Program (HDMP), where we observe detailed data on heroin purity, source, and type. We find significant and growing increases in heroin and fentanyl overdose deaths in white powder heroin markets relative to black tar markets following the onset of the potency shocks. We next conduct a series of robustness checks, document a rise in the mortality rate among heroin users as a key mechanism, and show how these findings help explain the abrupt geographic and demographic shifts observed in the opioid epidemic.

3.1 Methodology

We examine the causal impacts of exposure to white powder heroin potency shocks by exploiting variation in which commuting zones the shocks occurred, driven by differences in their initial

[10] See U.S. vs. Lopez, available at: https://www.justice.gov/archives/opa/press-release/file/1579746/dl.

share of heroin purchases that were white powder, with the following event-study specification:

$$Y_{ct} = \rho_t \text{White\_Powder\_Market}_c + \lambda_c + \gamma_t + \nu_{ct}, \tag{1}$$

where Y_{ct} are overdose death rates per 100,000 in commuting zone c in year t. In our main specification, we define a commuting zone as a white powder heroin market ($\text{White\_Powder\_Market}_c$) if it has an above median share of pre-potency shock heroin purchases being white powder from 2004 to 2011, and we interact it with year fixed effects. λ_c and γ_t are commuting zone and year fixed effects, respectively, and regressions are population-weighted. Standard errors are clustered on commuting zones. The coefficients of interest are therefore ρ_t, normalizing the year before the initial shock (2011) to zero, which capture the year-by-year differences in within-changes among commuting zones that are exposed to the potency shocks relative to ones that are not.

We also estimate an average effects version of Equation (1) with

$$Y_{ct} = \beta(\text{White\_Powder\_Market}_c \times \text{Post}_t) + \lambda_c + \gamma_t + \varepsilon_{ct}, \tag{2}$$

where all variables are defined as before except for Post_t, which is an indicator variable for the period from 2012 to 2019. The coefficient of interest is therefore β, which captures the average mortality impact among commuting zones that are exposed to the potency shocks relative to ones that are not.

To extend our analysis nationwide, we replace the variable $\text{White\_Powder\_Market}_c$ in Equations (1) and (2) with a variable denoting whether the centroid of each commuting zone is east of -91 degrees longitude (Eastern_Market_c) and use all contiguous U.S. commuting zones, instead of only ones that we have HDMP data for. The decision to use longitude as a delineation for exposure to the potency shocks is driven by what we observe in Figure 1: a clear geographic segmentation of the U.S. heroin market at around -91 degrees. However, the results are not sensitive to using alternative thresholds to divide areas into east and west.

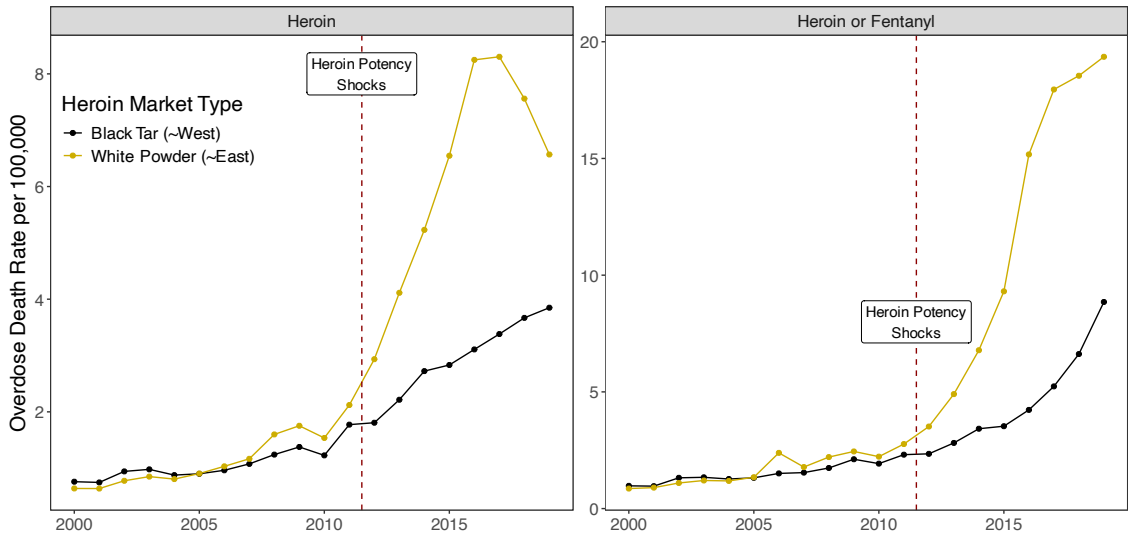
Identification relies on the assumption that, absent exposure to potency shocks beginning in 2012, overdose mortality rates would have followed similar trends in cities with white powder and black tar heroin markets. To support this, we examine pre-trends in opioid mortality for both market types below. Before doing so, however, Appendix Figure A.5 assesses whether cities with different heroin markets had baseline characteristics that could have influenced post-2012 mortality trends. We find that cities with white powder and black tar heroin markets had nearly identical pre-period overdose mortality rates and socioeconomic characteristics. One potential concern is that eastern cities, where white powder heroin was dominant, may have experienced greater exposure to the OxyContin reformulation in 2010, which could have led to differential mortality trends (Alpert et al. 2018; Evans et al. 2019). However, these cities had nearly identical pre-reformulation OxyContin shipment rates as well. The only significant baseline difference observed is in the share of heroin that was white powder versus black tar, reinforcing that black tar heroin markets provide a strong control group for estimating counterfactual mortality trends absent exposure to heroin potency shocks.

3.2 Dynamic and Average Impacts

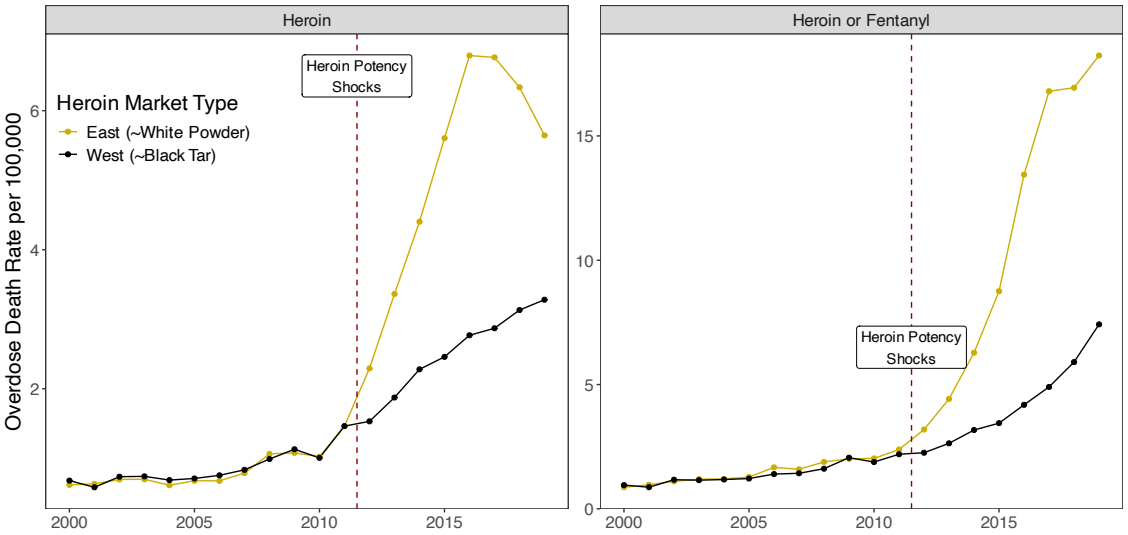
We start by plotting raw trends in illicit opioid death rates among commuting zones by heroin market type (white powder versus black tar) in Figure 4. As shown, mortality rates from heroin or any illicit opioid trend similarly from 2000 to 2011 in both samples. Then, starting in 2012, at the same time as the potency shocks in white powder heroin markets, overdose mortality diverges significantly and increases to a much greater extent in cities with white powder relative to black tar heroin markets. This differential increase continues to grow over time.[11]

Figure 4: Yearly Illicit Opioid Overdose Death Rates by Market Type

Panel A: HDMP Sample



Panel B: Nationwide Sample



Notes: This figure presents illicit opioid overdose death rates using National Vital Statistics System's restricted mortality data. In Panel A, we limit the sample to commuting zones that had a city that participated in the HDMP. In Panel B, we use data for the contiguous US and define heroin markets by whether they are East or West of the Mississippi River.

[11] Appendix Figure A.6 shows the distribution of changes in illicit opioid deaths from 2011 to 2019 across HDMP commuting zones by heroin market type. Most commuting zones with white powder markets saw larger mortality increases than those with black tar markets.

Next, we summarize these differential changes using our event study specification. The left panel of Figure 5 provides the event studies from estimating Equation (1) separately for overdose deaths involving heroin and those involving fentanyl. Again, we do not observe a significant pre-trend in illicit opioid mortality between commuting zones with white powder versus black tar heroin markets for over ten years prior to the potency shocks. Then, we see an immediate and dynamic increase in the heroin death rate in white powder heroin markets relative to black tar heroin markets that lasts for approximately five years. Afterwards, it slowly declines but remains significant. As the heroin death rate declines in white powder heroin markets, those same markets experience a dynamic and large increase in fentanyl overdose death rates.[12,13]

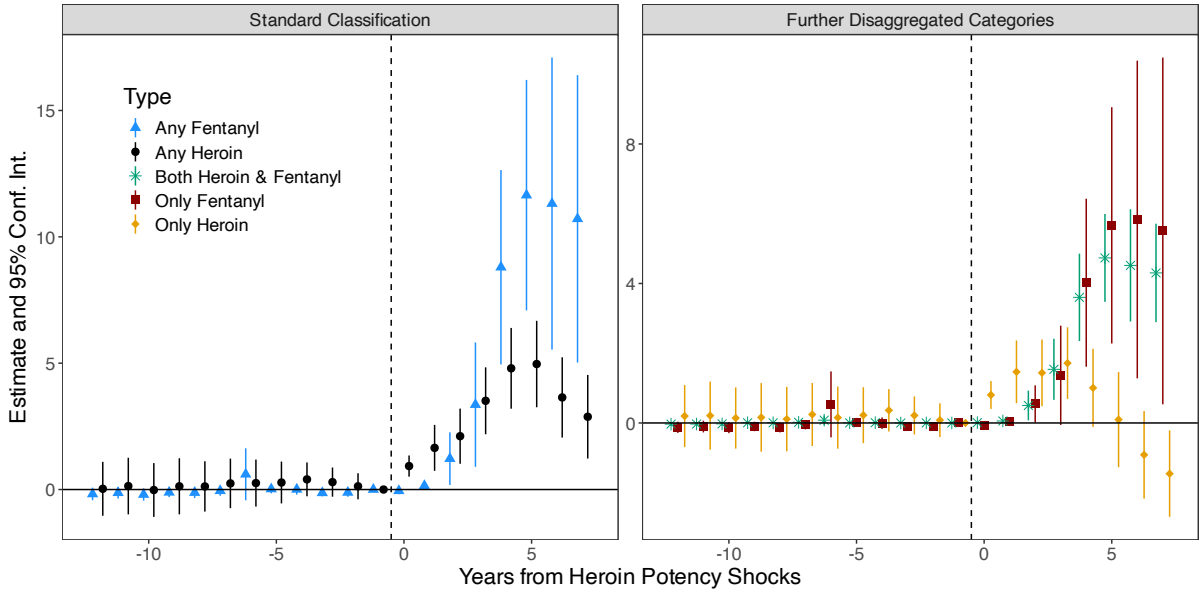


Figure 5: Dynamic Mortality Impacts of Exposure to Potency Shocks

Notes: These figures present the ρ_t coefficients from estimating Equation (1). The White Powder Heroin treatment indicator variable is defined as having an above median share of total pre-potency shock heroin purchases being white powder. The models include commuting zone and year fixed effects, standard errors are clustered at the commuting zone, and the regressions are population weighted. Outcomes are overdose deaths per 100,000 and the sample includes 31 commuting zones where we have HDMP data on heroin type. The left panel shows deaths involving heroin and deaths involving fentanyl separately, while the right panel breaks these down further into deaths involving only fentanyl (i.e., no heroin present), only heroin, and both heroin and fentanyl.

The right panel of Figure 5 repeats the event study analysis for overdose deaths involving both heroin and fentanyl, only fentanyl, and only heroin.[14] The patterns show fentanyl progressively replacing heroin in white powder heroin markets. Initially—just after the 2012 shift in white powder heroin production to Mexico—deaths involving only heroin significantly increased. Combined with the results in Section 2, this suggests that early mortality increases were largely driven by increasingly strong and variable heroin. However, over time and especially after 2014, these heroin-only deaths gave way to a steady rise in deaths involving heroin-fentanyl

[12]The Mexican DTOs' experimentation with fentanyl in eastern markets referenced in Section 2 and observed in Figure A.2 can be seen in event time -6 for fentanyl overdose deaths in Figure 5.

[13]Appendix Figure A.7 re-estimates Equation (1) for overdose death rates but uses a leave-one-out procedure, showing that these results are not driven by any single commuting zone. Appendix Figure A.8 presents the event study equivalent for the nationwide analysis, showing results that closely align with these HDMP findings.

[14]Except for this brief breakdown, all remaining analyses focus on overdose deaths involving any heroin, any fentanyl, or either substance.

combinations and eventually fentanyl alone.

This dynamic reflects a broader transition: the heroin potency shocks served as a gateway for fentanyl's entry into the market, first as an adulterant and then as a standalone product. A key mechanism for this is thick market externalities for addictive products (Cutler and Donahoe 2024). Once heroin users were inadvertently exposed to fentanyl, some would have become addicted to it or even developed a preference for it due to higher potency, leading to increased demand and enabling the formation of thick fentanyl-only markets. In this way, an initially exogenous shock triggered a structural transformation of the illicit opioid market. This mechanism echoes prior findings, such as the role of OxyContin's aggressive marketing in initiating downstream substitution towards heroin and later fentanyl (Alpert et al. 2022).

We next estimate Equation (2) and present the average mortality impacts of the potency shocks in Table 1.[15] The average effect in the left panel of Figure 5 for heroin corresponds to Column (1) of Table 1, indicating an increase in heroin overdose deaths of 2.894 per 100,000—a 233% rise from the pre-treatment mean. Column (2) shows the corresponding average effect for fentanyl overdose deaths from the left panel of Figure 5, with an increase of 5.928 deaths per 100,000, amounting to a 901% increase. Column (3) demonstrates that this increase is concentrated in overdoses involving either heroin or fentanyl. In contrast, Column (4) shows a small and imprecise estimate for non-opioid overdose deaths, and Column (5), which measures all-cause overdose mortality, is similar to Column (3), confirming that the rise in mortality is driven by illicit opioids.

Table 1: Average Mortality Impacts of Exposure to Potency Shocks

	Any Heroin (1)	Any Fentanyl (2)	Heroin or Fentanyl (3)	Non-Opioids (4)	Any Drug (5)
(White Powder Market)X(Post)	2.894***	5.928***	6.416***	-0.4562	5.343***
	(0.6703)	(1.351)	(1.454)	(0.5956)	(1.657)
Pre-treatment mean	1.24	0.658	1.87	4.58	10.9
R^2	0.792	0.648	0.743	0.794	0.807
Observations	620	620	620	620	620

Notes: This table presents the β coefficients from estimating Equation (2). The White Powder Heroin treatment indicator variable is defined as having an above median share of total pre-potency shock heroin purchases being white powder and Post is an indicator for 2012 and after. The sample is commuting zones that had a city that participated in the Heroin Domestic Monitor Program (HDMP). The models include commuting zone and year fixed effects, standard errors are clustered at the commuting zone, and the regressions are population weighted. Outcomes are overdose deaths per 100,000.

3.3 Robustness Checks

We test alternative explanations for our results by re-estimating Equation (2) and adding controls for other potential drivers of rising heroin death rates discussed in the literature, which are summarized in Figure 6 for heroin and fentanyl.[16] We first examine whether previously studied legal market interventions attenuate our estimates. Specifically, we control for pre-reformulation OxyContin shipments using ARCOS data and interact this with an indicator for the post-2010

[15] Appendix Tables B.1 and B.2 utilize different pre-potency shock white powder heroin treatment definitions. Appendix Table B.3 is the nationwide equivalent of Table 1.

[16] Event study results that incorporate each of these controls are in Appendix Figure A.9.

period, when OxyContin was reformulated. We do this separately using continuous OxyContin shipments and an indicator for above versus below median OxyContin shipments. Neither leads to any attenuation of our results.

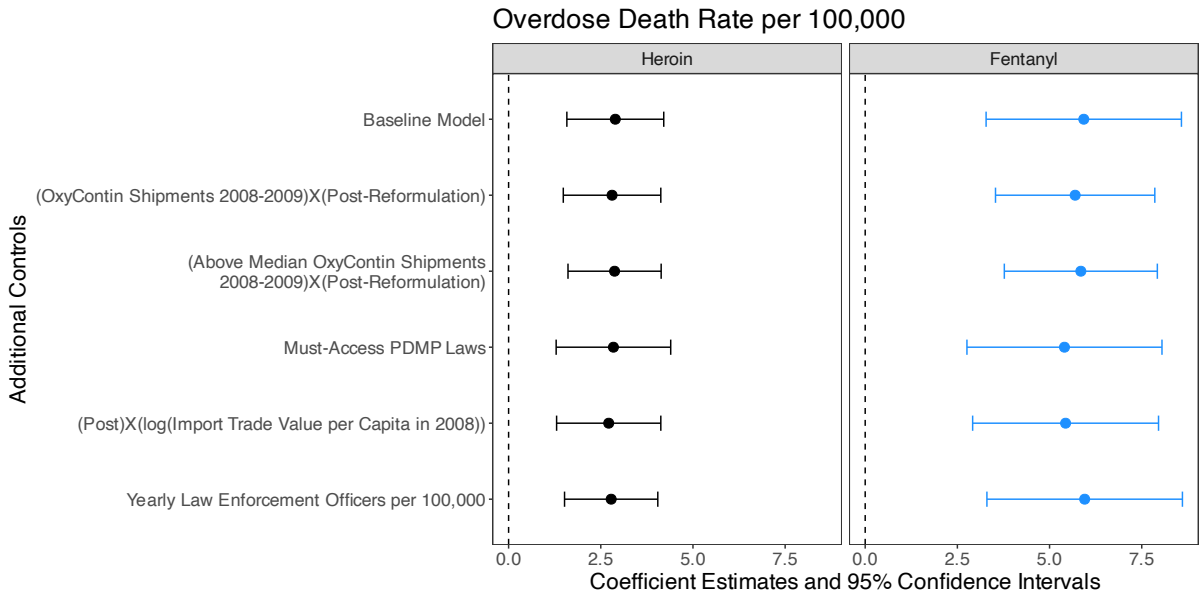


Figure 6: Average Mortality Impacts of Exposure to Potency Shocks with Additional Controls

Notes: This figure presents the β coefficients from estimating Equation (2) with different controls. Each control is added to the baseline model and estimated independently, except for the triple interaction term, which includes an additional interaction term. The White Powder Heroin treatment indicator variable is defined as having an above median share of total pre-potency shock heroin purchases being white powder, and Post is an indicator for 2012 and after. The models include commuting zone and year fixed effects, standard errors are clustered at the commuting zone, and the regressions are population weighted. Outcomes are overdose deaths per 100,000 (left for heroin, right for fentanyl) and the sample includes only commuting zones where we have HDMP data. Appendix Tables B.4 and B.5 are the table versions, and Appendix Figure A.9 provides the associated event studies.

Next, we include indicators for the period after a state passes a must-access Prescription Drug Monitoring Program, a state-level policy intended to prevent prescription opioid diversion that prior literature shows increased illicit opioid death rates (Kim 2021; Balestra et al. 2021). This exercise also shows that our main coefficients of interest, the βs for both heroin and fentanyl overdose death rates, are very stable and suggests that our results are not affected by policies intended to reduce prescription opioid misuse. The remainder of Figure 6 explores whether enforcement or trade affects our main results. More specifically, we first control for the yearly number of officers per 100,000 in a given commuting zone using Law Enforcement Officers Killed and Assaulted (LEOKA) data. This is our best nationwide measure of whether enforcement changed during our sample period. Second, we use the same trade data as in Moore et al. (2023), namely those from the U.S. Census' Trade Online portal on imports in 2008 based on the "state of destination" code. This is meant to capture smuggling of fentanyl via legal trade packages. We interact it with a Post indicator variable.[17] Both of these exercises show that our main coefficients of interest are again very stable. Appendix Figure A.10 and Appendix Tables B.6 and B.7 repeat this for all contiguous counties and yield similar conclusions.

[17]Because only state-level trade data are available, our main specification assigns these values to all CZs within each state, which may introduce measurement error (that we try to mitigate by weighting by CZ population). As an additional check, we re-estimate Appendix Tables B.4 and B.5 at the state-level in Appendix Table B.8.

We also estimate models that include a triple interaction between pre-reformulation OxyContin shipments, being in a white powder heroin market, and the post-reformulation period, as well as all corresponding double interactions (reported in Appendix Tables B.4 and B.5). This tests whether substitution from OxyContin to heroin was stronger in white powder heroin markets—where the products may be closer substitutes—than in black tar heroin markets, or whether the shocks had larger effects because of more people substituting from heroin to OxyContin. Across these specifications, however, we continue to find no evidence of attenuation of our main results—the increases in mortality are driven by exposure to white powder heroin potency shocks, independently of prior OxyContin use. Moreover, the coefficient on this triple interaction is negative, suggesting greater substitution to black tar heroin (rather than white powder heroin) heroin following OxyContin reformulation.

As a final nonparametric exercise to demonstrate robustness of inference, we conduct a permutation test to examine how extreme the increases in opioid mortality in the 31 HDMP markets following the potency shocks were relative to overall variability in opioid mortality in these cities over this period. For each outcome of interest, we randomize with replacement which commuting zone that participated in the HDMP gets "treated," (i.e., has a white powder heroin market) then run Equation (2) 1,000 times using a new sample each time but with the post period still starting in 2012. Appendix Figure A.11 presents the distribution of the placebo coefficients obtained from these regressions, where the dotted vertical red line is our estimated coefficient. Our estimated increases in heroin and fentanyl mortality for cities exposed to the potency shocks were above the 99^{th} percentile of their respective placebo estimate distributions.

3.4 An Increase in the Mortality Rate of Heroin Users (Mechanism)

The preceding results document large increases in heroin and fentanyl mortality in areas with white powder heroin markets following the integration of heroin supply chains in Mexico and the onset of fentanyl adulteration. In this section, we assess whether these mortality increases reflect an increasing rate of death among existing heroin users, which may come through accidental use of more lethal products (e.g., more variable in purity or fentanyl-adulterated heroin) as well as heroin users migrating to more lethal fentanyl after exposure fentanyl-adulterated heroin.

We begin by testing whether areas with higher pre-2012 heroin use experienced larger increases in overdose deaths, as would be expected if exposure to heroin potency shocks disproportionately affected larger, heavier-use heroin markets. We proxy baseline heroin use with heroin-related overdose death rates in the years prior to the supply chain shift, using two periods: 2005–2011 and, for robustness, 2005–2009, which excludes the OxyContin reformulation period. Panel A of Appendix Table B.9 shows that heroin mortality rose sharply in eastern white powder heroin markets following the supply shocks, with especially pronounced effects in areas with higher baseline heroin mortality. In our main specification, each additional pre-shock heroin death per 100,000 is associated with a 38 percent larger increase in post-shock overdose deaths. The pattern is even stronger for fentanyl-related deaths and total opioid mortality, while non-opioid overdose deaths remain small and insignificant. Results are similar if we instead use pre-OxyContin reformulation rates of heroin death rates to proxy pre-shock heroin use (Panel B of Appendix Table B.9), further supporting the interpretation that the observed mortality

increases stem from exogenous changes in the lethality of the heroin supply in areas with larger heroin markets independent of the OxyContin reformulation.

We further assess whether rising mortality reflects a more lethal heroin supply by estimating changes in the annual probability of overdose death conditional on heroin use. To do this, we combine heroin overdose death counts from the NCHS with self-reported past-year heroin use from the National Survey on Drug Use and Health (NSDUH). The NSDUH provides the only consistent national data on heroin use over time, though it is not publicly available at the state level. Thus, we can only use it to provide national estimates and cannot present estimates solely for white powder heroin markets. One additional concern with the NSDUH is that it undercounts heroin use due to under-reporting and omits high-risk populations (e.g., individuals experiencing homelessness) (Reuter et al. 2021). However, assuming this under-counting is time-invariant—an assumption that we support by examining pre-period trends below—the data still allow us to assess how the risk of overdose among heroin users evolved following the potency shocks that began in 2012.

Figure 7 presents our estimates of the annual overdose mortality risk among heroin users. Consistent with the assumption of time-invariant under-reporting, the estimated annual probability of overdose death among past-year heroin users remains flat at approximately 0.73 percent from 2002 to 2011 (slope = 0.00004, p = 0.68). Notably, the estimate remains stable in 2011, during which prior literature and we (in Section 4) show heroin use and mortality was increasing (Alpert et al. 2018; Evans et al. 2019). This shows that the NSDUH adequately picked up increases in heroin use in that year and that the estimate of changes in the mortality rate among heroin users remained unbiased despite rising use. The estimate of 0.73 percent also aligns with estimates from epidemiological studies conducted prior to the fentanyl era, which places annual overdose risk from heroin use at around 0.52 percent (Keyes et al. 2022). Beginning in 2012—at the onset of the white powder heroin potency shocks—there is then a statistically significant level increase of 0.33 percentage points (p = 0.001), followed by an annual increase of 0.20 percentage points (p < 0.001). These estimates imply that the mortality risk among users rose by 232 percent from 2011 to 2019. This pattern provides further evidence that people who use heroin began to overdose at a much higher rate beginning in 2012, driven by increased variability in heroin purity and fentanyl adulteration.

Trends in heroin use and overdose deaths are presented separately in Appendix Figure A.12. Estimates of past-year heroin use increased at a fairly linear rate from roughly 2002 to 2017, before declining and dipping below pre-2012 levels between 2017 and 2019. When combined with the results in Figure 7, this pattern suggests that by 2019, elevated heroin overdose death rates were almost entirely driven by a higher probability of death among those using heroin, rather than by increased prevalence of use. However, earlier increases—particularly those leading up to 2017—were partly attributable to rising heroin use. From 2010 to 2017, we estimate that 21 percent of the national increase in heroin overdose deaths was due to greater use, while the remaining 79 percent resulted from higher mortality risk among users.[18]

[18]The first part comes from quantifying the change in heroin use from 2010 to 2017, interacted with the 2010 death rate. This alone resulted in 2,600 more heroin overdose deaths in 2017 relative to 2010. The second part comes from interacting the number of heroin users in 2017 with the change in death rates from 2010 to 2017, which resulted in roughly 9,900 more deaths.

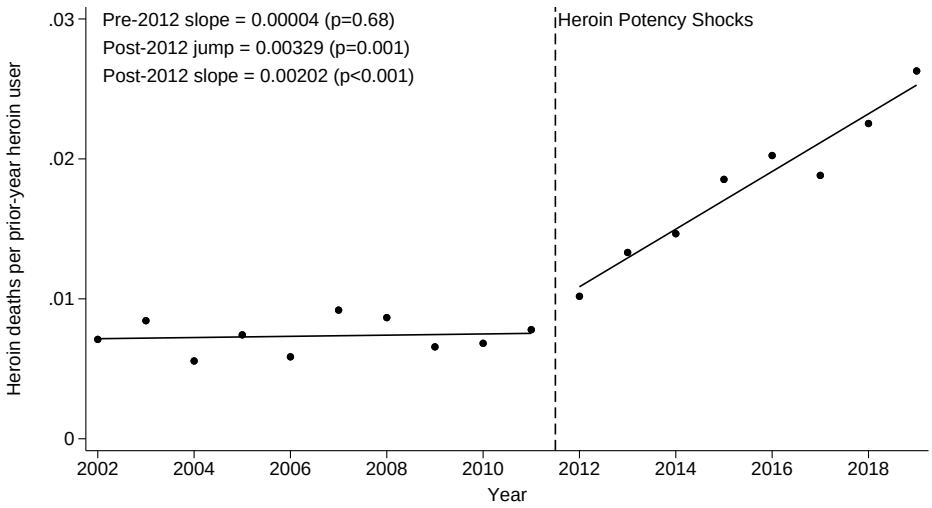


Figure 7: Yearly Trends in Ratio between Heroin Use (NSDUH) and Overdose Mortality (CDC)

Notes: This figure shows the estimated annual probability of heroin overdose death conditional on any prior-year heroin use. Heroin mortality counts are from CDC Vital Statistics; heroin use estimates are based on self-reported past-year use from the National Survey on Drug Use and Health (NSDUH). The plotted series reflects the ratio of overdose deaths to estimated users in each year. Estimates are derived from a segmented linear regression with a breakpoint at 2012. The results indicate a statistically significant level shift of 0.33 percentage points ($p = 0.001$) in 2012, followed by an additional yearly increase of 0.20 percentage points ($p < 0.001$), relative to a flat pre-2012 trend. These findings are consistent with a sharp and sustained rise in the lethality of the heroin supply beginning in 2012.

3.5 The Changing Geography and Demographics of the Opioid Epidemic

Next, we examine the extent to which our findings can explain two puzzles of the opioid epidemic: why eastern states bore the brunt of the illicit opioid waves despite a nationwide prescription crisis, and why mortality rose sharply among demographic groups with low exposure to prescription opioids after 2012. We show that both patterns are explained by potency shocks hitting eastern U.S. areas with white powder heroin markets and having broad impacts across racial and ethnic groups, independent of prior prescription opioid epidemic exposure.

We begin with the changing geography of the epidemic. In Panel A of Appendix Figure A.13, we plot the state-level change in prescription opioid overdose death rates from 2000 to 2009, the period before the OxyContin reformulation, against the 2004–2009 state-level OxyContin misuse rate used in Alpert et al. (2018). We also overlay best-fitting regression lines from a regression of changes in mortality on OxyContin misuse and a dummy variable for being east of the Mississippi River (i.e., a white powder heroin market). There is a strong positive and statistically significant relationship between changes in prescription opioid death rates and OxyContin misuse rates over this period—each unit increase in misuse is related to a 4.4-percentage point greater increase in prescription opioid death rates—and the regression lines for states east and west of the Mississippi river overlap. Neither the East dummy nor its interaction with OxyContin misuse is significant, indicating that rates of OxyContin misuse were the main predictor of which areas were being most affected by the opioid epidemic and geography was not a relevant factor.

Panel B of Appendix Figure A.13 shows the change in heroin- and fentanyl-related overdose death rates from 2010 to 2019 against the same misuse measure. Here, the slope on misuse is small and insignificant, but there is a large and significant east-of-Mississippi shift that is

independent of exposure to OxyContin: eastern states saw roughly 15.8 more deaths on average than western states. The interaction term is small and insignificant, suggesting that prior OxyContin misuse does not explain this divergence. This stark East–West divergence in illicit-opioid mortality dovetails with our potency-shock mechanism—white powder heroin markets, predominantly in the East, experienced increases in heroin purity variability and fentanyl adulteration, which in turn drove the regional spike in overdose deaths.

We next assess whether the effects of the potency shocks varied by race. The left panel of Appendix Figure A.14 highlights that prescription opioid overdose rates were significantly higher for White individuals and followed a distinct trend compared to Black individuals. However, the right two panels shows that illicit opioid overdose deaths were similar across racial groups, both in levels and trends. A poorly understood question is why Black individuals have been so much more impacted by the heroin and fentanyl epidemic, relative to their much lower exposure to the prescription opioid epidemic compared to White individuals (Ruhm 2022; Mulligan 2024). One potential explanation for this is that heroin use was similar for Black individuals (as suggested by Appendix Figure A.14) and, thus, Black individuals were affected similarly to White individuals by heroin potency increasing in eastern markets post-2012.

The regression results in Appendix Table B.10 are consistent with this hypothesis. The estimated impacts of potency shocks are generally largest for groups with the highest pre-shock heroin death rates (a proxy for use); however, since pre-shock death rates are quite similar across these groups, the impacts are also similar relative to the much larger differences in the extent of the prescription opioid epidemic.[19] Panel A shows that illicit opioid deaths increased by 6.42 per 100,000 (a 343% increase) in HDMP commuting zones, with broad effects across racial and ethnic groups. Estimates are similarly large and statistically significant for White, Black, and Hispanic individuals, and differences in estimates are not statistically different from one another across groups. The results are similar in the nationwide analysis (Panel B), except for Native Americans, whose estimated effect is considerably larger and statistically significant in the nationwide analysis. This discrepancy is likely due to the smaller Native American population in the HDMP sample.

4 The Overall Determinants of Heroin and Fentanyl Mortality

In this final section, we integrate our findings with prior literature that identified policy interventions—namely the OxyContin reformulation and must-access Prescription Drug Monitoring Programs (PDMPs)—as the primary drivers of increases in illicit opioid death rates. To do so, we first estimate state-level event study models to replicate their approach, and then incorporate controls for exposure to the potency shocks. We find that including controls for east-by-year fixed effects substantially attenuates the estimated effects of the OxyContin reformulation and PDMPs. We conclude that unintended policy consequences played a smaller, though still consequential, role in driving illicit opioid mortality, with potency shocks contributing roughly equally to these policy effects in fueling the illicit waves of the opioid epidemic.

[19] Appendix Figure A.15 provides an alternative comparison of the impacts by race using a unified model and arrives to a similar conclusion.

4.1 Background on Policy Interventions

In response to the first wave of the opioid epidemic, numerous interventions were introduced during the 2010s to more tightly control prescription opioid supply. A key conclusion in the literature examining these legal market interventions is that they backfired by stimulating demand for illicit opioids, which are pharmacological substitutes for prescription opioids, and caused the majority of the transition to the illicit waves of the opioid epidemic. This includes the reformulation of OxyContin (a widely abused prescription opioid) to be abuse-deterrent (Alpert et al. 2018; Evans et al. 2019) and the adoption of state-level programs requiring physicians to screen patients for risky opioid prescribing histories before prescribing opioids (PDMPs) (Kim 2021; Balestra et al. 2021). However, key results in this literature overlook the potency shocks we identify, which emerged around the same time as the OxyContin reformulation (August 2010) and the state-level rollout of must-access PDMPs (beginning in 2012).

Studying the overall determinants of rising heroin and fentanyl mortality—including these policy interventions and potency shocks—is crucial for two reasons. First, from a policy evaluation perspective, it is important to assess the independent effects of the OxyContin reformulation and must-access PDMPs on illicit opioid mortality after adjusting for heroin potency shocks. If the effects of these interventions differ from prior estimates, their costs and benefits should be reconsidered. Second, the literature suggests these policies were the main drivers of the transition to the heroin (Alpert et al. 2018; Evans et al. 2019) and fentanyl (Powell and Pacula 2021) waves of the opioid epidemic. If these conclusions change in light of our new evidence on potency shocks, it calls for rethinking interventions to curb the epidemic and prevent further mortality increases.

4.2 OxyContin Reformulation

We start by studying the OxyContin reformulation and extend the work of Alpert et al. (2018) and Powell and Pacula (2021). Aggregating our mortality data to the state-level, we estimate

$$Y_{st} = \alpha_s + \gamma_t + \delta_t \text{OxyMisuse}_s^{Pre} + \beta_t \text{White\_Powder\_Market}_s + \epsilon_{st}, \tag{3}$$

where the first four terms are the same as in Equation (1) of Alpert et al. (2018). Y_{st} are yearly overdose death rates in a given state, and we examine deaths due to heroin (the focus of prior literature) as well as deaths involving fentanyl. α_s and γ_t are state and year fixed effects, respectively, to adjust for time-invariant factors affecting opioid mortality across states and time-varying factors that affect all states across years. $\delta_t \text{OxyMisuse}_s^{Pre}$ interacts year fixed effects with each state's fixed pre-reformulation rate of OxyContin misuse, drawn from the 2004-2009 National Survey on Drug Use and Health. We normalize the 2009 coefficient (the year before reformulation) to zero. Thus, the δ_t coefficients identify differential changes in illicit opioid mortality rates after the reformulation for states with one percentage point higher pre-reformulation prevalence of OxyContin misuse. We then add $\beta_t \text{White\_Powder\_Market}_s$, the same variable to identify exposure to potency shocks from Section 3: being east of -91 degrees longitude and measured based on a state's centroid, interacted with year fixed effects. We weight regressions by state population and cluster standard errors at the state-level.

Panel A of Appendix Figure A.16 shows that, consistent with prior studies, the specification that does not control for exposure to potency shocks reveals large increases in heroin overdose death rates following reformulation in states with higher OxyContin misuse beginning in 2011. However, after controlling for potency shocks, estimates attenuate substantially. While effects remain in 2011–2012, they diminish sharply from 2013 to 2019, and collectively, the estimates averaged across all years post-reformulation attenuate by 58% and are not statistically significant.

Two concerns may lead us to understate the effects of the OxyContin reformulation in this specification. First, pre-reformulation OxyContin misuse may be correlated with unobserved factors influencing mortality trends, such as shifts in prescribing patterns or policies targeting areas with high prescription opioid misuse. To address this, Panel B adds controls for general pain reliever misuse from the 2004–2009 NSDUH interacted with year effects, following Alpert et al. (2018), Beheshti (2019), and Park (2025). This approach identifies the effects of the reformulation from variation in baseline OxyContin misuse, conditional on overall prescription opioid misuse. While baseline estimates increase modestly, attenuation after adjusting for potency shocks persists (55%). Second, measurement error in NSDUH OxyContin misuse rates could bias estimates toward zero. Following Alpert et al. (2018), we attempt to address this by instrumenting for pre-reformulation misuse (2008–2009) with earlier misuse (2004–2005). These instrumental variable estimates (Panel C) similarly show a 55% attenuation after accounting for potency shocks. Using state-level pre-reformulation (2006-2009) OxyContin shipments from ARCOS—an exact measure of OxyContin flows into states that is unaffected by reporting error but an imperfect proxy for misuse due to cross-state consumption and incomplete correspondence between prescribing and misuse—yields quantitatively similar results, with 52% attenuation following controlling for exposure to potency shocks.

We also explore whether the OxyContin reformulation interacted with potency shocks (e.g., by drawing in more vulnerable, inexperienced users) via a triple interaction of pre-reformulation misuse, geography, and year fixed effects. However, the negative interaction coefficient reported in Section 3 (Appendix Tables B.4 and B.5) rejects this hypothesis. Appendix Figure A.17 illustrates this further by presenting a figure that resembles Evans et al. (2019)'s analysis of heroin mortality trends by state OxyContin shipment rates. We extend their approach by separately presenting trends for eastern vs. western states with above vs. below median pre-reformulation OxyContin shipment rates. Western states show a clear increase in heroin deaths after reformulation in high-shipment areas, as shown in Evans et al. (2019). However, eastern states—which were exposed to potency shocks beginning around 2012—experience much larger increases in mortality, irrespective of their baseline rate of OxyContin shipments.

Overall, our evidence suggests the impact of the OxyContin reformulation on heroin overdose mortality is roughly half the size previously reported. Nonetheless, there remains a measurable effect during 2011–2012, particularly in western states, with longer-term effects attenuated and imprecisely estimated. Appendix Figures A.18 and A.19 present analogous analyses for fentanyl and net illicit opioid (i.e., heroin or fentanyl) mortality rates, similar to Powell et al. (2020). Results are similar: controlling for potency shocks attenuates estimated reformulation effects by 40 to 55%; however, there is a larger potential role for OxyContin reformulation in explaining

longer-term rises in fentanyl death rates. The relationship between pre-reformulation OxyContin and fentanyl mortality grows over time. This could stem from people who the OxyContin reformulation caused to transition to heroin in early years (2011-2012) later being impacted by fentanyl-adulterated heroin or transitioning to fentanyl as it became more available.

Appendix Figure A.20 presents results for the impacts of exposure to heroin potency shocks on heroin, fentanyl, and illicit opioid mortality, before and after controlling for OxyContin reformulation. This is similar to the results presented in Section 3, but using the same state-level event study models used in prior literature. Controlling for exposure to OxyContin reformulation attenuates these estimates by no more than 1 to 7 percent.

4.3 Must-Access PDMPs

We also examine the effects of must-access Prescription Drug Monitoring Programs (PDMPs) on heroin and fentanyl mortality. We estimate a two-way fixed effects model with indicators for each year relative to PDMP adoption, both with and without controlling for the interaction between east and year fixed effects.[20] Exposure to OxyContin reformulation is controlled for by interacting 2006–2009 OxyContin shipments with year fixed effects, as in Kim (2021). Due to staggered adoption timing, some states lack observations in distant relative future periods. Following Kim (2021) and leveraging our extended data, we construct a balanced sample of 17 treated states with a -8 to +3 year window relative to adoption and 15 control states without PDMP adoption by 2019. Indicators outside this window are trimmed. We also test robustness using the Callaway and Sant'Anna (2021) estimator, which accounts for heterogeneous treatment effects under staggered adoption. Regressions are weighted by state population, with standard errors clustered at the state level.

Results in Appendix Figure A.21 reveal a pattern similar to that found for the OxyContin reformulation. After controlling for potency shocks, estimated effects of must-access PDMPs on heroin mortality attenuate sharply—by 91% in the two-way fixed effects model (Panel A). The Callaway and Sant'Anna (2021) estimator yields comparable results (Panel B).[21] These findings indicate that the unintended consequences of must-access PDMPs on illicit opioid mortality are considerably smaller—and largely null—once potency shocks in eastern states are accounted for, contrasting with prior literature that omits this adjustment. On the other hand, controlling for exposure to PDMPs only modestly attenuates estimates of the effects of exposure to heroin potency shocks in the same models (by 16 to 18 percent) (Appendix Figure A.20).

[20] Our replication largely follows Kim (2021) with some differences: we use annual rather than quarterly data with additional years available; we adjust for under-reporting of opioid-related deaths using the Ruhm (2018) method to maintain consistency with our cause-of-death coding; and we do not include state-level time-varying controls beyond exposure to OxyContin reformulation and potency shocks. Otherwise, key aspects of Kim (2021)'s approach are retained.

[21] Results for fentanyl and illicit opioid mortality, shown in Appendix Figures A.22 and A.23, also exhibit substantial attenuation.

4.4 Overall Decomposition of Illicit Opioid Mortality Trends

Lastly, to decompose the overall determinants of rising illicit opioid mortality rates, we estimate

$$Y_{st} = \alpha_s + \gamma_t + \delta_t \text{OxyMisuse}_s^{Pre} + \beta_t \text{White\_Powder\_Market}_s + \phi_r \text{PDMP}_s + \epsilon_{st}, \quad (4)$$

which includes interactions between each policy/shock and relative year dummies during the post-period, while omitting interactions with pre-period dummies. This omission isolates the effects of each policy/shock during periods before others occurred.[22] We use this specification to examine dynamic effects and assess how exposure to each policy/shock evolves over time. The analysis uses data from all states, weights observations by state population, and clusters standard errors at the state level.

To quantify each policy/shock's contribution, we simulate counterfactual mortality trends by sequentially setting the effects of exposure to each policy/shock to zero and comparing these scenarios to observed mortality. Importantly, this decomposition includes the possibility the heroin potency shocks caused dynamic spillovers (e.g., individuals initially exposed to fentanyl-adulterated heroin later independently using fentanyl) and spatial spillovers (e.g., fentanyl use spreading through social networks). It also partly reflects the effects of the earlier, long-standing prescription opioid epidemic, which expanded the population vulnerable to these shocks by increasing opioid addiction and transitions to heroin and synthetic opioids over time (Compton et al. 2016; Eichmeyer and Zhang 2021). For further discussion of these foundational drivers and their role in mortality trends, see Alpert et al. (2022), Cutler and Donahoe (2024), and Evans and Lieber (2025).

Figure 8 displays results from the dynamic specification for any illicit opioid death (involving heroin or fentanyl), plotting observed national death rates alongside three counterfactual scenarios. The first counterfactual sets the OxyContin reformulation effect to zero, illustrating mortality trajectories absent the reformulation. Death rates under this scenario are somewhat lower—especially in 2011–2012—but still rise sharply following the potency shocks beginning in 2012. Consistent with prior results, must-access PDMPs show fairly small effects. However, when potency shocks in eastern states are also set to zero in the counterfactual, death rates flatten after 2013. The figure highlights the increasing importance of potency shocks over time in driving the illicit opioid epidemic. In total, we estimate that exposure to potency shocks accounts for approximately 47% of elevated illicit opioid death rates by 2019. OxyContin reformulation explains about 35% and PDMPs explain the remaining 18%, though these latter estimates are somewhat imprecise and not statistically significant (Appendix Table B.11).

5 Conclusion

This paper identifies a new and significant driver of the transition from the prescription opioid wave to the heroin and fentanyl waves of the opioid epidemic: heroin purity shocks following

[22] Pre-trends are parallel and null for each outcome, as shown in prior sections, so results are robust to this choice. It mainly helps clarify dynamics for early shocks that preceded others—e.g., the OxyContin reformulation occurred before must-access PDMPs or potency shocks and thus should explain all divergence in mortality trends prior to those later shocks. Including pre-period interactions for PDMPs and potency shocks can obscure this interpretation.

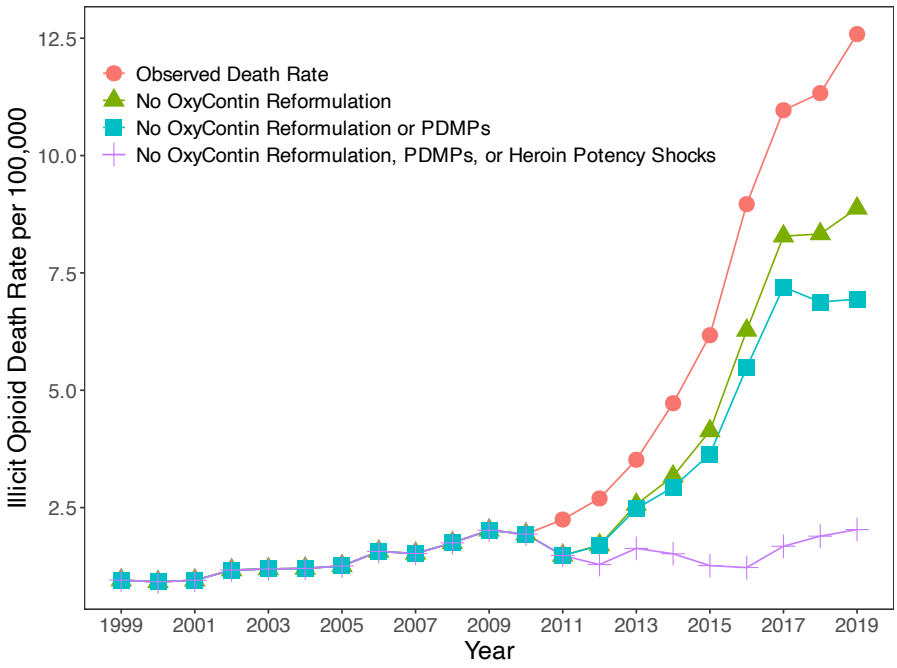


Figure 8: Counterfactual Trends in Illicit Opioid Mortality Rates With vs. Without Exposure to Legal Market Interventions or Heroin Potency Shocks

Notes: This figure presents trends in national illicit opioid (heroin or fentanyl) death rates from 1999 to 2019 and counterfactual trends under three separate scenarios: (1) if OxyContin had not been reformulated (green line with triangle markers), (2) if must-access PDMPs had also not been implemented (blue line with square markers), and (3) if there had also not been an increase in the variability of heroin purity following the transition of heroin production from Colombian to Mexico or supply-side adulteration of heroin with fentanyl (purple line with pluses). We estimate these counterfactuals using estimates of Equation (4).

the integration of white powder heroin supply chains in Mexico and the onset of fentanyl adulteration of white powder heroin supply. We estimate that exposure to these shocks accounts for roughly half of the rise in heroin and fentanyl overdose deaths between 2010 and 2019. More broadly, we document substantial variation in heroin source, formulation, potency, and adulteration across markets and over time—factors that have critical implications for overdose risk but remain under-emphasized in both research and policy.

Our findings highlight the importance of supply-side dynamics in shaping the trajectory of the opioid epidemic. The earlier and more severe impact of fentanyl in eastern states reflects longstanding geographic segmentation in heroin markets and greater prevalence of white powder heroin there, where consumers had less information and ability to know whether they were being sold fentanyl rather than heroin. This sparked a long-run divergence, with fentanyl seemingly supplanting white powder heroin use altogether as evidenced by rising death rates solely due to fentanyl. This illustrates how the unregulated drug market and supplier-driven changes in drug purity or adulteration can lead to significant public health harms. Yet policy responses to the opioid epidemic remain focused on either interdicting opioid supply or addressing the demand side—e.g., by disrupting prescription opioid misuse to reduce subsequent demand for illicit opioids or expanding treatment access. While these are all potentially important ways of reducing overdose mortality, they largely overlook how to address the changes in drug purity and adulteration that played a critical role in igniting the illicit opioid waves of the epidemic.

A key implication of our work is the potential need to integrate drug market surveillance more fully into public health responses to the opioid epidemic. Systems capable of tracking shifts in drug purity and adulteration in real time—such as early warning networks or enhanced toxicology monitoring—may be critical for responding to future changes in supply that increase drug-related harms. Legacy programs like the Heroin Domestic Monitoring Program and Arrestee Drug Abuse Monitoring Program could play a role if restructured to reflect contemporary market risks. More generally, future research should examine how interventions may effectively address informational asymmetries in illicit drug markets—such as through provision of drug testing kits or regulated supply to high risk users—and lower overdose mortality. A more complete understanding of strategies to reduce harms related to unregulated drug supply is essential for developing targeted strategies that address the increasingly lethal U.S. drug market.

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A Additional Figures

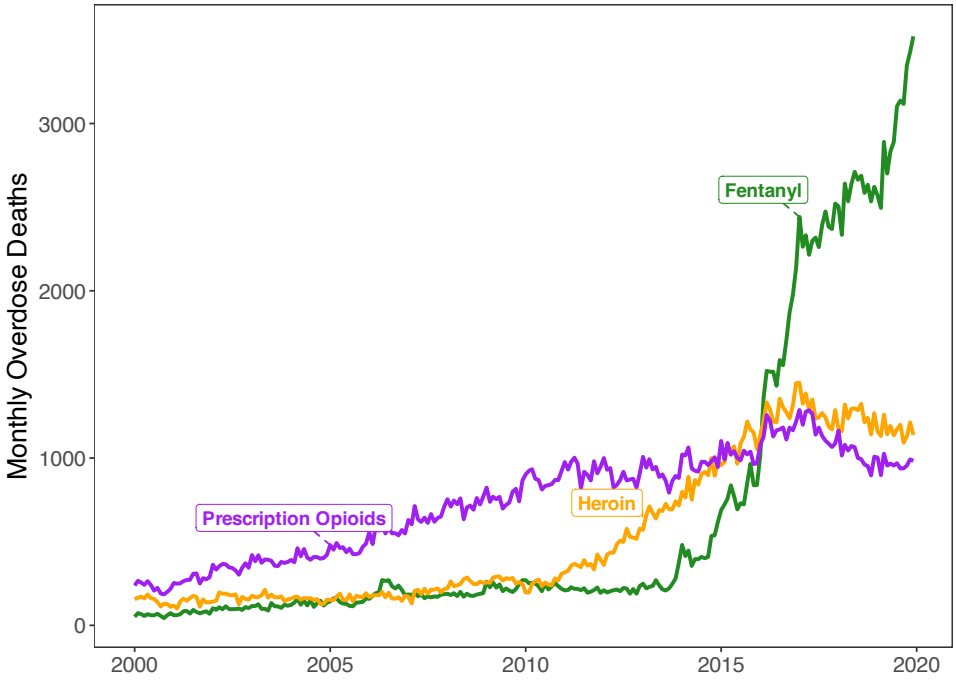


Figure A.1: Monthly U.S. Overdose Deaths by Opioid Type

Notes: Monthly mortality data are from the National Vital Statistics System (NVSS). We use the following ICD-9 codes for overdose death types: T40.2 for prescription opioids, T40.1 for heroin, and T40.4 for fentanyl.

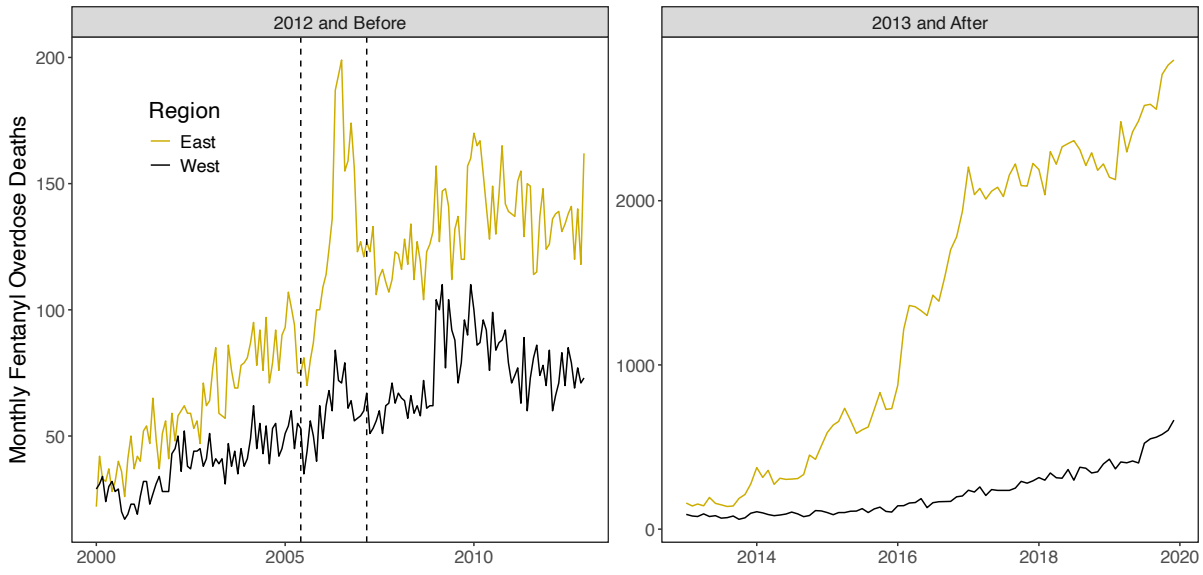


Figure A.2: Monthly Fentanyl Overdose Deaths

Notes: Data are from the National Vital Statistics System, where we use the ICD-9 code of T40.4 for fentanyl, and the delineation for East and West is the Mississippi River. The left panel highlights the short fentanyl epidemic that occurred when Mexican DTOs made a first attempt at introducing fentanyl in white powder heroin markets (between the two hashed vertical lines). They were a small player in these markets at the time and it led to a spike in fentanyl deaths in eastern cities that ended after the lab that manufactured the fentanyl in Toluca, Mexico was raided in May 2006 (CDC 2008).

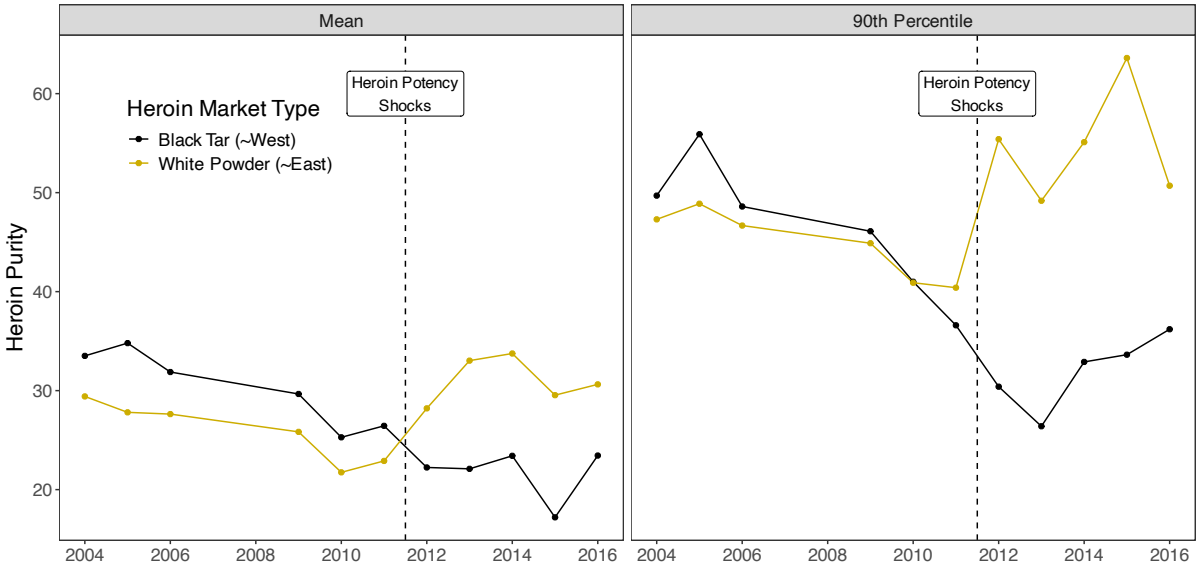
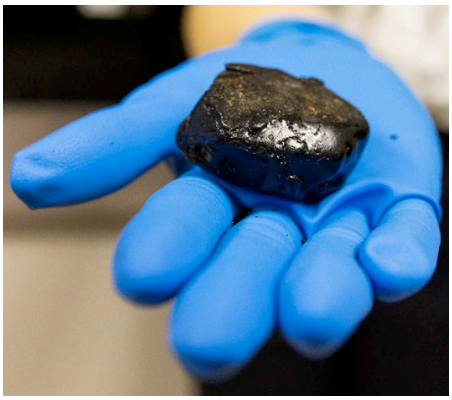


Figure A.3: Trends in Heroin Purity by Market Type

Notes: Data come from the Heroin Domestic Monitoring Program (HDMP) and the figure shows the yearly trends in heroin purity by market. The two measures are the average and the 90th percentile.

Figure A.4: Images of Black Tar Heroin, White Powder Heroin, and Fentanyl

Panel A: Black Tar Heroin



Panel B: White Powder Heroin (left) and Illicitly-Produced Fentanyl (right)

Notes: Images are obtained from here, here, and here, respectively.

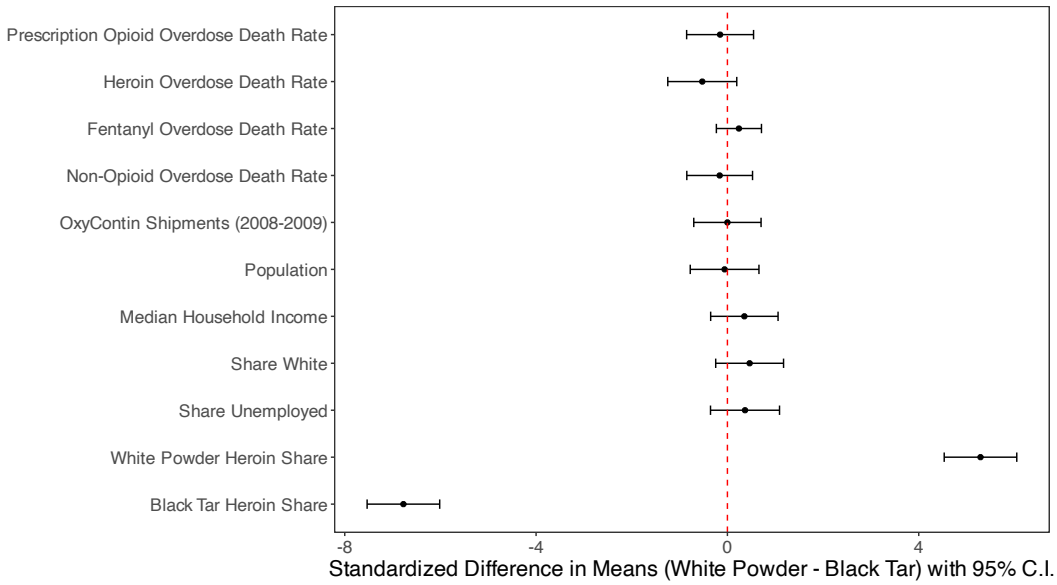


Figure A.5: Characteristics of White Powder and Black Tar Heroin Markets in 2011

Notes: This figure uses CDC mortality data and ACS census data from 2011, the year before the potency shocks, to compare our treated and control commuting zones for the HDMP sample. The final two rows, White Powder and Black Tar Heroin Shares, use the DEA's HDMP data from 2004 to 2011.

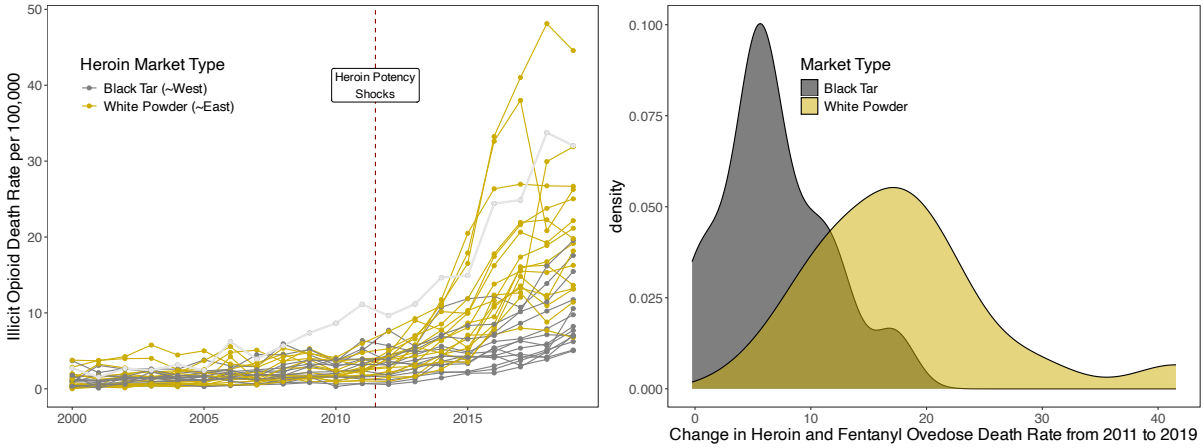


Figure A.6: Illicit Opioid Overdose Death Rates by Market

Notes: These figures are based on data from the National Vital Statistics System. The left panel shows the raw trends in heroin and fentanyl mortality (illicit opioids) by individual commuting zone in each market type. The commuting zone with St. Louis is colored in light grey. The right panel shows the distribution of changes in overdose death rates involving heroin and fentanyl by market type using commuting zones that had a city participating in the HDMP.

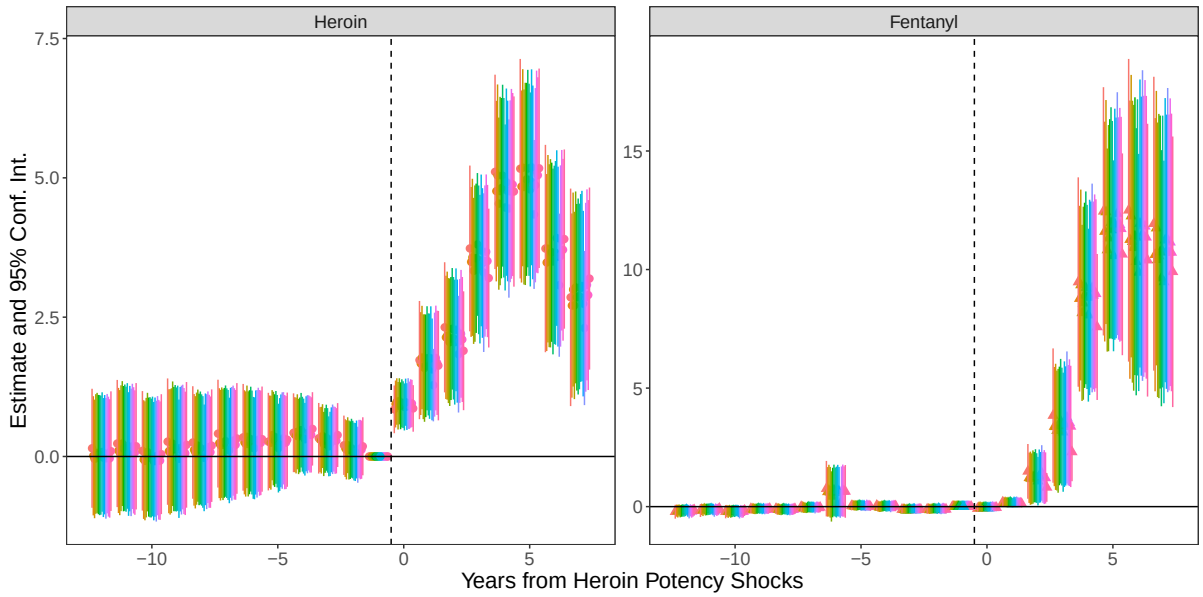


Figure A.7: Dynamic Mortality Impacts of Potency Shocks (Leave One Out Procedure)

Notes: This figure present the ρ_t coefficients from estimating Equation (1) for different samples, namely each one has a different treated commuting zone removed to test whether one is driving the results; each sample is in a different color. Treatment is defined as having an above median share of total pre-potency shock heroin purchases being white powder. The models include commuting zone and year fixed effects, standard errors are clustered at the commuting zone, and the regressions are population weighted. The outcomes are overdose deaths per 100,000 and the sample includes only commuting zones where we have HDMP data.

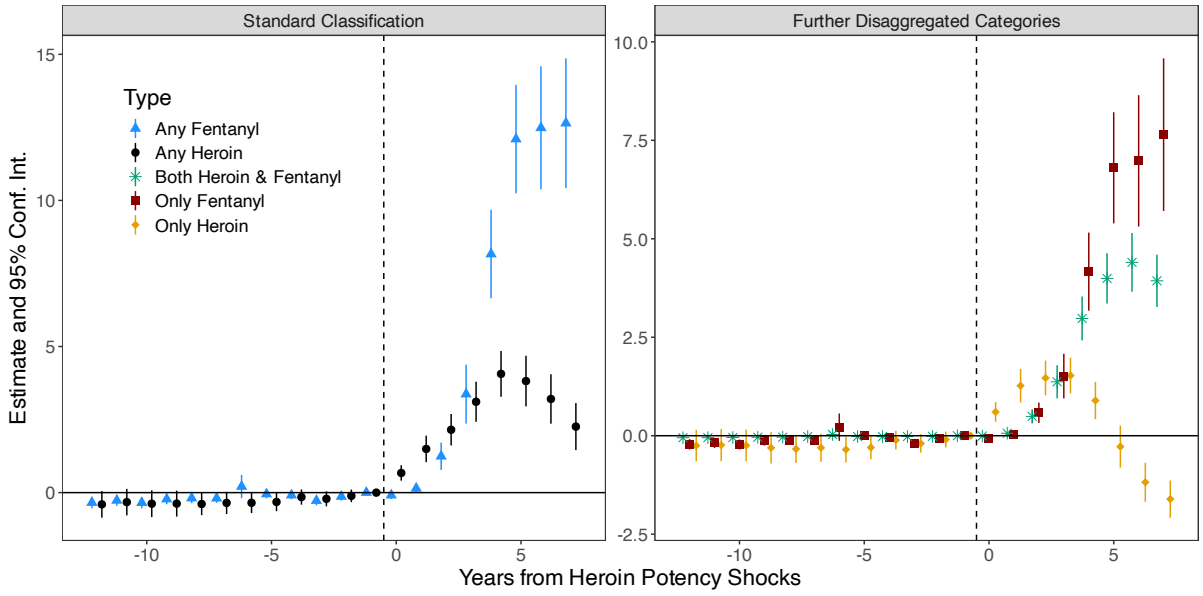


Figure A.8: Dynamic Mortality Impacts of Potency Shocks (Nationwide)

Notes: These figures present the ρ_t coefficients from estimating Equation (1). The models include commuting zone and year fixed effects, standard errors are clustered at the commuting zone, and the regressions are population weighted. Outcomes are overdose deaths per 100,000 and the sample includes all commuting zones in the contiguous United States.

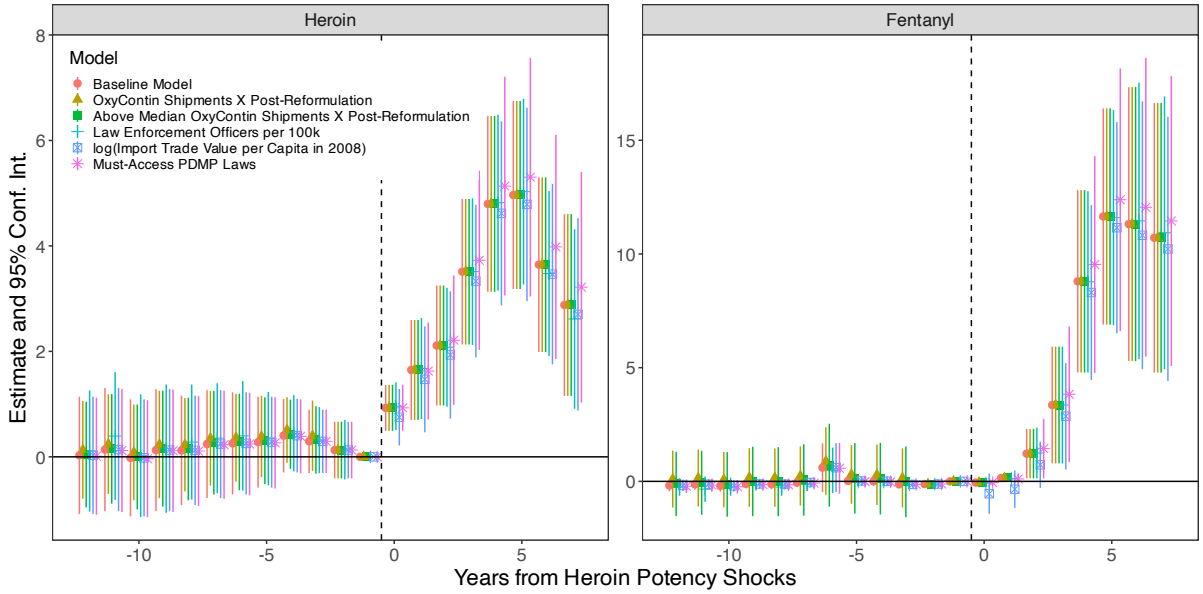


Figure A.9: Dynamic Mortality Impacts of Potency Shocks with Additional Controls

Notes: These figures present the ρ_t coefficients from estimating Equation (1) with additional controls, i.e., the baseline model plus a control variable. The models include commuting zone and year fixed effects, standard errors are clustered at the commuting zone, and the regressions are population weighted. Outcomes are overdose deaths per 100,000 and the sample includes 31 commuting zones where we have HDMP data on heroin type.

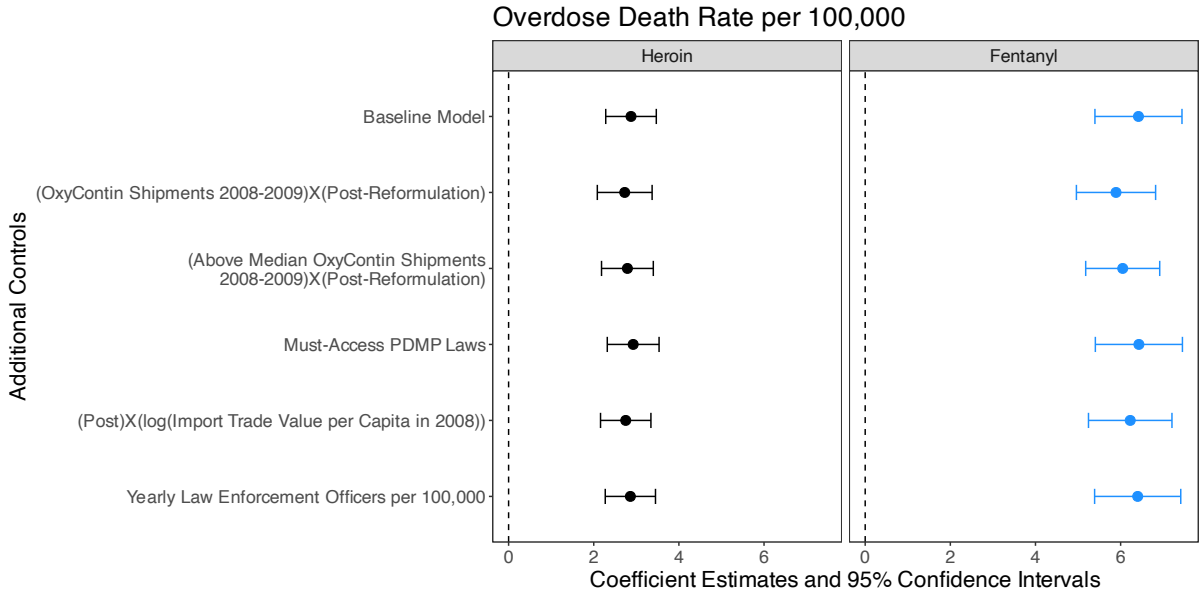


Figure A.10: Average Mortality Impacts of Potency Shocks with Additional Controls (Nationwide)

Notes: This figure presents the β coefficients from estimating Equation (2) with different control variables. The Eastern Market binary treatment variable is equal to one for commuting zones east of -91 degrees longitude and Post is an indicator for 2012 and after. The models include commuting zone and year fixed effects, standard errors are clustered at the commuting zone, and the regressions are population weighted. Outcomes are overdose deaths per 100,000 and the sample includes all commuting zones in the contiguous United States.

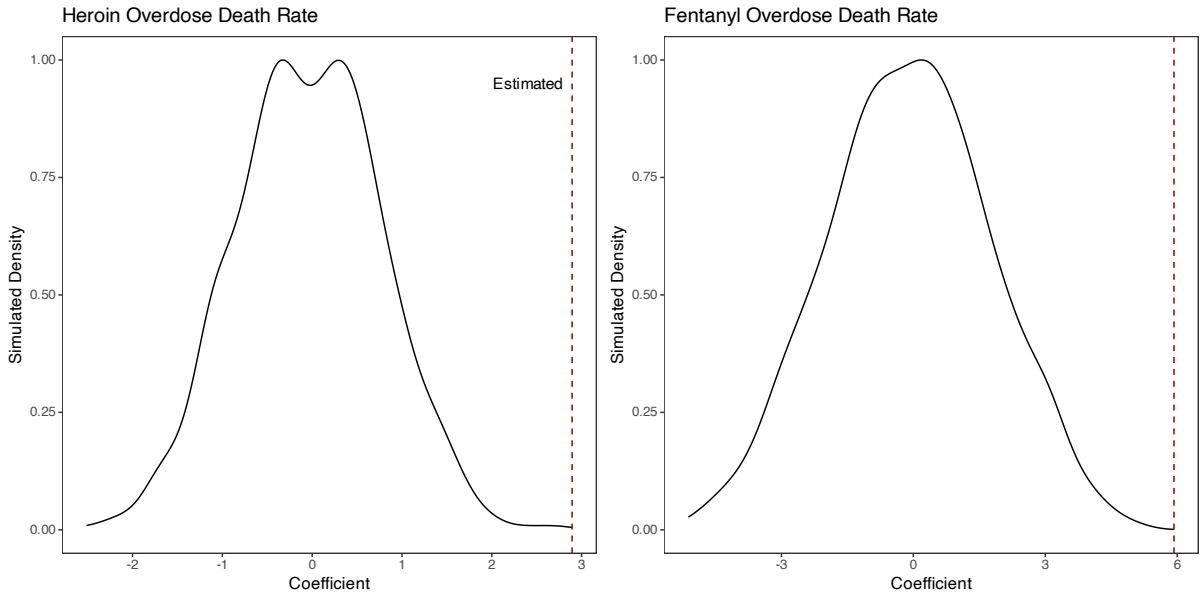


Figure A.11: Permutation Tests for HDMP Market Analysis

Notes: For these tests, we randomize which commuting zone gets "treated" and then run Equation (2) 1000 times using a new sample each time. The figures present the distribution of coefficients obtained from these regressions. The dotted vertical red line is the estimated coefficient.

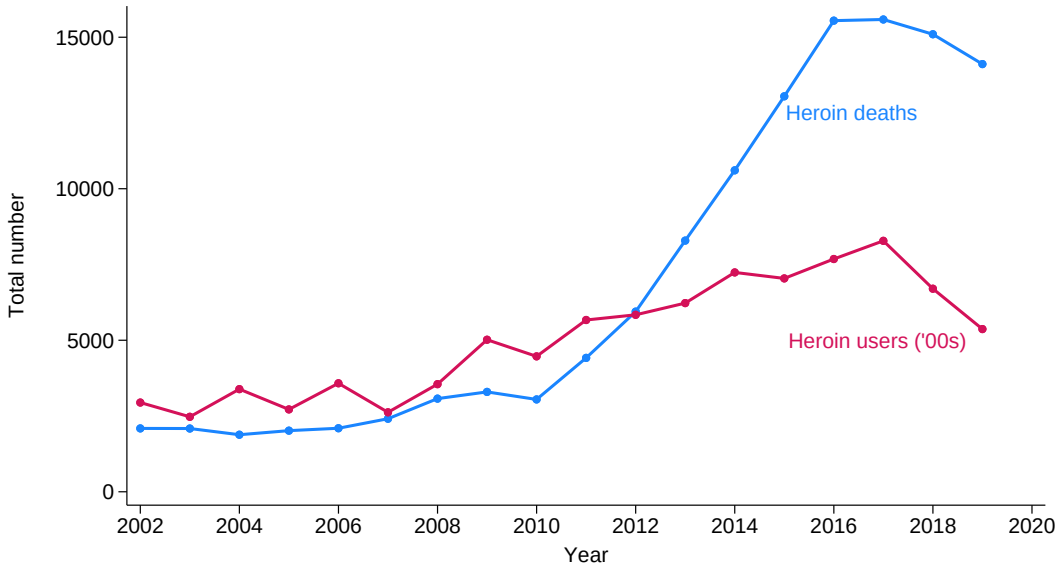
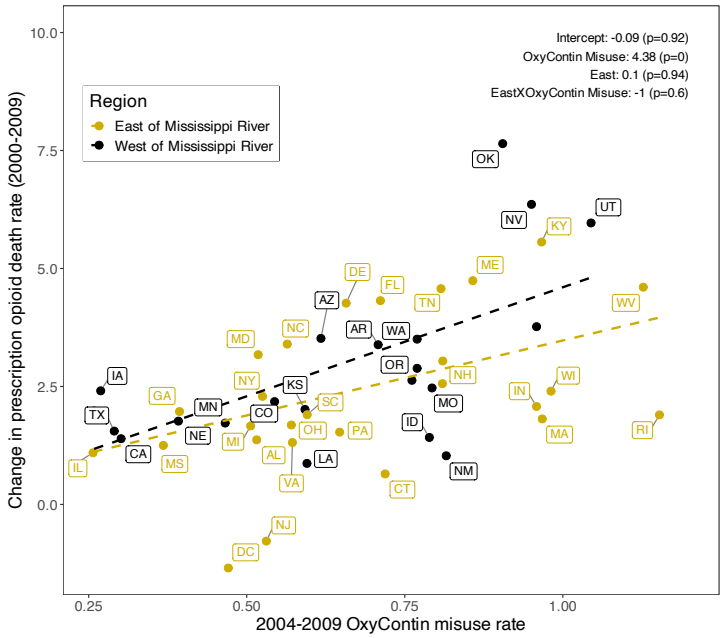


Figure A.12: Yearly Trends in Heroin Use (NSDUH) and Overdose Mortality (CDC)

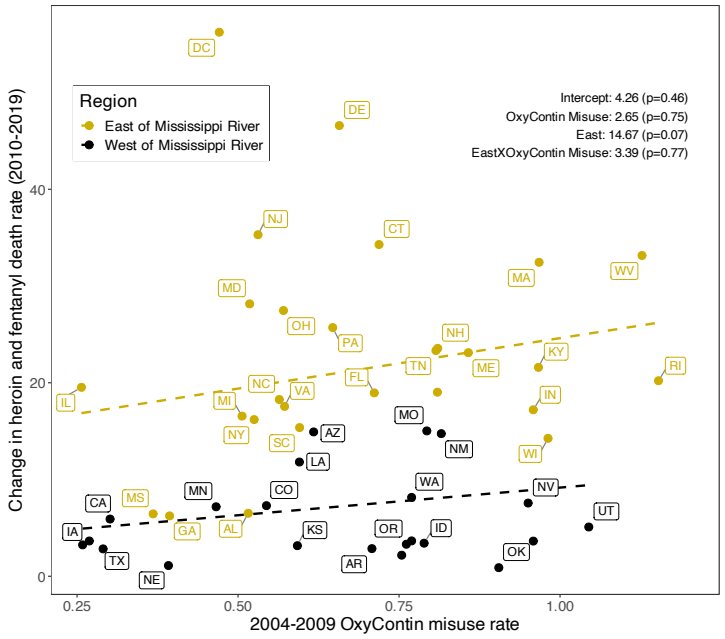
Notes: The National Survey on Drug Use and Health (NSDUH) data capture self-reported heroin use, while mortality trends reflect overdose death records from the CDC.

Figure A.13: Geography of Epidemic during the Prescription Opioid and Illicit Opioid Waves

Panel A: Change in Prescription Opioid Death Rate (2000-2009)



Panel B: Change in Illicit Opioid Death Rate (2010-2019)



Notes: In both panels, the x-axis uses the state-level NSDUH measure of the OxyContin misuse rate from 2004 to 2009 found in Alpert et al. (2018). The y-axis in Panel A is the change in prescription opioid overdose deaths before the OxyContin reformulation (from 2000 to 2009). In Panel B, it is the change in illicit opioid overdose deaths (heroin and fentanyl) after the OxyContin reformulation (from 2010 to 2019). We also include the results from a simple linear regression in the top right of each figure, where we regress the change in death rates on the misuse measure, whether the state is east of the Mississippi river, and their interaction.

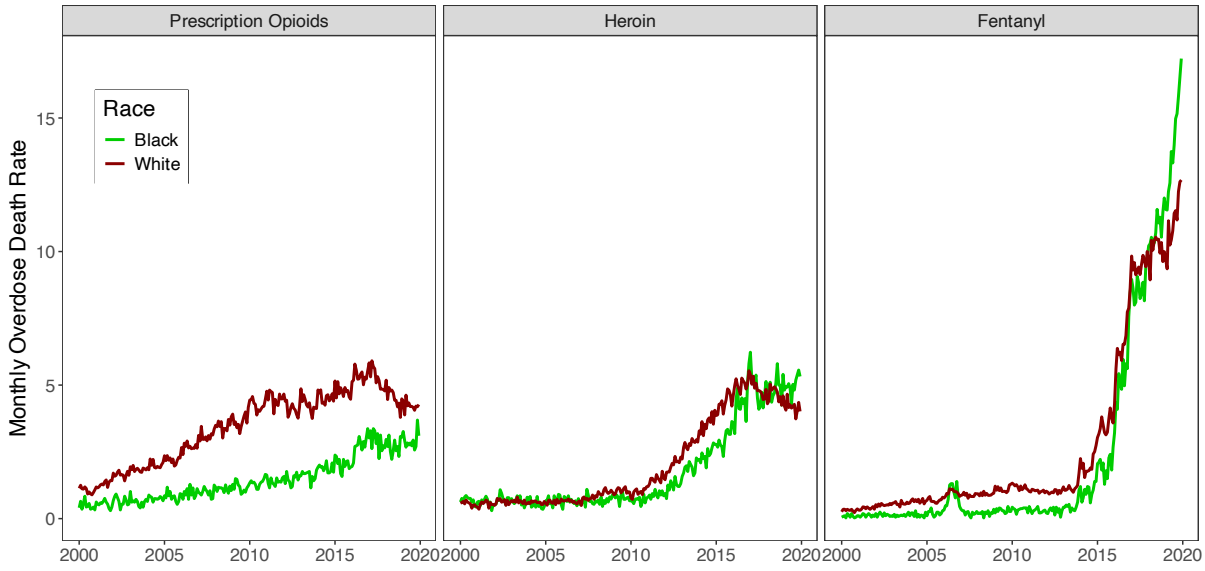


Figure A.14: Monthly Trends in Opioid Overdose Deaths by Race and Opioid Class

Notes: Monthly mortality data are from the National Vital Statistics System (NVSS). We use the following ICD-9 codes for overdose death types: T40.2 for prescription opioids, T40.1 for heroin, and T40.4 for fentanyl. Rates are calculated separately by race and opioid class.

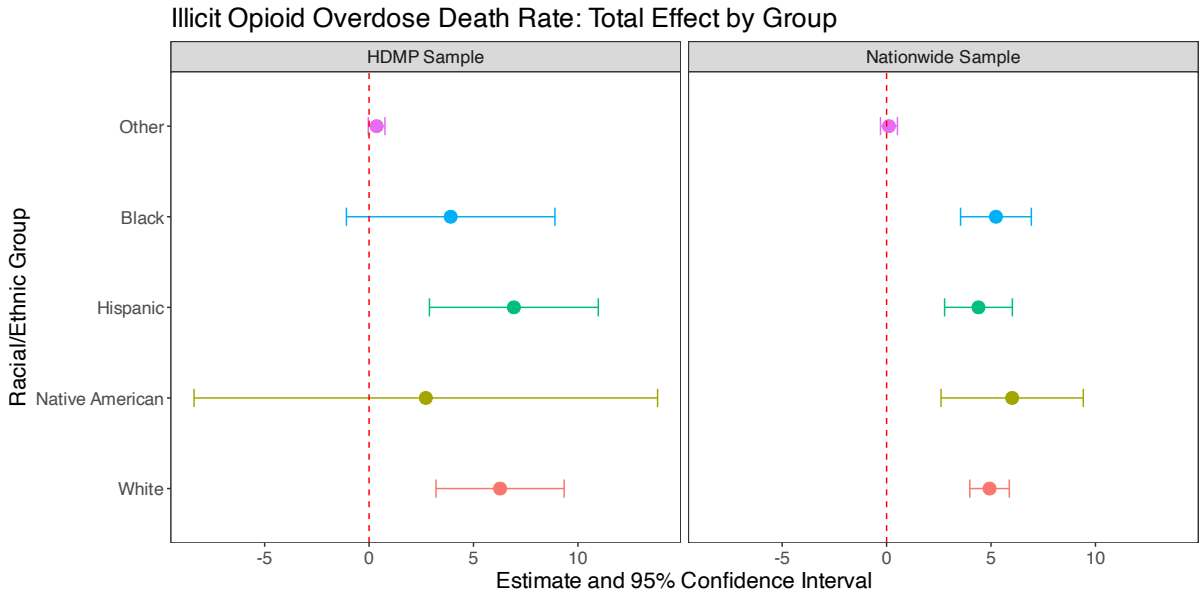
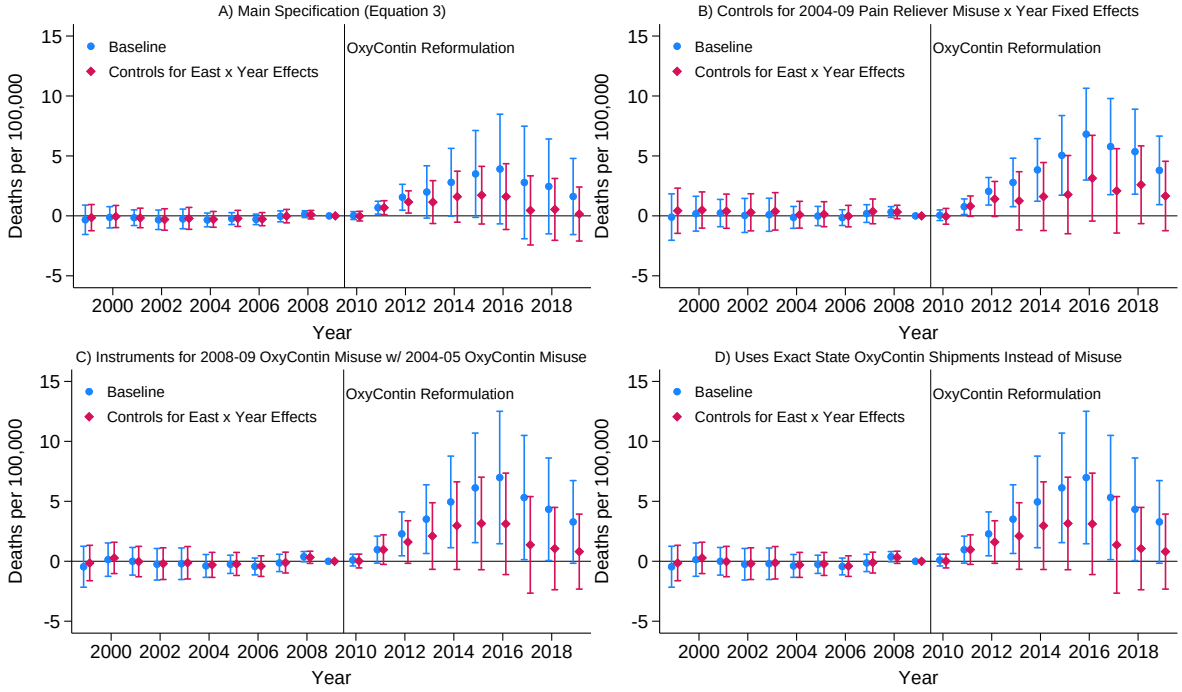


Figure A.15: Average Mortality Impacts of Potency Shocks by Race/Ethnicity

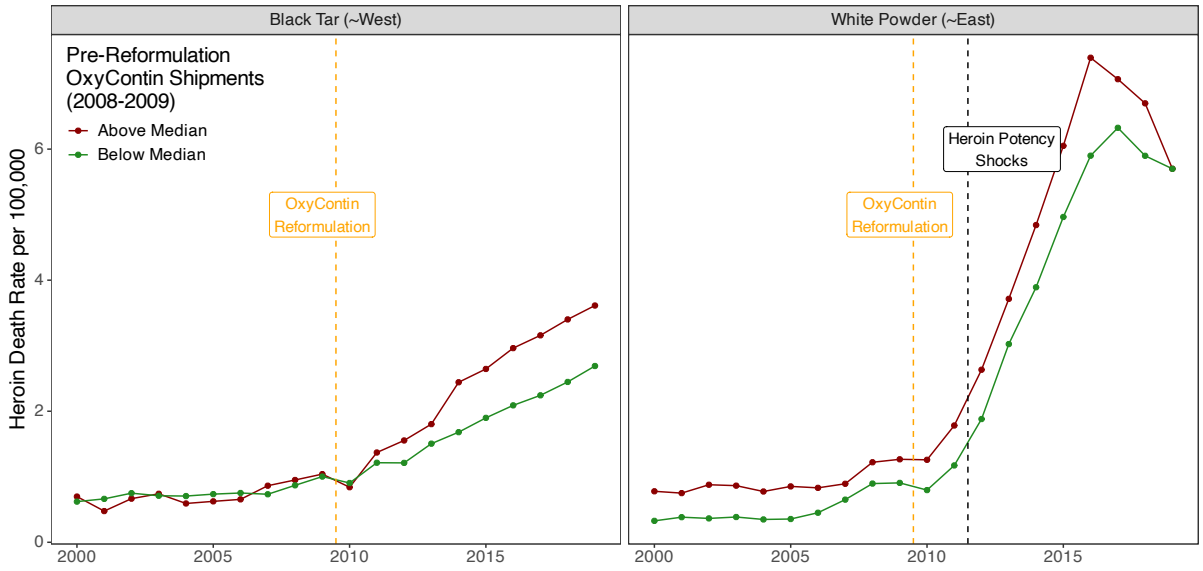
Notes: This figure presents the total effects for each race group within a unified model. The models include an interaction between the White Powder Heroin treatment indicator (left panel, defined as having an above median share of total pre-potency shock heroin purchases being white powder) and the Eastern Market treatment indicator (right panel, equal to one for commuting zones east of -91 degrees longitude), as well as commuting zone and year fixed effects. The outcomes are illicit opioid overdose deaths per 100,000 (heroin and fentanyl) for each race group and standard errors are clustered at the commuting-zone level. The reference group is "Other," i.e., treatment × Post, and the other race groups are the sum of this estimate and the interaction with their respective race group.

Figure A.16: Replication and Extension of OxyContin Reformulation's Impacts on Heroin Mortality



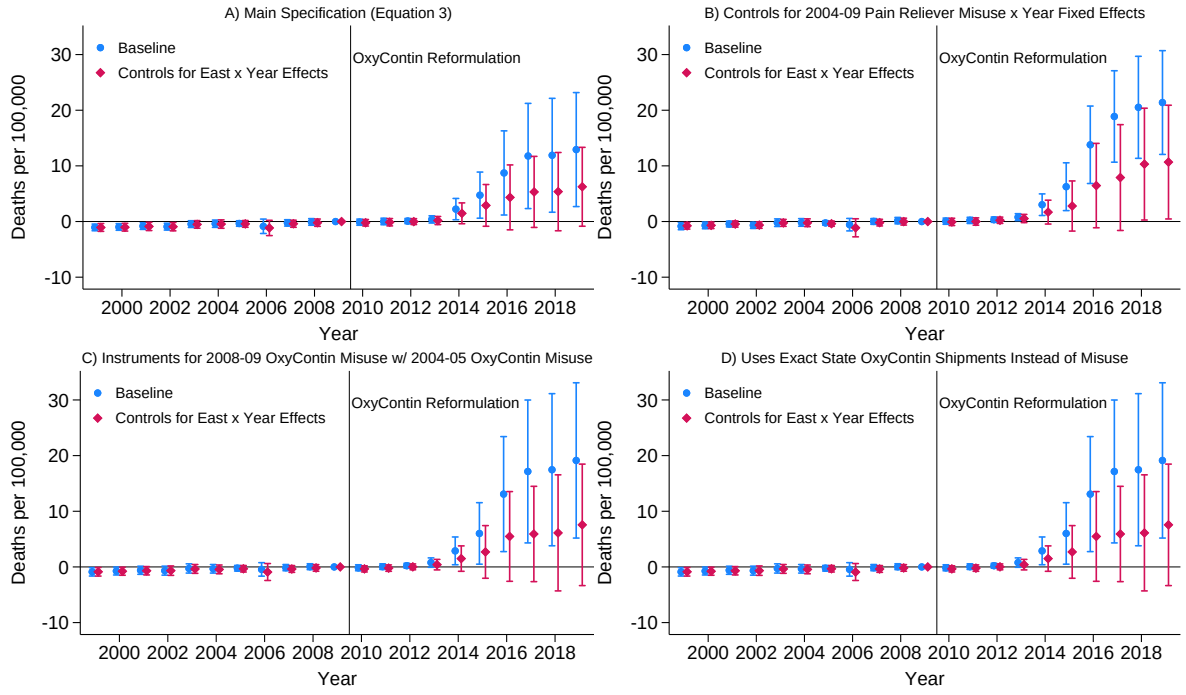
Notes: This figure presents estimates of the impact of one percentage point higher state OxyContin misuse prevalence on heroin overdose mortality rates each year relative to when OxyContin was reformulated to be abuse-deterrent (2010). Each panel presents estimates with and without controlling for an interaction between being an eastern state and year fixed effects. Panel A replicates and extends the baseline specification (Equation 1) in Alpert et al. (2018) (Equation 3 in this manuscript). Panel B adds controls for 2004-2009 pain reliever misuse prevalence interacted with year fixed effects, to adjust for the fact that pre-reformulation OxyContin misuse is non-random (Alpert et al. 2018; Beheshti 2019; Park 2025). Panel C instruments uses 2008-2009 OxyContin misuse prevalence (rather than 2004-2009 OxyContin misuse) and instruments for it using 2004-2005 OxyContin misuse prevalence to address measurement error in OxyContin misuse prevalence (Alpert et al. 2018). Panel D estimates Equation 3 using exact 2006-2009 state OxyContin shipment rates (morphine equivalent grams per capita) as an alternative measure of exposure to OxyContin reformulation. Shipments rates in this specification are scaled to give the implied effect in the average state. See Section 4 of the text for more details.

Figure A.17: Heroin Mortality By Market Type and OxyContin Exposure



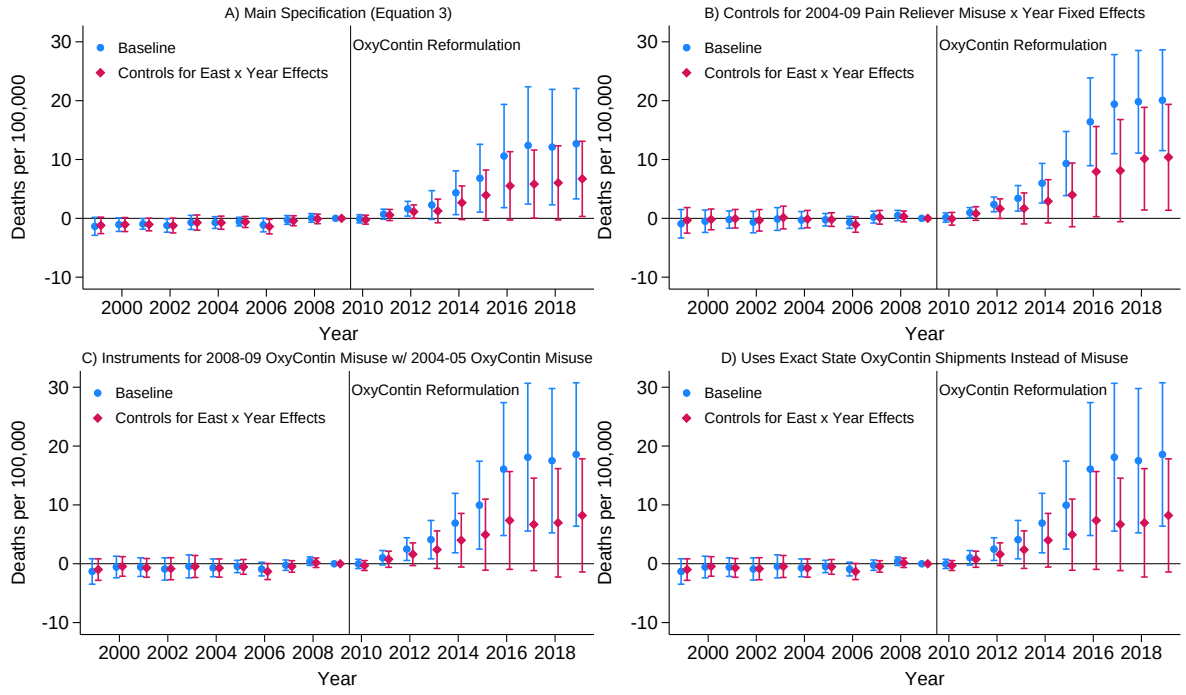
Notes: This figure extends the work of Evans et al. (2019) by examining trends in heroin overdose mortality separately for eastern vs. western states with above vs. below median OxyContin shipments from 2008-2009, before and after the OxyContin reformulation (mid-2010) and the potency shocks (2012) described in Section 2.

Figure A.18: Replication and Extension of the OxyContin Reformulation's Impacts on Fentanyl Mortality



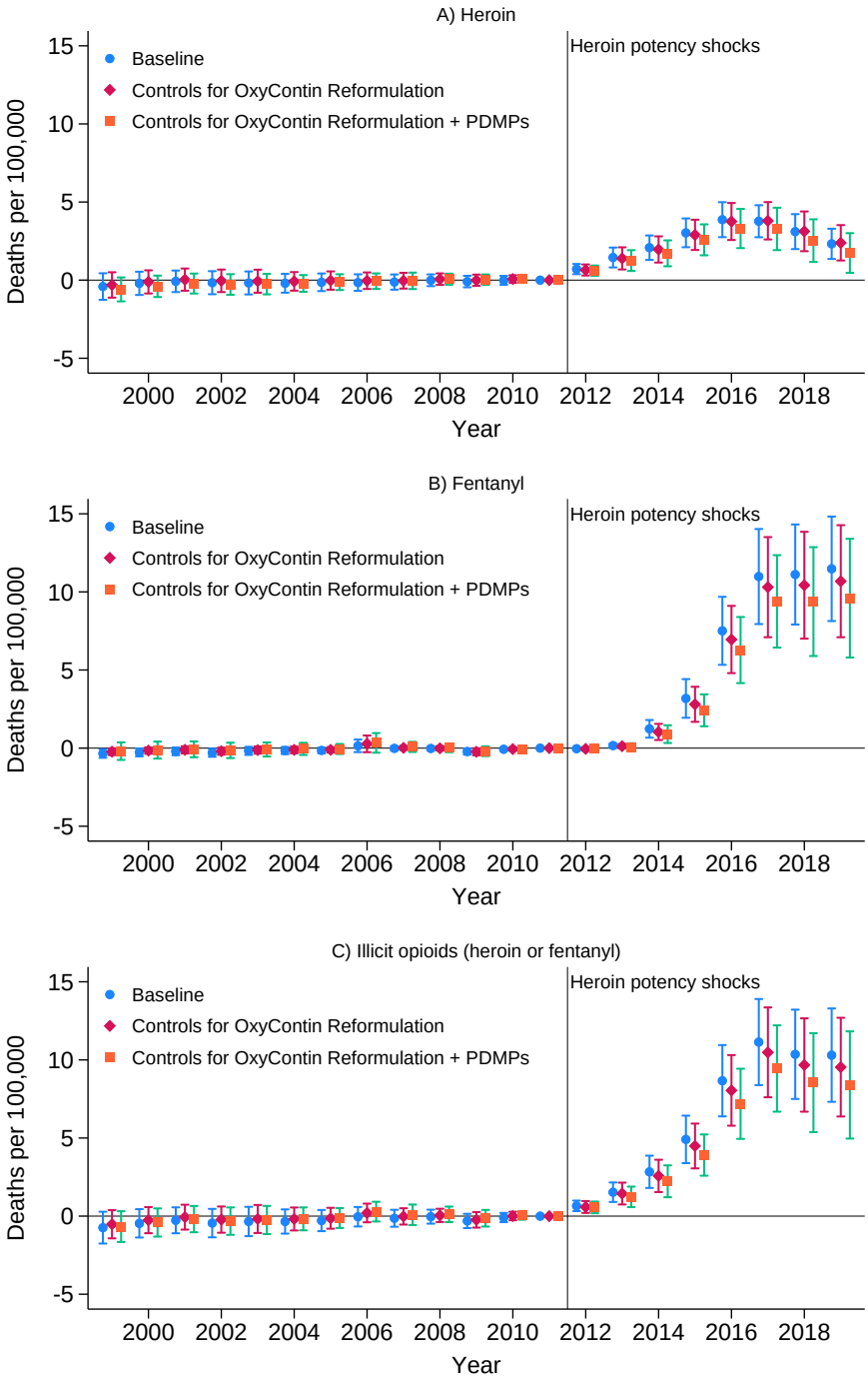
Notes: This figure presents estimates of the impact of one percentage point higher state OxyContin misuse prevalence on synthetic opioid (i.e., fentanyl) overdose mortality rates each year relative to when OxyContin was reformulated to be abuse-deterrent (2010). Each panel presents estimates with and without controlling for an interaction between being an eastern state and year fixed effects. Panel A replicates and extends the baseline specification (Equation 1) in Alpert et al. (2018) (Equation 3 in this manuscript). Panel B adds controls for 2004-2009 pain reliever misuse prevalence interacted with year fixed effects, to adjust for the fact that pre-reformulation OxyContin misuse is non-random (Alpert et al. 2018; Beheshti 2019; Park 2025). Panel C instruments uses 2008-2009 OxyContin misuse prevalence (rather than 2004-2009 OxyContin misuse) and instruments for it using 2004-2005 OxyContin misuse prevalence to address measurement error in OxyContin misuse prevalence (Alpert et al. 2018). Panel D estimates Equation 3 using exact 2006-2009 state OxyContin shipment rates (morphine equivalent grams per capita) as an alternative measure of exposure to OxyContin reformulation. Shipments rates in this specification are scaled to give the implied effect in the average state. See Section 4 of the text for more details.

Figure A.19: Replication and Extension of the OxyContin Reformulation's Impacts on Illicit Opioid Mortality



Notes: This figure presents estimates of the impact of one percentage point higher state OxyContin misuse prevalence on illicit opioid (i.e., heroin or fentanyl) overdose mortality rates each year relative to when OxyContin was reformulated to be abuse-deterrent (2010). Each panel presents estimates with and without controlling for an interaction between being an eastern state and year fixed effects. Panel A replicates and extends the baseline specification (Equation 1) in Alpert et al. (2018) (Equation 3 in this manuscript). Panel B adds controls for 2004-2009 pain reliever misuse prevalence interacted with year fixed effects, to adjust for the fact that pre-reformulation OxyContin misuse is non-random (Alpert et al. 2018; Beheshti 2019; Park 2025). Panel C instruments uses 2008-2009 OxyContin misuse prevalence (rather than 2004-2009 OxyContin misuse) and instruments for it using 2004-2005 OxyContin misuse prevalence to address measurement error in OxyContin misuse prevalence (Alpert et al. 2018). Panel D estimates Equation 3 using exact 2006-2009 state OxyContin shipment rates (morphine equivalent grams per capita) as an alternative measure of exposure to OxyContin reformulation. Shipments rates in this specification are scaled to give the implied effect in the average state. See Section 4 of the text for more details.

Figure A.20: Robustness of Impacts of Heroin Potency Shocks (State-level Model)



Notes: This figure presents estimates of the impacts of exposure to heroin potency shocks in eastern states on heroin (Panel A), fentanyl (Panel B), and illicit opioid (heroin or fentanyl; Panel C) mortality rates, before and after controlling for pre-reformulation OxyContin misuse interacted with year effects and indicators for each year relative to must-access PDMP adoption in the state-level event study specifications of Section 4. Regressions are weighted by state population, with standard errors clustered on states. See Section 4 of the text for more details.

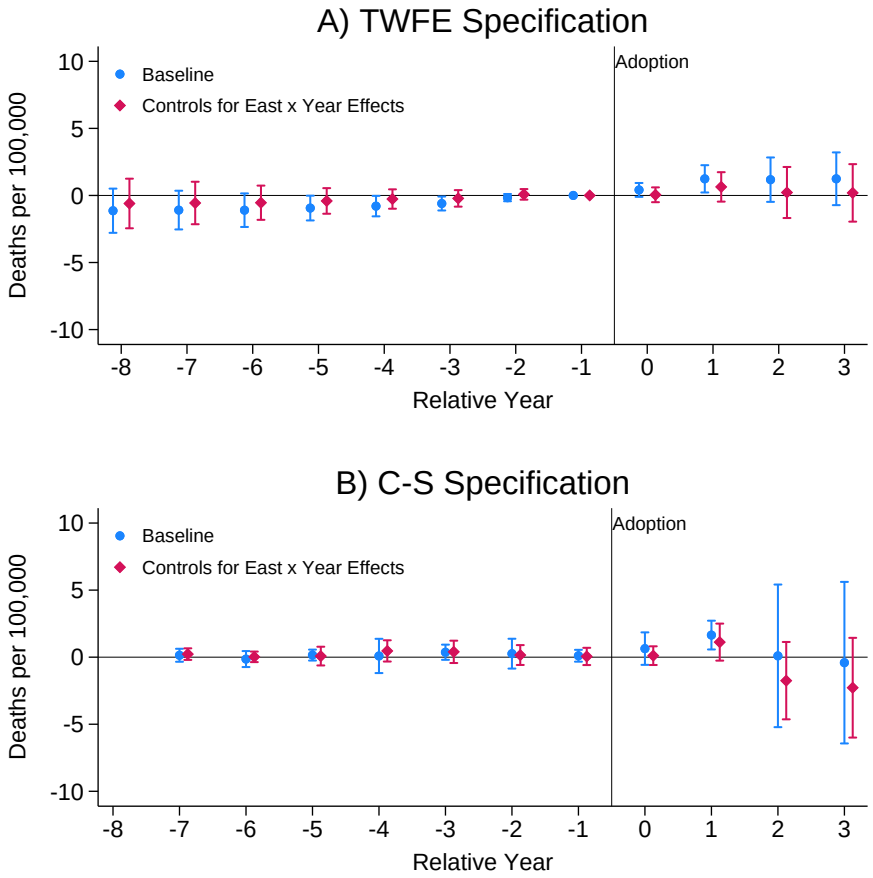


Figure A.21: Extension of the Impacts of Must-Access PDMPs on Heroin Mortality

Notes: The figure presents estimates of the event study coefficients for the impacts of must-access Prescription Drug Monitoring Programs (PDMPs) on heroin overdose mortality rates. Panel A uses a two-way fixed effects model and Panel B uses the estimator described in Callaway and Sant'Anna (2021). In both models, we control for exposure to OxyContin reformulation by interacting pre-reformulation OxyContin shipments with year fixed effects and present results with and without controlling for east interacted with year fixed effects to account for exposure to potency shocks.

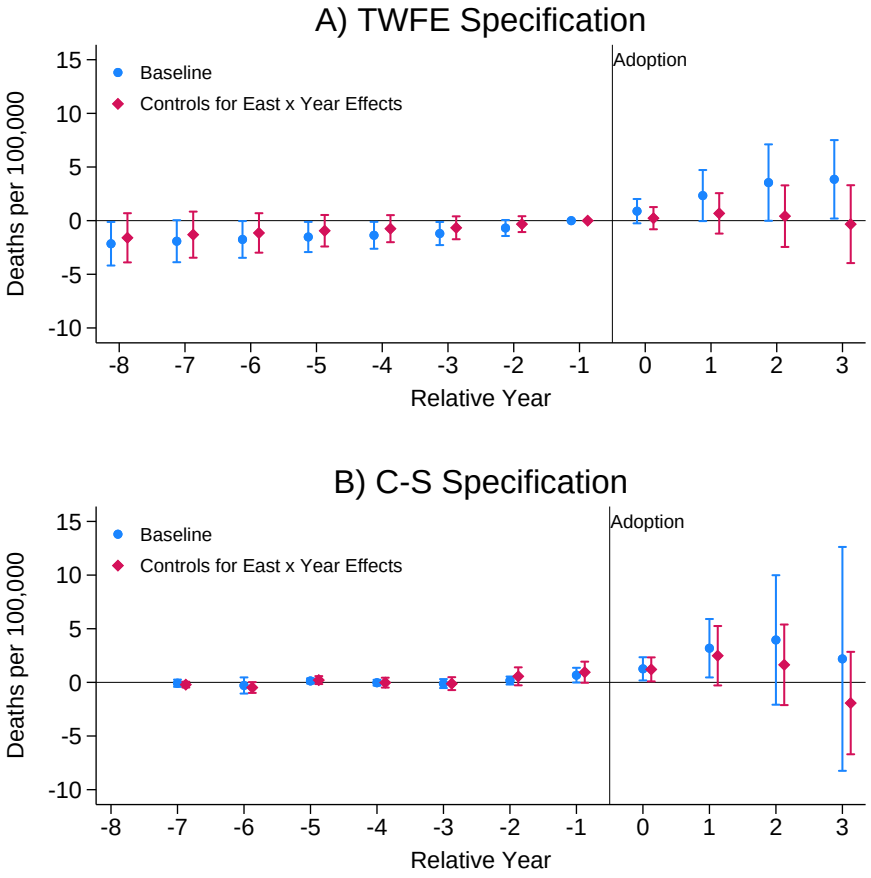


Figure A.22: Extension of the Impacts of Must-Access PDMPs on Fentanyl Mortality

Notes: The figure presents estimates of the event study coefficients for the impacts of must-access Prescription Drug Monitoring Programs (PDMPs) on synthetic opioid (i.e., fentanyl) overdose mortality rates. Panel A uses a two-way fixed effects model and Panel B uses the estimator described in Callaway and Sant'Anna (2021). In both models, we control for exposure to OxyContin reformulation by interacting pre-reformulation OxyContin shipments with year fixed effects and present results with and without controlling for east interacted with year fixed effects to account for exposure to potency shocks.

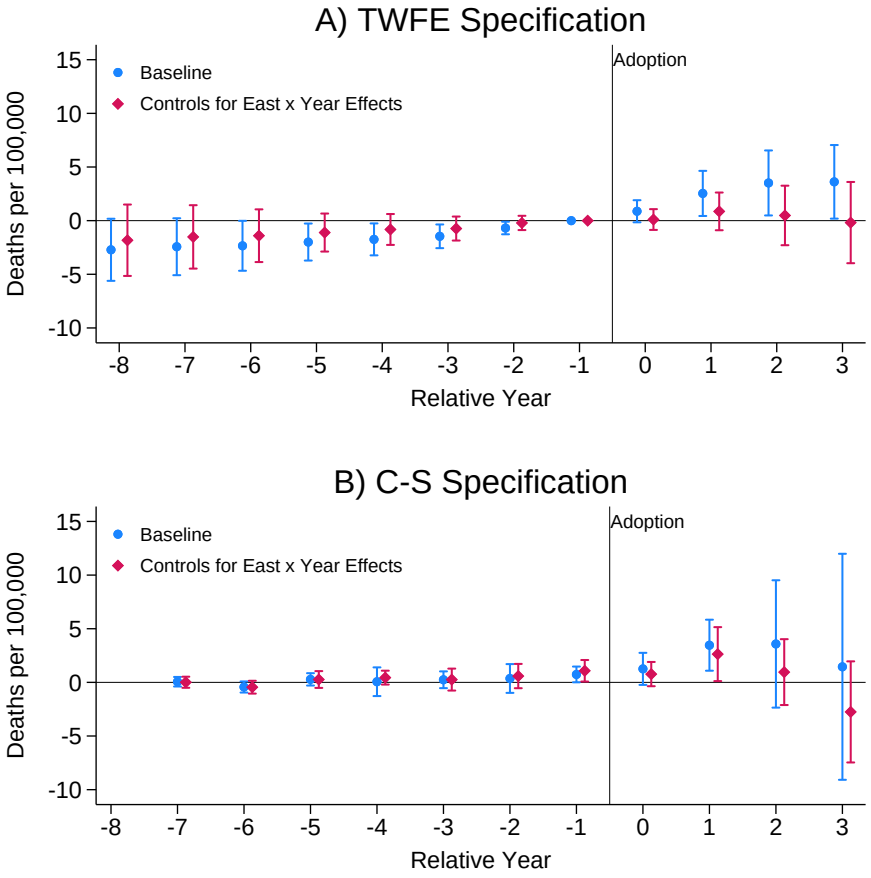


Figure A.23: Extension of the Impacts of Must-Access PDMPs on Illicit Opioid Mortality

Notes: The figure presents estimates of the event study coefficients for the impacts of must-access Prescription Drug Monitoring Programs (PDMPs) on illicit opioid (i.e., heroin or fentanyl) overdose mortality rates. Panel A uses a two-way fixed effects model and Panel B uses the estimator described in Callaway and Sant'Anna (2021). In both models, we control for exposure to OxyContin reformulation by interacting pre-reformulation OxyContin shipments with year fixed effects and present results with and without controlling for east interacted with year fixed effects to account for exposure to potency shocks.

B Additional Tables

Table B.1: Average Mortality Impacts of Potency Shocks (Continuous Treatment)

	Any Heroin (1)	Any Fentanyl (2)	Heroin or Fentanyl (3)	Non-Opioids (4)	Any Drug (5)
(Pre-Takeover White Powder Heroin Share)X(Post)	0.0357***	0.0833***	0.0873***	-0.0015	0.0771***
	(0.0098)	(0.0196)	(0.0219)	(0.0095)	(0.0251)
Pre-treatment mean	1.24	0.658	1.87	4.58	10.9
R^2	0.779	0.652	0.742	0.793	0.810
Observations	620	620	620	620	620

Notes: This table presents the β coefficients from estimating Equation (2) using a continuous treatment measure of white powder heroin in the pre-potency shock period. Post is an indicator for 2012 and after. The models include commuting zone and year fixed effects, standard errors are clustered at the commuting zone, and the regressions are population weighted. Outcomes are overdose deaths per 100,000 and the sample includes only commuting zones where we have HDMP data.

Table B.2: Average Mortality Impacts of Potency Shocks (Binned Treatment)

	Any Heroin (1)	Any Fentanyl (2)	Heroin or Fentanyl (3)	Non-Opioids (4)	Any Drug (5)
(Post) × WhitePowderQuartile = 2	-0.7543	0.6746	-0.3084	0.4534*	0.5835
	(0.7685)	(1.018)	(1.410)	(0.2474)	(1.417)
(Post) × WhitePowderQuartile = 3	2.941***	5.755***	6.150***	-0.9501**	5.049***
	(0.8774)	(1.656)	(1.679)	(0.3595)	(1.629)
(Post) × WhitePowderQuartile = 4	1.958**	6.892***	6.312***	0.5600	6.318**
	(0.7618)	(1.810)	(1.891)	(1.110)	(2.454)
Pre-treatment mean	1.24	0.658	1.87	4.58	10.9
R^2	0.798	0.650	0.743	0.801	0.808
Observations	620	620	620	620	620

Notes: This table presents the β coefficients from estimating Equation (2) using a binned treatment measure of white powder heroin in the pre-potency shock period, where the reference category is the first quartile. Post is an indicator for 2012 and after. The models include commuting zone and year fixed effects, standard errors are clustered at the commuting zone, and the regressions are population weighted. Outcomes are overdose deaths per 100,000 and the sample includes only commuting zones where we have HDMP data.

Table B.3: Average Mortality Impacts of Potency Shocks (Nationwide)

	Any Heroin (1)	Any Fentanyl (2)	Heroin or Fentanyl (3)	Non-Opioids (4)	Any Drug (5)
(Eastern Market)X(Post)	2.875***	6.419***	7.116***	-0.9879***	6.330***
	(0.3030)	(0.5216)	(0.5906)	(0.2756)	(0.7062)
Pre-treatment mean	0.381	0.931	1.30	5.13	10.5
R^2	0.704	0.624	0.705	0.680	0.762
Observations	13,740	13,740	13,740	13,740	13,740

Notes: This table presents the β coefficients from estimating Equation (2). The East binary treatment variable is equal to one for commuting zones east of -91 degrees longitude, and Post is an indicator for 2012 and after. The models include commuting zone and year fixed effects, standard errors are clustered at the commuting zone, and the regressions are population weighted. The sample includes all commuting zones in the contiguous United States. Outcomes are overdose deaths per 100,000.

Table B.4: Average Heroin Mortality Impacts of Potency Shocks (HDMP, Additional Controls)

	Any Heroin							
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
(White Powder Market)X(Post)	2.894***	2.874***	3.343***	2.805***	3.809***	2.843***	2.782***	2.715***
	(0.6703)	(0.6446)	(0.6208)	(0.6746)	(0.7964)	(0.7925)	(0.6452)	(0.7209)
(Above Median OxyContin 2008-09)X(Post-Reformulation)		0.8306	1.546*					
		(0.6137)	(0.7835)					
(White Powder Market)X(Post-Reformulation)X(Above Median OxyContin 2008-09)			-1.399					
			(1.027)					
(OxyContin 2008-09)X(Post-Reformulation)				1.321	1.858***			
				(0.7892)	(0.5248)			
(White Powder Market)X(Post-Reformulation)X(OxyContin 2008-09)					-1.353**			
					(0.5641)			
Post-Must Access PDMP Reform						-0.1568		
						(0.7546)		
Yearly Law Enforcement Officers per 100,000							-0.0084*	
							(0.0048)	
(Post)X(log(Import Trade Value per Capita in 2008))								-0.3087
								(0.2417)
Pre-treatment mean	1.24	1.24	1.24	1.24	1.24	1.24	1.24	1.24
R^2	0.792	0.797	0.802	0.805	0.813	0.792	0.796	0.794
Observations	620	620	620	620	620	620	620	620

Notes: This table presents the β coefficients in the first row from estimating Equation (2) with different control variables. The White Powder Heroin treatment indicator variable is defined as having an above median share of total pre-potency shock heroin purchases being white powder, and Post is an indicator for 2012 and after. The models include commuting zone and year fixed effects, standard errors are clustered at the commuting zone, and the regressions are population weighted. Outcomes are overdose deaths per 100,000 and the sample includes only commuting zones where we have HDMP data.

Table B.5: Average Fentanyl Mortality Impacts of Potency Shocks (HDMP, Additional Controls)

	Any Fentanyl							
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
(White Powder Market)X(Post)	5.928***	5.848***	5.003***	5.694***	5.468***	5.404***	5.952***	5.435***
	(1.351)	(1.059)	(0.7222)	(1.102)	(1.152)	(1.349)	(1.353)	(1.286)
(Above Median OxyContin 2008-09)X(Post-Reformulation)		3.366***	2.075**					
		(0.9802)	(0.9000)					
(White Powder Market)X(Post-Reformulation)X(Above Median OxyContin 2008-09)			2.524					
			(1.511)					
(OxyContin 2008-09)X(Post-Reformulation)				3.491***	3.370***			
				(0.7392)	(0.6082)			
(White Powder Market)X(Post-Reformulation)X(OxyContin 2008-09)					0.3049			
					(0.9200)			
Post-Must Access PDMP Reform						-1.613		
						(2.688)		
Yearly Law Enforcement Officers per 100,000							0.0018	
							(0.0089)	
(Post)X(log(Import Trade Value per Capita in 2008))								-0.8511
								(0.5349)
Pre-treatment mean	0.658	0.658	0.658	0.658	0.658	0.658	0.658	0.658
R^2	0.648	0.671	0.675	0.673	0.673	0.651	0.648	0.653
Observations	620	620	620	620	620	620	620	620

Notes: This table presents the β coefficients in the first row from estimating Equation (2) with different control variables. The White Powder Heroin treatment indicator variable is defined as having an above median share of total pre-potency shock heroin purchases being white powder, and Post is an indicator for 2012 and after. The models include commuting zone and year fixed effects, standard errors are clustered at the commuting zone, and the regressions are population weighted. Outcomes are overdose deaths per 100,000 and the sample includes only commuting zones where we have HDMP data.

Table B.6: Average Heroin Mortality Impacts of Potency Shocks (Nationwide, Additional Controls)

	Any Heroin							
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
(Eastern Market)X(Post)	2.875***	2.791***	2.842***	2.728***	2.749***	2.926***	2.860***	2.751***
	(0.3030)	(0.3103)	(0.3437)	(0.3284)	(0.3708)	(0.3103)	(0.3010)	(0.3019)
(Above Median OxyContin OxyContin 2008-09)X(Post-Reformulation)		0.4786	0.5502**					
		(0.3069)	(0.2602)					
(Eastern Market)X(Post-Reformulation)X(Above Median OxyContin OxyContin 2008-09)			-0.1156					
			(0.3976)					
(OxyContin OxyContin 2008-09)X(Post-Reformulation)				0.6232*	0.6449**			
				(0.3597)	(0.2966)			
(Eastern Market)X(Post-Reformulation)X(OxyContin OxyContin 2008-09)					-0.0277			
					(0.2317)			
Post-Must Access PDMP Reform						0.4252*		
						(0.2186)		
Yearly Law Enforcement Officers per 100,000							-0.0016	
							(0.0010)	
(Post)X(log(Import Trade Value per Capita in 2008))								-0.4710***
								(0.0825)
Pre-treatment mean	0.381	0.381	0.381	0.381	0.381	0.381	0.381	0.381
R^2	0.704	0.706	0.706	0.707	0.707	0.706	0.705	0.717
Observations	13,740	13,740	13,740	13,740	13,740	13,740	13,740	13,740

Notes: This table presents the β coefficients in the first row from estimating Equation (2) with different control variables. The Eastern Market binary variable is equal to one for commuting zones east of -91 degrees longitude and Post is an indicator for 2012 and after. The models include commuting zone and year fixed effects, standard errors are clustered at the commuting zone, and the regressions are population weighted. Outcomes are heroin overdose deaths per 100,000 and the sample includes all commuting zones in the contiguous United States.

Table B.7: Average Fentanyl Mortality Impacts of Potency Shocks (Nationwide, Additional Controls)

	Any Fentanyl							
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
(Eastern Market)X(Post)	6.419***	6.049***	5.225***	5.892***	5.414***	6.429***	6.401***	6.226***
	(0.5216)	(0.4435)	(0.3494)	(0.4746)	(0.4951)	(0.5218)	(0.5162)	(0.5002)
(Above Median OxyContin OxyContin 2008-09)X(Post-Reformulation)		2.095***	0.9343***					
		(0.3671)	(0.2353)					
(Eastern Market)X(Post-Reformulation)X(Above Median OxyContin OxyContin 2008-09)			1.874***					
			(0.3936)					
oxycontin_0809 × postreformulation				38.38***	29.85***			
				(5.589)	(4.700)			
long91 × oxycontin_0809 × postreformulation					10.87***			
					(3.663)			
Post-Must Access PDMP Reform						0.0846		
						(0.4619)		
Yearly Law Enforcement Officers per 100,000							-0.0019	
							(0.0024)	
(Post)X(log(Import Trade Value per Capita in 2008))								-0.7330***
								(0.1987)
Pre-treatment mean	0.931	0.931	0.931	0.931	0.931	0.931	0.931	0.931
R^2	0.624	0.632	0.635	0.634	0.634	0.624	0.625	0.632
Observations	13,740	13,740	13,740	13,740	13,740	13,740	13,740	13,740

Notes: This table presents the β coefficients in the first row from estimating Equation (2) with different control variables. The Eastern Market binary variable is equal to one for commuting zones east of -91 degrees longitude and Post is an indicator for 2012 and after. The models include commuting zone and year fixed effects, standard errors are clustered at the commuting zone, and the regressions are population weighted. Outcomes are heroin overdose deaths per 100,000 and the sample includes all commuting zones in the contiguous United States.

Table B.8: Average Mortality Impacts of Potency Shocks (State-level, Additional Controls)

	Any Heroin					log(heroin)		Any Fentanyl					log(fentanyl)
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
(Eastern Market)X(Post)	2.653***	2.543***	2.986***	2.600***	2.700***	0.9169***	6.118***	5.748***	5.484***	6.091***	6.114***	1.090***
	(0.5170)	(0.5172)	(0.5363)	(0.5128)	(0.4985)	(0.2532)	(0.8463)	(0.8125)	(0.9032)	(0.7945)	(0.8257)	(0.1393)
(OxyContin Misuse 2004-2009)X(Post-Reformulation)		0.6943	1.115*					2.341**	2.091**			
		(0.6563)	(0.6014)					(1.055)	(0.8440)			
(Eastern Market)X(OxyContin Misuse 2004-2009)X(Post-Reformulation)			-0.6678						0.3978			
			(0.4040)						(0.6350)			
Yearly Law Enforcement Officers per 100,000				-0.0060						-0.0030		
				(0.0044)						(0.0115)		
Must-Access PDMP Laws					0.3428						-0.0270	
					(0.3828)						(0.6372)	
(Post)X(Log(Import Trade Value per Capita in 2008))						-0.0445						0.0969
						(0.2046)						(0.1245)
Pre-treatment mean	0.784	0.784	0.784	0.784	0.784	0.784	0.788	0.788	0.788	0.788	0.788	0.788
R^2	0.788	0.790	0.791	0.790	0.789	0.808	0.716	0.721	0.722	0.716	0.716	0.879
Observations	980	980	980	980	980	902	980	980	980	980	980	969

Notes: This table presents the β coefficients in the first row from estimating Equation (2) with different control variables. The Eastern Market binary variable is equal to one for states with centroids east of -91 degrees longitude and Post is an indicator for 2012 and after. All models include state and year fixed effects. Standard errors are clustered at the state-level, and regressions are weighted by state population. The outcome is overdose deaths per 100,000, except for Columns 6 and 12 (logarithms), where Columns 1-6 are for heroin and 7-12 are for fentanyl. The sample includes all contiguous U.S. states.

Table B.9: Average Mortality Impacts of potency shocks by Pre-Existing Heroin Use

Panel A: Pre-Potency Shocks (2005 to 2011)

	Any Heroin (1)	Any Fentanyl (2)	Heroin or Fentanyl (3)	Non-Opioids (4)	Any Drug (5)
(Eastern Market)X(Post)	1.857***	3.646***	4.375***	-1.100***	3.514***
	(0.3598)	(0.5971)	(0.6816)	(0.3458)	(0.7939)
(2005-2011 Heroin Death Rate)X(Post)	0.0799***	0.0221	0.0997***	-0.0327	0.0485
	(0.0259)	(0.0171)	(0.0371)	(0.0224)	(0.0457)
(2005-2011 Heroin Death Rate)X(Eastern Market)X(Post)	0.1322***	0.3846***	0.3703***	0.0197	0.3872***
	(0.0510)	(0.0840)	(0.1029)	(0.0352)	(0.0982)
Pre-treatment mean	0.381	0.931	1.30	5.13	10.5
R^2	0.746	0.661	0.746	0.681	0.782
Observations	13,740	13,740	13,740	13,740	13,740

Panel B: Pre-OxyContin Reformulation (2005 to 2009)

	Any Heroin (1)	Any Fentanyl (2)	Heroin or Fentanyl (3)	Non-Opioids (4)	Any Drug (5)
(Eastern Market)X(Post)	1.976***	3.804***	4.613***	-1.075***	3.864***
	(0.3425)	(0.5895)	(0.6586)	(0.3516)	(0.7730)
(2005-2009 Heroin Death Rate)X(Post)	0.1018***	0.0227	0.1227**	-0.0444	0.0575
	(0.0350)	(0.0228)	(0.0491)	(0.0325)	(0.0633)
(2005-2009 Heroin Death Rate)X(Eastern Market)X(Post)	0.1933***	0.5844***	0.5510***	0.0233	0.5480***
	(0.0669)	(0.1206)	(0.1420)	(0.0568)	(0.1372)
Pre-treatment mean	0.381	0.931	1.30	5.13	10.5
R^2	0.736	0.657	0.738	0.681	0.777
Observations	13,740	13,740	13,740	13,740	13,740

Notes: This table presents the coefficients from estimating Equation (2) with additional interaction terms. The Eastern Market binary treatment variable is equal to one for commuting zones east of -91 degrees longitude and Post is an indicator for 2012 and after. In Panel A, we use Heroin OD$c, 2005-2011$, the heroin overdose death rate from 2005 to 2011, while in Panel B, we use Heroin OD$c, 2005-2009$, the heroin overdose death rate from 2005 to 2009. The models include commuting zone and year fixed effects, standard errors are clustered at the commuting zone, and the regressions are population weighted. Outcomes are overdose deaths per 100,000 and the sample includes all commuting zones in the contiguous United States.

Table B.10: Average Mortality Impacts of Potency Shocks by Race/Ethnicity

Panel A: HDMP Analysis

	Heroin or Fentanyl (1)	White (2)	Black (3)	Hispanic (4)	Native (5)	Other (6)
(White Powder Market)X(Post)	6.416***	7.788***	5.083	5.579***	-1.192	0.4435***
	(1.454)	(1.498)	(3.459)	(1.602)	(5.515)	(0.1595)
Pre-treatment mean	1.87	2.55	1.65	1.10	1.84	0.100
R^2	0.743	0.802	0.664	0.626	0.509	0.603
Observations	620	620	620	620	620	620

Panel B: Nationwide Analysis

	Heroin or Fentanyl (1)	White (2)	Black (3)	Hispanic (4)	Native (5)	Other (6)
(Eastern Market)X(Post)	7.112***	7.960***	6.327***	5.793***	7.030***	0.4927***
	(0.5920)	(0.6907)	(1.166)	(0.8912)	(2.311)	(0.0954)
Pre-treatment mean	1.33	1.61	0.878	0.575	1.78	0.046
R^2	0.705	0.715	0.594	0.572	0.265	0.281
Observations	12,009	12,009	12,009	12,009	12,009	12,009

Notes: This table presents the β coefficients from estimating Equation (2) for overdose deaths for each race category. In Panel A, the White Powder Heroin treatment indicator variable is defined as having an above median share of total pre-potency shock heroin purchases being white powder and in Panel B, the Eastern Market treatment variable is equal to one for commuting zones east of -91 degrees longitude. The sample in Panel A is only commuting zones that had a city that participated in the Heroin Domestic Monitor Program (HDMP) and in Panel B, it is all commuting zones in the contiguous United States. Post is an indicator for 2012 and after. The models include commuting zone and year fixed effects, standard errors are clustered at the commuting zone, and the regressions are population weighted. Outcomes are overdose deaths per 100,000 and the sample includes only commuting zones where have population counts for all races. Appendix Figure A.15 provides an alternative comparison of the impacts by race using a unified model.

Table B.11: Decomposition of Changes in Average Annual Opioid Death Rates (Nationwide), 2009 to 2019

	Heroin	Fentanyl	Illicit Opioids
	(1)	(2)	(3)
Heroin Potency Shocks	1.07	5.64	4.99
	[0.26, 1.87]	[3.35, 7.92]	[2.85, 7.14]
OxyContin reformulation	0.11	3.04	3.71
	[-1.45, 1.68]	[-1.01, 7.10]	[-0.03, 7.46]
Must-access PDMPs	1.00	1.72	1.93
	[0.06, 1.94]	[-0.80, 4.25]	[-0.56, 4.45]
Average Increase (rel. 2009)	3.17	10.03	10.57

Notes: Decomposition of changes in heroin, synthetic opioid (fentanyl), and illicit opioid (heroin or fentanyl) from 2009 to 2019 based on interacting 2019 coefficients from Equation (4) with weights proportional to the impact of each intervention/shock in the average state. 95% confidence intervals are presented in brackets and use standard errors that were constructed via the Delta method. The bottom row presents the average annual change in each cause of death from 2009 to 2019, for comparison.