Did the Electronic Logging Device Mandate Reduce Accidents?

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On December 18th, 2017, the U.S. Department of Transportation implemented a controversial mandate requiring the vast majority of truck drivers to record their working hours using electronic logging devices (ELDs). ELDs are harder to manipulate than traditional handwritten paper logbooks, and thus make it more difficult for drivers to violate restrictions on their working hours without getting caught by government inspectors. Because the work-hour restrictions (known as "hours-of-service" (HOS) regulations) are designed to reduce driver fatigue, the ultimate goal of the mandate was to reduce accidents on roads and highways. We combine detailed data from millions of driver inspections and all federally-recordable crashes from January 1st, 2017 through September 1st, 2018 to assess the effectiveness of the mandate. Using a difference-in-differences strategy, we show the mandate clearly achieved its first-order effect: drivers increased their compliance with HOS regulations, with drivers for small carriers most affected because many large carriers had already adopted ELDs and violated HOS regulations infrequently prior to the mandate. However, there is no evidence to suggest that the number of accidents decreased. Our results show that accident counts for small carriers did not fall relative to large carriers, and may have increased. Further, drivers for small carriers appear to have increased their frequency of unsafe driving (e.g., speeding) in response to the productivity losses caused by the mandate, which could explain why accidents did not decrease. We discuss implications for policymakers.

Keywords: *government regulations, policy analysis, electronic monitoring, transportation safety*

1. Introduction

On December 18th, 2017, a mandate issued by the U.S. Department of Transportation (DOT) requiring truck drivers to use electronic logging devices (ELDs) went into effect. ELDs automate the logging of a driver's work history, replacing the more-easily-manipulated handwritten logbooks (Cannon 2018). The DOT also regulates the legal working hours of truck drivers through the "hours of service" (HOS) regulations. Because an ELD increases the likelihood that a driver operating in violation of HOS regulations is detected, ELDs incentivize drivers to violate HOS regulations less often. According to the DOT, the mandate should reduce the number of fatigued drivers by increasing compliance with HOS regulations (Stern et al. 2018). Because fatigued drivers are more dangerous than non-fatigued drivers (Williamson et al. 2011), the end result should be a reduced number of accidents.

But not all agreed with this line of reasoning (Johnston et al. 2014, Schremmer 2017).[1] There are several reasons why ELDs might have little to no effect on accident rates. First, there is little moral hazard in the case of truck drivers and accidents because drivers bear the consequences of their actions – they face significant physical, financial, and emotional costs in the case of an accident, especially if people are hurt. Thus, drivers are highly incentivized to avoid accidents (Sykes 1983). Second, it is unclear how many accidents are caused by fatigued drivers, with estimates ranging from 1.4% (Craft 2010, p. 21) to "less than 4%" (Fisher 2018, p.1) to 13% (Stern et al. 2018). Third, drivers have specific information (Jensen and Meckling 1992) that could be useful when deciding whether to drive, which inflexible regulations cannot take into account. For example, a driver who is delayed while unloading at a warehouse could be well-rested, while the HOS regulations could restrict him or her from driving. Finally, if ELDs reduce a driver's overall productivity (Patrick 2018) then drivers could try to offset this effect by increasing their work intensity (e.g., they could drive faster), which has been shown to be a more frequent cause of accidents than fatigue (Craft 2010, p. 21). Anecdotal evidence from a long-time industry observer suggests this may have happened: "I am hearing about drivers rushing to get loads done when they wouldn't have before…[ELD implementation] prevents some abusive practices and long days, but it also forces drivers to rush and cut corners. I don't know what the net effect is in the long-term" (Viscelli 2018, p. 1).

[1] The Owner-Operator Independent Drivers Association, Inc., (OOIDA) contested the ELD mandate on multiple grounds. Among their complaints, they state that the "FMCSA [Federal Motor Carrier Safety Administration] has no credible data on the relationship between the use of ELDs and actual HOS compliance, and even less data on the relationship between HOS compliance and highway safety. There is virtually nothing in the record that would allow one to defend FMCSA's cost-benefit analysis as support for reasoned decision making" (Johnston et al. 2014, p. 7).

Considering the substantial costs associated with the mandate, the potential effects on public safety[2], and the widespread impact on supply chains (Cassidy 2018, Patrick 2018), it is important to understand the safety benefits associated with the ELD policy intervention. In this study, we exploit a technology-induced shift in the probability that drivers in violation of HOS regulations are caught by inspectors to analyze (i) how driver compliance with HOS regulations changed after the mandate, (ii) whether the behavioral changes resulted in fewer accidents, and (iii) whether the mandate affected other driver behavior, such as unsafe driving. To do so, we use data from millions of roadside inspections of drivers from January 1st, 2017 through September 1st, 2018, during which the inspector records whether the driver is compliant with HOS regulations and, if not, documents the specific violations. We combine this with detailed crash data from the same time period, which includes identifiers for the carriers that were involved in the crashes and when and where the crashes occurred. Our identification strategy relies on the fact that large asset-based carriers[3] were practically unaffected by the mandate—they already had ELDs and high HOS compliance rates well before the mandate, which is clear from our data—while small carriers and independent owner-operators largely did not.

We report several findings. First, the mandate increased HOS compliance, with the percentage of inspections with an intentional violation[4] dropping from 6.0% before the mandate to 3.8% during a light enforcement period (a 36.7% reduction) and further to 2.9% during a strict enforcement period (a 51.7% reduction). As hypothesized, there was substantial heterogeneity based on the size of the carrier. The percentage of inspections with an HOS violation for independent owner-operators (i.e., drivers who operate as a single-truck firm) fell from 10.7% to 8.0% to 6.0% for the three respective enforcement

[2] The DOT estimated the costs associated with the ELD mandate at roughly $2.5 billion per year and estimated the safety benefits as a reduction in almost 2,000 accidents, 562 injuries, and 26 deaths (Federal Register 2015).
[3] Large asset-based carriers, defined as J.B. Hunt Transport, Schneider National, U.S. Xpress, Werner Enterprises, Knight-Swift Transportation (these two companies merged in 2017; we include data from the independent and combined companies), C.R. England, and Maverick Transportation, have been using ELDs long before January 1st, 2017 (OOIDA 2016). "Asset-based" means that the carrier owns most of the trucks they operate, as opposed to "non-asset-based" carriers who act as aggregators of owner-operators, such as Landstar Ranger.
[4] We define "intentional" violations later in Section 4; in short, these are obviously intentional actions, such as exceeding legal driving hours (Scott and Nyaga 2018).

periods (a 43.9% reduction overall), whereas the same percentages were 0.85%, 0.89%, and 0.75% for large asset-based carriers. Second, crash counts for the carriers most affected by the mandate did not fall over this period. When comparing crash counts for small carriers to crash counts for large asset-based carriers using difference-in-differences, we fail to reject the null hypothesis that the mandate had no impact on crashes, and this finding is robust to several controls that account for, e.g., overall load volumes and the number of trucks operated by large and small carriers. Third, our data suggest that unsafe driving infractions for small carriers and independent owner-operators increased relative to large asset-based carriers after the mandate was implemented, thus suggesting a potential mechanism for the lack of a decrease in accidents. We close with a discussion of the policy implications of our study.

2. Research Setting

2.1 Regulations and Enforcement

The DOT regulates all large trucks and buses involved in interstate commerce via the Federal Motor Carrier Safety Administration (FMCSA), whose primary goal is to "prevent commercial motor vehicle-related fatalities and injuries" (FMCSA 2018a, p. 1). To achieve this goal, they regulate the legal working conditions of vehicles and drivers. Vehicles must be maintained in a minimally-acceptable condition to legally operate on roads and highways; for example, they must have working headlights, cargo must be properly secured, and they must not exceed specified weight limits. Drivers must comply with HOS restrictions, which require rest breaks through the course of a work day and limit the total driving time in a day and over the course of several days to reduce driver fatigue (FMCSA 2018b, Stern et al. 2018).

To enforce HOS regulations, the FMCSA requires that drivers log their work and non-work schedules, and DOT inspectors check these logs periodically through unannounced roadside inspections (Cantor et al. 2016). Drivers have traditionally used either handwritten paper logs or ELDs, which automatically record their work based on the operation of the truck's engine. ELDs are harder for a driver to manipulate than paper logs (Cannon 2018), so their usage should increase compliance with HOS regulations (Federal Register 2010). Thus, the FMCSA passed rule 49 CFR Parts 385, 386, 390, and 395

(Federal Register 2015) (henceforth, ELD mandate) on December 16th, 2015, which requires nearly all commercial vehicles to use ELDs to track a driver's work hours by December 18th, 2017.

DOT-approved inspectors conduct millions of roadside inspections per year in all 50 states and the District of Columbia (Scott 2018). During a roadside inspection, an inspector checks a driver's documents – medical certificates, licenses, and electronic or paper logs – to ensure that they are operating legally. The inspector can then end the inspection or perform a more thorough vehicle inspection (Kahaner 2015). Prior to the December 18th, 2017, a driver could use a paper log ("pretreatment" period). After and including December 18th, 2017, the FMCSA required drivers to use an ELD but enforced the mandate relatively lightly, only issuing discretionary citations for non-compliant drivers ("light enforcement" period). After and including April 1st, 2018, the FMCSA strictly enforced the ELD mandate ("strict enforcement" period); for example, they ordered non-compliant drivers "out of service" for 10 hours if they did not have an appropriate ELD (Jaillet 2017).

2.2 Industry Overview

Trucking is the dominant mode of transportation in the U.S. (ATA 2018), moving roughly 67% of all tonnage nationwide (Corridore 2014). For-hire carriers are a particularly important subsector of trucking, of which there are hundreds of thousands utilized to move goods through virtually every major supply chain (Caplice 2007, Scott, Parker, and Craighead 2017). Carriers range from independent owner-operators (Cantor et al. 2013, Monaco and Redmon 2012) to small carriers with a handful of trucks to large carriers with thousands of trucks (Miller, Schwieterman, and Bolumole 2018b).

Size differences introduce an important distinction with regards to the value of ELDs for carriers. ELDs enable carriers to better monitor their drivers (Cubitt 2016), increasing their ability to reduce undesirable behaviors such as non-compliance with HOS regulations (Baker and Hubbard 2004). This is especially valuable for larger carriers because these firms have far greater inspection exposure (Miller et al. 2018c). Accordingly, most large carriers already used ELDs prior to and irrespective of the mandate (Cantor et al. 2006, Cantor et al. 2009). The monitoring and informational advantages of ELDs are reduced for small carriers, whose operations are less complex compared to large carriers, and the benefits are practically non-existent for independent owner-operators (except for a reduction in paperwork) because they self-monitor as the residual claimant (Hubbard 2000, Nickerson and Silverman 2003).

Perhaps unsurprisingly, then, the ELD mandate (and past incarnations) was supported by the largest carriers (e.g., J.B. Hunt Transport (Woodruff 2014), Schneider National (VandeHei 2011), Werner Enterprises (Reiser 2011)) and ardently opposed[5] by small carriers and independent owner-operators, particularly the Owner-Operator Independent Drivers Association (OOIDA) (Johnston et al. 2014). Many, though not all[6], large carriers in support of the bill argued that ELDs would improve safety. Small carriers and independent owner operators had several complaints—(1) the cost (Cruz 2017), both of the device itself and the implicit costs of reduced driving hours, (2) a reduction in the flexibility of driving hours (Wilcox 2018), (3) a lack of evidence that ELDs actually improve safety (Johnston et al. 2014), and (4) a fear of "big brother" looking over their shoulders (Selko 2017).

Thus, given the mandate's substantial costs and structurally asymmetric impact on carriers of different sizes, it is clear why the opposing parties were in dispute. In-line with the FMCSA's mission to develop and enforce "data-driven regulations that balance motor carrier (truck and bus companies) safety with efficiency" (FMCSA 2018c, p. 1), the goal of this paper is to evaluate whether the mandate reduced accidents and, if so, by how much.

3. Theory and Hypotheses

3.1 Costs and Benefits of Cheating

[5] Thousands of comments for and against the regulation can be found at https://www.regulations.gov/docketBrowser?rpp=25&so=DESC&sb=commentDueDate&po=0&dct=PS&D=FMCSA-2017-0356 and https://www.regulations.gov/docketBrowser?rpp=25&so=DESC&sb=commentDueDate&po=0&dct=PS&D=FMCSA-2010-0167.

[6] Werner Enterprises, Inc., a carrier with thousands of trucks, offers an interesting commentary on the adoption of ELDs. For example, they claim that after implementing ELDs they cannot conclude that ELDs enhance safety: "we have never claimed a significant reduction in accident frequency or severity as a result of our use of a paperless logging system…a carrier doing a good job of operating using a paper logging system should not see any change in its accident rate attributable to a conversion to EOBR [ELD] use. Also, when one considers the relatively small percentage of accidents in which fatigue is the precipitating factor and the fact that even 100% compliance with HOS regulations will not totally eliminate fatigue, one would not expect to see a dramatic reduction in total accidents even if a carrier achieves 100% compliance with HOS regulations" (Reiser 2011, p. 2).

To conceptualize how ELDs affect a driver's behavior, we consider a driver deciding whether to intentionally violate HOS regulations. A "rational cheater" (Nagin et al. 2002, p. 855) balances the costs and benefits of cheating based on the severity and certainty of punishment, choosing to cheat if the payoffs associated with cheating exceed the expected costs (Becker 1968, Malik 1990). This conceptualization applies to drivers with significant decision-making autonomy (Jensen and Meckling 1992), such as independent owner-operators and drivers for small carriers with paper logs and/or loose operational controls (Swartz and Douglas 2009). Large carriers, who combine ELDs with task-assignment authority (Viscelli 2016), largely remove the opportunity for drivers to cheat.

Drivers can increase their productive output by violating HOS regulations, which increases their income because interstate truck drivers are almost universally paid per mile or as a percentage of load revenue (Masten 2009). This can occur in two ways: by increasing their total work time or by adding flexibility to their work schedule. The first case is obvious – a driver can violate the restrictions on legal driving hours by driving more than the allowed time, which allows them to produce more and hence get paid more (Miller, Fugate, and Golicic 2018b).

In the second case, flexibility can increase a driver's output because a driver's workday is filled with interruptions – e.g., traffic, loading and unloading delays, and waits for load assignment (Masten 2009). For example, consider delays caused by loading or unloading a truck. Drivers with single tractor-trailer combinations must wait to be loaded or unloaded by workers at the origin or destination, which can significantly reduce a driver's productive work time (Viscelli 2016). In the words of a frustrated independent owner-operator:

> The inflexible hours of service combined with the electronic logging device (ELD) stuck at the diagnostic port of my engine since December 18th of 2017 have turned my job into a miserable day to day activity, without the monetary compensation for being away from home more than necessary. I will not let anybody tell me when I should be awake to drive or that I need to go to sleep when I am energetic after resting all day in various warehouses waiting for hours for them to leisurely come around to take their freight of[f] my trailer. This entire industry needs an overhaul [including more] efficient warehouse operations and most importantly flexible hours of service (Wilcox 2018, p. 1).

Thus, violating HOS regulations can increase a driver's production by allowing them to work longer and by increasing their ability to reorganize their work schedules in response to unexpected delays. The marginal benefits of a violation can be thought of as a change in a driver's income if they cheat minus the driver's income if they do not cheat. We denote this as:

$$\Delta Income(violates\ HOS) = Income(violates\ HOS) - Income(does\ not\ violate\ HOS) \quad (1)$$

The costs associated with a detected HOS violation include fines (England 2017) and points against the driver and carrier's safety record (Doyle 2018). An important contextual factor is that HOS compliance is only checked during inspections of a driver's logbook during a roadside inspection. In other words, cheating drivers who do not get inspected do not get caught. And because inspections are relatively infrequent (for example, we conservatively estimate that about 0.64% of trips were inspected in 2016)[7], drivers often cheat HOS regulations intentionally.[8] Thus, the marginal cost of an HOS violation is:

$$\Delta Cost(violates\ HOS) = Cost(violates\ HOS) - Cost(does\ not\ violate\ HOS) \quad (2)$$

where the second term—the cost associated with not violating HOS regulations—is zero because drivers who are in compliance are not punished. The first term is:

$$Cost(violates\ HOS) = cost * \Pr(detected|inspected) * \Pr(inspected) \quad (3)$$

because only drivers who are actively cheating HOS regulations, are inspected, and the cheating is detected during the inspection, are punished by the FMCSA. The rational cheater model then predicts that a driver will cheat when:

$$\Delta Income(violates\ HOS) > cost * \Pr(detected|inspected) * \Pr(inspected) \quad (4)$$

and not cheat when the left-hand-side of equation 4 is less than or equal to the right-hand-side.

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[7] Trucks moved roughly 11,641 million short tons of cargo in the United States in 2016 (FMCSA 2018d). Conservatively estimating that trucks move fully loaded at 44,000 lbs. (22 tons) and knowing that there were 3.4 million roadside inspections in 2016 (FMCSA 2018d), this means that about 0.64% of truck moves were inspected.

[8] Scott and Nyaga (2018) report that 7.1% of all roadside inspections from 2012 to 2015 had an intentional HOS violation, with significant variation by carrier size. For example, around 12-13% of inspections of individual owner-operators had an intentional HOS violation, while carriers with more than 5,000 trucks violated about 1-3% of the time.

3.2 How Do ELDs Affect a Rational Cheater?

ELDs affect cheating decisions primarily through the $\Pr(detected|inspected)$ term on the right-hand-side of equation 4. Prior to ELDs, a driver using a paper log could alter the log to make it appear as though they are in compliance when in fact they are not. Thus, the probability of an inspector detecting a violation when the driver is truly in violation is less than one, and likely considerably less than one. ELDs are designed to remove this possibility. Thus, the probability of detecting an HOS violation for a cheating driver with an ELD will be greater than a driver with a paper log, and likely close to one.

Another potential effect of universal ELD adoption is that an inspection of an ELD log is easier than a paper log and therefore decreases the duration of an inspection. For example, in 2017 the average inspection time of a "driver only" inspection (also known as a Level 3 inspection (Scott 2018)) was 17.5 minutes for carriers with 1,000 or more trucks and 18.3 minutes for carriers with one to six trucks, a difference in average inspection time of 4.6%. This could increase the number of inspections an inspector performs, which increases the probability of being inspected (the third term on the right-hand-side of equation 4). Both of these effects would be directionally the same for a rational cheater—fewer violations. Because most large carriers already used ELDs well before the ELD mandate (Cubitt 2016) while small carriers (Lockridge 2018) and independent owner-operators (Dorf 2018) did not, the latter two should be affected more. We therefore propose:

H1a: HOS violations decreased more for small carriers and independent owner-operators than for large carriers after the ELD mandate.

During the strict enforcement period, the FMCSA increased penalties for drivers who are non-compliant with the ELD mandate. Starting April 1, 2018 the FMCSA (i) placed non-exempt trucks out-of-service Jaillet 2017) and (ii) reported ELD violations on carriers' publicly available Compliance, Safety, and Accountability scores (Heine 2017) that are utilized by shippers as an input into their carrier selection decisions and performance monitoring processes (Lueck and Brewster 2012). Furthermore, prior to the April 1, 2018, some states did not enforce the ELD mandate, whereas others gave enforcement agents discretion for whether to record such violations (Jaillet 2017). However, all states were required to enforcement the ELD mandate come April 1, 2018. Consequently, strict enforcement should increase compliance for a rational cheater because both the severity and certainty of punishment has increased relative to the light enforcement period. That, is, both the first and second terms on the right hand side of equation 3 have increased. Thus, we predict the following:

H1b: HOS violations decreased more during strict enforcement than during light enforcement.

While the rational cheater model is useful in explaining why a driver violates HOS regulations (Miller et al. 2018b, Scott and Nyaga 2018), it does not predict that a driver who cheats is more likely to get in an accident. The reason is straightforward: since the costs of an accident are high, drivers are incentivized to avoid them if possible (Sykes 1983). Since rational cheaters should internalize the costs of fatigue, a rational cheater will take fatigue seriously while occasionally choosing to violate HOS regulations. Nonetheless, there is also evidence that truck drivers over-estimate their resilience to fatigue (Arnold et al. 1997) and, consequently, may choose to work excessive hours when they are overly fatigued. Thus, the mechanism through which increased HOS compliance reduces accidents is through the reduction of fatigue, assuming there are no unintended effects of increased HOS compliance.

To understand why reducing fatigued driving should reduce accidents, a brief review regarding how worker fatigue affects outcomes is warranted. The negative effects of fatigue on employee performance has been documented in a variety of settings (e.g., Roy 1960, Yoshitake 1978, Smith et al. 2005, Ibanez and Toffel 2018). As workers exert effort over time, they lose energy, motivation, and concentration (Jaber, Givi, and Neumann 2013), causing them to make more mistakes (Kopardekar and Mital 2007) and perform tasks less thoroughly (Oliva and Sterman 2001). Rest breaks are widely used to mitigate the negative effects of fatigue (Bechtold, Janaro, and Sumners 1984, Jett and George 2003), which allow employees to recover to their fully-rested state if the break is long enough (Dai et al. 2015).

Fatigue and rest breaks are precisely the reason for the HOS regulations. Overly-fatigued drivers have been linked with increased accidents (Williamson et al. 2011), and the FMCSA requires rest breaks to reduce fatigue (Stern et al. 2018). Therefore, if increased HOS compliance reduces driver fatigue with no other effects on their behavior, and if fatigued is a significant cause of accidents, then the ELD mandate should reduce accidents. Moreover, since large carriers already had high levels of HOS compliance, the crash counts of independent owner-operators and small carriers should be most affected by the ELD mandate. Figure 1 shows the causal pathway of the effect of the ELD mandate on accidents. We propose the following hypothesis:

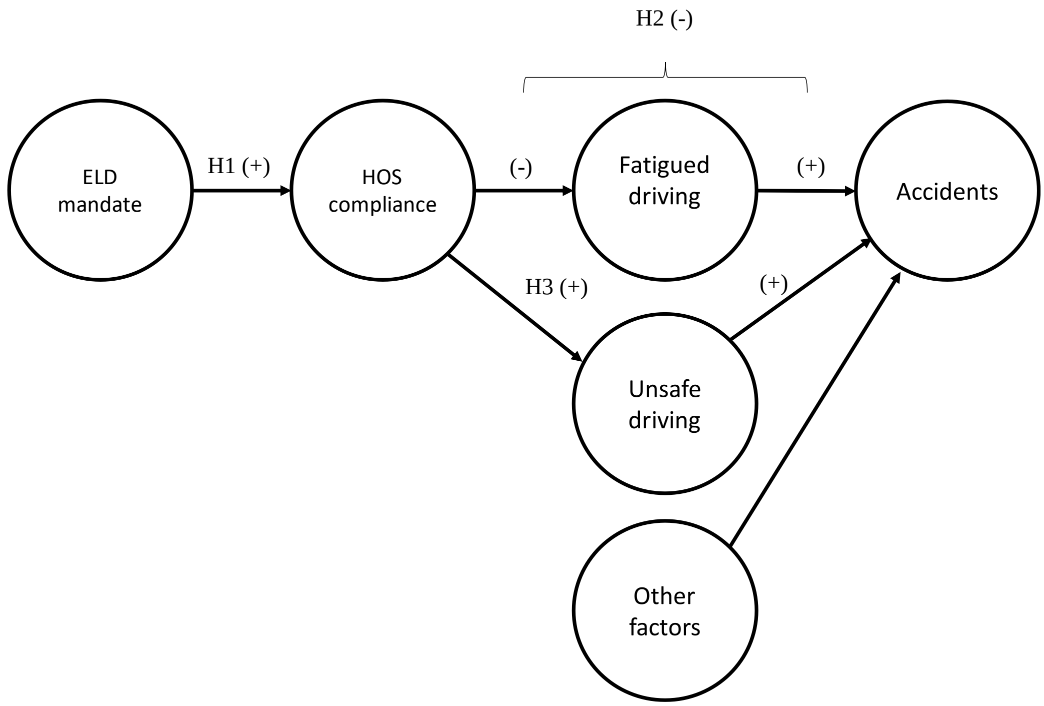
H2: Accidents decreased more for small carriers and independent owner-operators relative to large carriers after the ELD mandate.

For drivers who routinely violate HOS regulations, stricter adherence as a result of the ELD mandate will reduce weekly hours (Balthrop and Wilkin 2018) and, perhaps, income. Recent literature suggests that drivers are to some extent income targeters: rather than choosing work hours to optimally balance consumption and leisure, they instead work until they have reached a desired income target (Belzer and Sedo 2018, Farber 2008, Rodriguez, Targa, and Belzer 2006). If drivers are income targeters, then they may be incentivized to drive more intensively (e.g., drive faster, follow too closely, or change lanes more often). This behavioral response would lead to an increase in unsafe driving violations after increased compliance with HOS violations *ex post* ELD adoption.[9] We suggest the following hypothesis:

H3: Unsafe driving violations increased for small carriers and independent owner-operators relative to large carriers after the ELD mandate.

[9] The incentive to drive more intensively is preserved for "rational" (i.e., in the neoclassical economic sense) if the ELD mandate caused a spike in freight prices.

Figure 1. Effect of ELD Mandate on HOS Compliance, Unsafe Driving, and Accidents.



4. Data and Variables

4.1 Data

Our data come from the FMCSA, who collect data on inspections, crashes, and legally-authorized carriers to monitor carrier safety (Stern et al. 2018).[10] Four sets of files are important for our purposes: 1) inspection files, 2) violation files, 3) crash files, and 4) census files. We received the files on November 5th and 11th, 2018, with data that are accurate through at least September 1st, 2018.[11] The sample period for our analysis is from January 1st, 2017, through September 1st, 2018, which represents about a full year before the ELD mandate (January 1st, 2017 through December 17th, 2017, the pre-treatment period), about three months after the mandate with relatively light enforcement (December 18th, 2017 through March 31st, 2018, the light enforcement period), and five months after the mandate with strict enforcement (April 1st, 2018 through September 1st, 2018, the strict enforcement period). Therefore, our analysis pertains to

[10] Data can be purchased here: https://ask.fmcsa.dot.gov/app/mcmiscatalog/c_chap4. We are happy to share any and all of our data with interested researchers except the source files, which are purchased from the FMCSA.
[11] There appears to be a couple weeks of latency in reporting crashes to the FMCSA since these come from state agencies. For example, the weeks in October of 2018 are clearly not accurate in their counts of crashes. The data through September appear accurate, so we use September 1st as the cutoff to be conservative with our analysis.

behaviors and effects before and shortly after the mandate. It will be interesting to extend the research for longer-term effects after more time has passed. We focus our analysis on for-hire interstate truck carriers, excluding buses and private carriers, because these carriers are most affected by HOS regulations (Scott and Nyaga 2018) and the ELD mandate (Miller, Bolumole, and Schwieterman 2018a).

The inspection file[12] contains detailed information for every inspection performed by an authorized state or federal inspector during the sample period. This includes when and where the inspection occurred, the type of inspection, which carrier was inspected (every legal carrier has a unique identifying number, called a DOT number), and the number of violations that were found during the inspection. We are also interested in specific violations (e.g., driving longer than the legal time, skipping required breaks) listed in a violation file, which we link to the inspections via a unique inspection identifier. This file includes the exact violations reported by the inspector.

The crash file contains information on every crash involving a large truck or bus that resulted in an injury or death or required a vehicle to be towed away (Stern et al. 2018; called “federally-recordable accidents”). This file also includes information such as when and where the accident occurred and, importantly for our purposes, the DOT number of the carrier that was involved. Finally, the census files catalog every commercial carrier legally authorized to operate on federal roads and highways, including the carrier’s DOT number, whether they are an interstate and/or for-hire carrier, and the number of trucks they own. We use several census files – one each from December 2016, October 2017, June 2018, and August 2018. To link a carrier’s registration data, we use the closest census *before* an accident because an accident could affect a carrier – e.g., whether they stay in business, or the number of trucks they operate. Thus, the carrier census information will not be affected by any of the accidents in our sample time period.

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[12] A detailed description of the inspection data can be found here: https://ask.fmcsa.dot.gov/app/mcmiscatalog/d_inspection3-2; of the violation data, here: https://ask.fmcsa.dot.gov/app/mcmiscatalog/d_inspection3-2#IV; of the crash data, here: https://ask.fmcsa.dot.gov/app/mcmiscatalog/d_crash3; and of the census data, here: https://ask.fmcsa.dot.gov/app/mcmiscatalog/d_census_daEleDef.

In our sample, there were 4.0 million inspections performed by 15,266 inspectors on 224,878 for-hire interstate carriers. 191,576 (4.8%) of the inspections had at least one intentional[13] HOS violation, there were 268,427 unsafe driving violations, and 189,406 (70.6%) of those were speeding violations. There were 156,072 accidents involving a for-hire interstate truck during our sample period. For this paper, we refer to intentional HOS violations simply as HOS violations, ignoring paperwork errors.

4.2 Variables and Methodology

We are interested in the effect of the ELD mandate on three outcomes – (1) the propensity of drivers to violate HOS regulations, (2) the number of accidents, and (3) the number of unsafe driving violations. Our identification strategy relies on the fact that one population of drivers and carriers was highly affected by the mandate, while another population practically was not. Specifically, large asset-based carriers already used ELDs to monitor their driver's activities and had very low rates of HOS violations (see Table 1), whereas small carriers and independent owner-operators largely did not use ELDs and had relatively high rates of HOS violations.

We categorize carriers according to their size (see Table 1), where size is defined as the total number of power units reported by the carrier. The size categories are defined as an individual owner-operator with one truck and carriers with between two and six trucks, seven and 20 trucks, 21 and 100 trucks, 101 and 1,000 trucks, 1,001 and 50,000 trucks (excluding large asset-based carriers), more than 50,000 trucks, and large asset-based carriers identified in OOIDA (2016). In our analysis, we exclude the category of carriers with 50,000 or more trucks (this essentially excludes UPS and FedEx from our analysis). These categories are consistent with those used by the DOT when reporting truck and bus facts (FMCSA 2018d), with three more categories to allow for a more detailed analysis.

[13] There are six major categories of HOS violations, defined here: https://ask.fmcsa.dot.gov/euf/assets/mcmiscatalog/d_inspection6.html. Consistent with Scott and Nyaga (2018), we define intentional violations as categories two through six and exclude category seven. Violations included in the analysis are false logbooks, not taking proper breaks, exceeding daily driving limits, and exceeding multi-day driving limits.

Table 1. Carrier-size Category Definitions and Associated Statistics.

Carrier-size Category	Definition	Number of Carriers	Number of Inspections (% with an HOS Violation)	Unsafe Driving Violations	Speeding Violations	Crashes	Included?
0	Trucks not reported	945	5,189 (3.5%)	258	164	622	No
1	Independent owner-operator	108,698	416,202 (8.8%)	26,317	16,970	13,760	Yes
2	Two to six trucks	81,564	698,750 (7.5%)	44,944	31,130	21,529	Yes
3	Seven to 20 trucks	30,446	723,548 (5.6%)	46,426	33,833	22,684	Yes
4	21 to 100 trucks	13,271	977,999 (4.1%)	63,935	47,143	32,901	Yes
5	101 to 1,000 trucks	2,553	708,912 (2.3%)	50,659	36,567	33,191	Yes
6	1,001 to 50,000 trucks*	191	355,202 (1.3%)	24,651	16,382	21,612	Yes
7	More than 50,000 trucks	9	18,391 (0.7%)	2,591	1,928	3,452	No
8	Large asset-based carriers	8	105,710 (0.8%)	8,646	5,289	6,321	Yes
Total		**237,685****	**4,009,903 (4.8%)**	**268,427**	**189,406**	**156,072**	

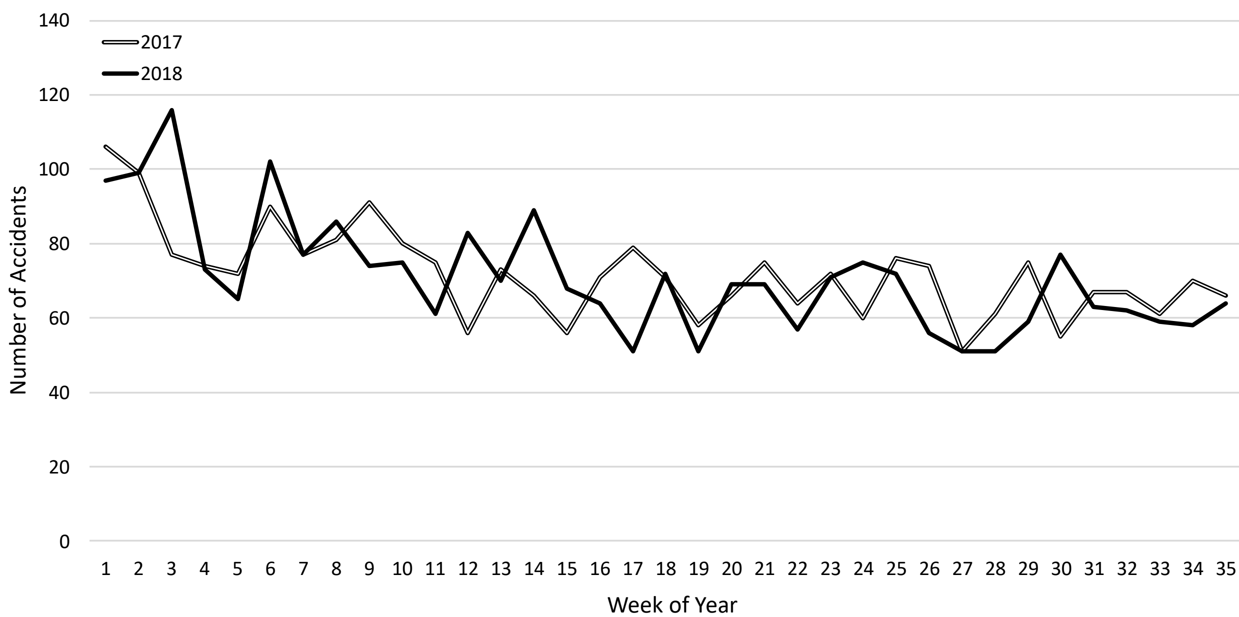
Notes. There are 9 carriers in size category 7, but 7 of those appear to have reported incorrect information to the DOT. For example, UPS and Fedex account for more than 99.9% of the inspections in that size category. Carriers in size category 0 did not report the number of trucks they operate. 97.4% of all crashes, 98.9% of all unsafe driving violations, and 99.4% of all inspections are included in the analysis. *This group excludes large asset-based carriers identified by OOIDA (2016). **This number differs from the 224,878 for-hire carriers reported in Section 4.1 because some carriers can be in different size categories if they changed the number of reported trucks during our sample period.

We analyze behavior over time, where time periods are defined at the week-level. Week one starts on Sunday, January 1st, 2017, and week 87 ends on Saturday, September 1st, 2018. The light enforcement period starts on Sunday, December 17th, 2017, a day before the official effective date of the mandate, and ends on Saturday, March 31st, 2018, the official end of the light enforcement period. These dates correspond to weeks 51 thru 65. The strict enforcement period starts on Sunday, April 1st, 2018, and ends on Saturday, September 1st, 2018. These dates correspond to weeks 66 through 87.

The ELD mandate provides us with a "quasi-experimental" framework to estimate the impact of ELD adoption. Prior to the mandate, one would expect ELDs to be adopted by the carriers with the largest benefits from adoption. The mandate serves as an instrumental variable, giving exogenous variation in ELD adoption. Because large asset-based carriers had already adopted ELDs, and are therefore unaffected by distortions related to ELD adoption, they provide a counterfactual comparison group. In effect, large asset-based carriers are used to control for time trends that might confound a strictly before-and-after comparison of groups that were induced into ELD adoption by the mandate.

To examine whether this assumption is accurate – that the mandate largely did not affect large asset-based carriers – we analyzed four pieces of information: HOS violation percentages, inspection frequencies, accidents, and production before and after the mandate. In the pretreatment, light, and strict enforcement periods, respectively, large asset-based carriers had an HOS violation detected in 0.85%, 0.89%, and 0.75% of inspections, respectively, and were inspected on average 1,213, 1,271, and 1,181 times per week. Neither of these variables show substantial change in behavior on either the carriers or the inspectors. Figure 2 shows the number of accidents involving large asset-based carriers over the same time periods for 2017 and 2018; there appear to be no detectable changes in accidents (the average weekly accidents are 71.8 and 71.0 for weeks one through 35 in 2017 and 2018, respectively).

Figure 2. Weekly Accident Counts for Large Asset-based Carriers from 2017 and 2018.



Dates shown: 2017: January 1st, 2017 to September 2nd, 2017
2018: December 31st, 2017 to September 1st, 2018

It is possible that these carriers improved safety if they increased their output while keeping accidents roughly the same. To assess the output of these carriers from 2017 to 2018, we looked at the second quarter earnings releases for J.B. Hunt Transport (Mee 2018), Schneider National (Schneider 2018), Werner Enterprises (Werner 2018), U.S. Xpress (US Xpress 2018), and Knight-Swift Transportation (Knight-Swift 2018). C.R. England and Maverick Transportation are private and do not provide quarterly reports. Comparing the first six months of 2017 to 2018, the two companies that report mileage reported a decrease (J.B. Hunt: 10.6% reduction in their Truck Division; U.S. Xpress: 1.5% reduction). Schneider National reported a decrease in average trucks from 11,764 to 11,626, and stated that while they had a 5% increase in overall revenue for the truck division, the increase in revenue per truck was 7% “primarily due to price, strong demand, and freight selection” (Schneider 2018, p. 2).

Werner Enterprises reported an increase in average trucks from 7,235 to 7,488 but a decrease in average length-of-haul per truck from 469 miles to 448 miles. Finally, Knight-Swift Transportation reported an increase in trucks for the Knight truck segment from 4,638 to 4,730; while they do not report the numbers for Swift from 2017 (when the merger occurred), Swift averaged 7,844 trucks for the first six months of 2018 and 7,473 trucks for the second quarter of 2018, indicating that this merged company is increasing trucks in their Knight division but decreasing trucks in the Swift division. In sum, it does not appear that large asset-based carriers significantly increased their output from 2017 to 2018, and the evidence suggests that they were largely unaffected by the ELD mandate.

4.2.1 Variables

The first dependent variable is the percentage of inspections for carrier size *i* in week *t* with an intentional HOS violation ($\%\ HOS\ Violations_{it}$). The second dependent variable is the number of accidents ($Accidents_{it}$) involving carriers of size *i* in week *t*. The third dependent variable is the number of unsafe driving violations ($Unsafe\ Violations_{it}$) committed by carriers of size *i* in week *t*. Unsafe driving violations include speeding, failing to obey traffic signals, following too closely, and improper lane changes. $Speeding_{it}$ is the subset of unsafe driving violations where the driver was pulled over for speeding.

We adopt a difference-in-differences empirical strategy (Angrist and Pischke 2009, Ho et al. 2017, Song, Tucker, and Murrell 2015), where fixed effects for carrier size category *i* (γ_i) and week *t* (λ_t) control for arbitrary time-invariant properties associated with each population of carrier-size categories and week fixed effects control for factors such as holiday weeks (and the associated increase or decrease in miles driven), average weather conditions, and the number of cars on the road. Our general model specification is:

$$y_{it} = \alpha + \gamma_i + \lambda_t + \sum_{i=1}^{6} \delta_i Size_i * D1_t + \sum_{i=1}^{6} \beta_i Size_i * D2_t + \mathbf{X}_{it}\boldsymbol{\theta} + \varepsilon_{it} \quad (5)$$

where the interaction variables $Size_i{*}D1_t$ are equal to 1 for carrier size *i* when week *t* falls within the light enforcement period (weeks 51 to 65) and $Size_i{*}D2_t$ interactions are equal to 1 for carrier size *i* when week t falls within the strict enforcement period (weeks 66 to 87). In all models, large asset-based carriers (Carrier-size Category 8 from Table 1) are the omitted category.[14]

A potential confound for the count dependent variables ($Accidents_{it}$, $Unsafe\ Violations_{it}$) not accounted for in the basic difference-in-differences strategy is a possible change in the number of trucks or miles driven by each carrier-size category over time. For example, if there are more independent owner-operators on the road relative to large carriers in the treatment periods,[15] we would expect them to be in more accidents even if each independent owner-operator were safer on average. To control for this possibility, we calculate the number of reported trucks ($Registrations_{it}$) from the nearest census after the particular week. For example, for the week of January 1st, 2017, we sum the number of trucks registered in the October 2017 census for carriers in each size category. If there are significant changes in the number of trucks in each size class, these should be reflected in the census registration data over time.

Another potential explanation for the number of accidents and unsafe driving violations is that all carriers drove more miles during the treated periods compared to the untreated periods. Such an effect will be consumed by the week fixed effects, and thus is controlled for in our specification. However, if the populations of the carrier size categories changed over time *and* the carriers within those size categories drove more miles over time, then our control variables do not perfectly control for the interaction of changing carrier composition and miles driven. To control for this possibility, we use the CASS Freight Shipment Index ($CASS_t$; CASS 2018). This index measures the total number of shipments delivered monthly by trucks in North America, based on billions of dollars of freight expenditures. Changes in $CASS_t$ will capture overall changes in freight volumes, and thus is a proxy for miles driven.

[14] Since all carriers are subject to ELD enforcement, the treatment dummies $D1_t$ and $D2_t$ are indexed by t, not i and t. Consequently, the linear terms for $D1_t$ and $D2_t$ cannot be included in Equation 5 because they are perfectly correlated with weekly time dummies λ_t. However, since the large asset-based carriers identified by OOIDA (2016) already operated with ELDs, the ELD mandate did not affect their use of these devices. Consequently, we can identify treatment effects because the δ_i coefficients capture whether the change in y_{it} for size category i during the light enforcement period relative to no enforcement was greater for category i relative to Carrier-size Category 8. Likewise, the β_i coefficients capture whether the change in y_{it} for size category i during the strict enforcement period relative to no enforcement was greater for category i relative to the large asset based carriers.

[15] Because more strict HOS enforcement favors large carriers relative to small carriers, one would expect carriers to increase in size on average and some small carriers to exit the market after the ELD mandate went into effect.

We interact this index (which is measured nationwide and not delineated by carrier-size categories) with *Registrations*$_{it}$ to control for the possibility that the number of trucks in a carrier-size category changed over time and that the trucks within those size categories drove more miles.

Another measure of changing carrier-size categories comes from the inspection data. We calculate the percentage of inspections in week *t* performed on carrier-size category *i* (*% of Inspections*$_{it}$). If more independent owner-operators are on the roads relative to large carriers, we would expect that to be reflected in the inspection percentages – i.e., the percentage of inspections on individual owner-operators should increase relative to large carriers in such a case. A potential problem with the *% of Inspections*$_{it}$ control is that exactly who to inspect is somewhat endogenous to the inspector (Scott 2018), and if an inspector suspects that small carriers are less likely to be ELD-compliant compared to large carriers, they may choose to inspect them more frequently after the mandate went into effect.[16] Table 2 shows the variable definitions and summary statistics.

Table 2. Variables and Summary Statistics.

Variable	Description	Mean	St. Dev.	Min	Max
% HOS Violations	Percentage of weekly inspections with an HOS violation	0.044	0.033	0.003	0.126
Accidents	Number of accidents	249.6	108.3	51	558
Unsafe Violations	Number of unsafe driving violations	436.1	212.2	60	991
Speeding	Number of speeding violations	307.6	162.5	34	741
Carrier-size category	Carrier-size categories (e.g., independent owner-operators, two to six trucks)	3.4	2.8	0	6
Week	Week 1 starts on January 1st, 2017; Week 87 ends on September 1st, 2018	44.0	25.1	1	87
CASS	CASS freight index value (monthly value)	1.165	0.067	1.005	1.307
Registrations	Number of registered trucks for each carrier-size category and week	400,587	252,257	69,734	916,364
% of Inspections	Percentage of overall inspections by carrier-size category and week	0.142	0.068	0.022	0.256

Notes. N=609.

5. Results

5.1 Hours-of-Service Violations

HOS violations declined during the light enforcement period and fell further during stricter enforcement, shown in Figure 3. The change in behavior varied considerably for carriers of different sizes. Pre-ELD mandate, independent owner-operators had at least one intentional HOS violation in 10.7% of inspections. During the light enforcement period, independent owner-operators had at least one intentional HOS

[16] Such behavior by inspectors will overestimate the number of independent owner-operators and small carriers on the road, making our analysis conservative.

violation in 8.0% of inspections, a decrease of 25.2%. In the strict enforcement period, the percentage of inspections with at least one intentional HOS violation was 6.0%, a decrease of 25.0% relative to the light enforcement period and 43.9% relative to the pretreatment period. Carriers with between two and six trucks showed similar changes in behavior, with the percentage of inspections with at least one HOS violation falling from 9.1% in the pretreatment period to 6.3% in the light enforcement period and to 4.7% in the strict enforcement period. These changes equate to a decrease in violation rates of 30.8% and 48.4% for the light and strict enforcement periods, respectively, relative to the pretreatment period. Large asset-based carriers, as discussed previously and shown in Figure 3, were practically unaffected by the mandate.

Figure 3. HOS Violation Percentages in the Pre-, Light-, and Strict Enforcement Periods.

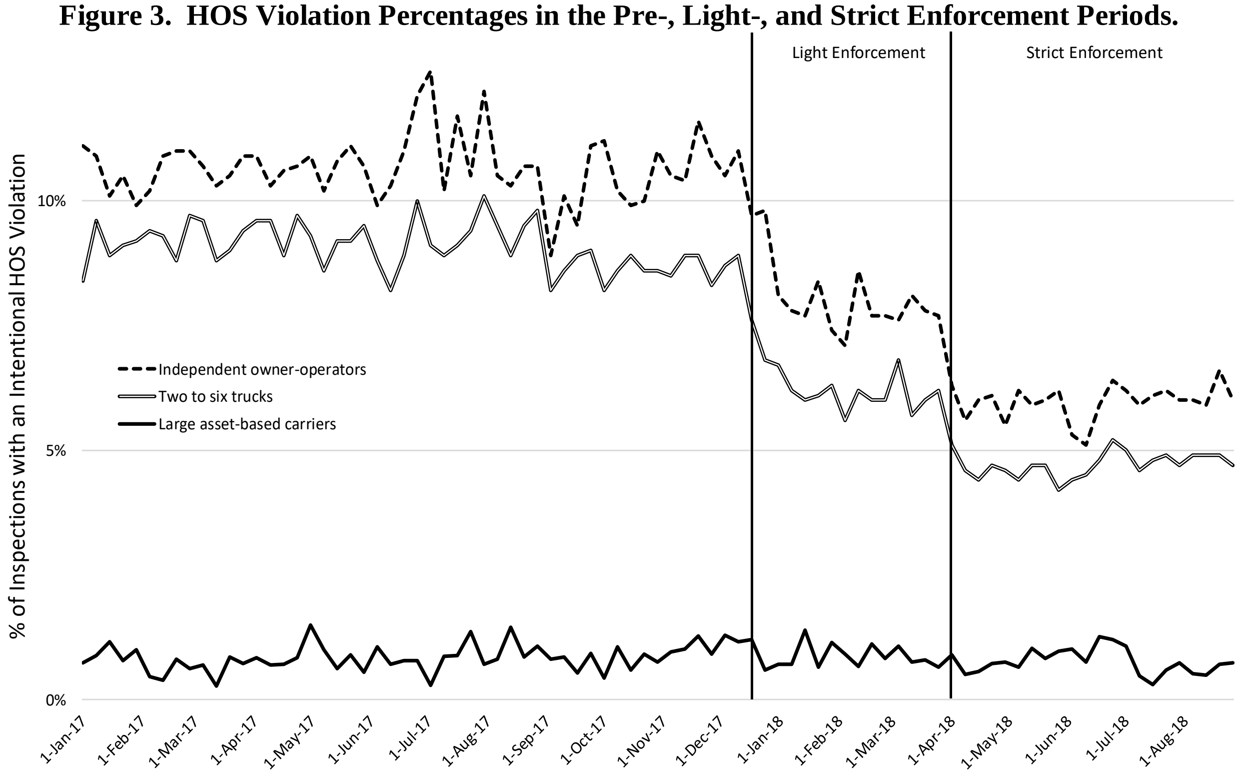


Table 3. Average Number of Weekly HOS Violations per 1,000 Inspections by Carrier Size in the Enforcement Periods.

Size Category	Pre-mandate	Light Enforcement	Strict Enforcement	Diff (Light)	Diff (Strict)	DD (Light)	DD (Strict)
Large asset-based carriers	8.5	8.9	7.5	0.4	-0.9	--	--
Independent owner operators	106.7	80.8	59.7	-25.9	-47.0	-26.3	-46.1
Two to six trucks	90.6	62.8	47.1	-27.8	-43.4	-28.1	-42.5
Seven to 20 trucks	71.3	43.5	30.8	-27.9	-40.5	-28.2	-39.6
21 to 100 trucks	53.7	26.7	20.7	-27.0	-32.9	-27.4	-32.0
101 to 1,000 trucks	29.1	15.3	13.1	-13.8	-16.0	-14.2	-15.0
1,001 to 50,000 trucks	16.0	10.9	10.0	-5.0	-5.9	-5.4	-5.0

Table 3 shows the average number of weekly HOS violations per 1,000 inspections for the different carrier sizes in the different enforcement periods and the associated differences in means. We test the effect of the ELD mandate using the difference-in-differences specification in equation 5, where the dependent variable is *% HOS Violations*$_{it}$. Table 4 reports the results, which support hypotheses H1a and H1b.[17] HOS violations decreased during the light enforcement period ($p < 0.001$); violations of independent owner-operators and carriers with two to six trucks decreased relative to the omitted category of large asset-based carriers (both with $p < 0.001$), and HOS violations decreased further during the strict enforcement period ($p < 0.001$). Light enforcement of the mandate reduced HOS violations for independent owner-operators by 2.6%, and by 2.8% for carriers with between two and six trucks and for carriers with between seven and 20 trucks. Strict enforcement decreased HOS violation percentages by 4.6%, 4.3%, and 4.0% for independent owner-operators, carriers with between two and six trucks, and carrier with between seven and 20 trucks, respectively, relative to large asset-based carriers. A Wald test of the joint hypothesis that violation rates decreased after strict enforcement relative to the light enforcement period is supported ($p < 0.001$), with the effect being statistically significant ($p < 0.05$) for independent owner-operators and carriers with between two and six trucks, between seven and 20 trucks, and between 21 and 100 trucks, but not for the other categories of carriers.

[17] We ran numerous specifications, including all of the specifications discussed in section 5.2 for accident counts, and the results never changed either statistically or practically.

Table 4. Difference-in-Differences Estimates of HOS Violations by Carrier-Size Group and Enforcement Periods.

Dependent Variable: *% HOS Violations*	Light Enforcement	Strict Enforcement
Independent owner-operators	-0.026*** (0.002)	-0.046*** (0.001)
Two to six trucks	-0.028*** (0.001)	-0.043*** (0.001)
Seven to 20 trucks	-0.028*** (0.001)	-0.040*** (0.001)
21 to 100 trucks	-0.027*** (0.001)	-0.032*** (0.001)
101 to 1,000 trucks	-0.014*** (0.001)	-0.015*** (0.001)
1,001 to 50,000 trucks	-0.006*** (0.001)	-0.005*** (0.001)
Constant	0.007*** (0.002)	
Controls		
Size Category fixed effects	Yes	
Week fixed effects	Yes	
R-squared	0.991	
N	609	

Notes. * p<0.05, ** p<0.01, *** p<0.001. Robust standard errors are in parentheses. Large asset-based carriers are the omitted category.

5.2 Accidents

The number of weekly truck accidents in the pretreatment period averaged 1,717 accidents, increased to 1,912 accidents (an 11.4% increase) in the light enforcement period, and dropped to 1,703 accidents per week (a 0.8% decrease) in the strict enforcement period. Table 5 shows that the number of accidents for all categories of carriers increased in the light enforcement period, with the largest carriers having the largest percentage increases (crashes involving carriers with between 101 and 1,000 trucks increased 16.1% and crashes involving large asset-based carriers increased 13.1%). Smaller carriers saw marginally smaller increases in the number of accidents, with 7.8% and 9.7% increases in average accident counts for independent owner-operators and carriers with between two and six trucks, respectively.

Table 5. Average Number of Weekly Accidents by Carrier-size in the Enforcement Periods.

Size Category	Pre-mandate	Light Enforcement	Strict Enforcement	Diff (Light)	Diff (Strict)	DD (Light)	DD (Strict)
Large asset-based carriers	73.4	83.0	64.0	9.6	-9.4	--	--
Independent owner operators	154.7	166.7	160.1	12.0	5.4	2.4	14.7
Two to six trucks	242.3	265.9	246.6	23.6	4.3	13.9	13.7
Seven to 20 trucks	254.1	282.5	261.1	28.4	7.0	18.8	16.4
21 to 100 trucks	373.7	406.1	369.4	32.5	-4.3	22.8	5.1
101 to 1,000 trucks	374.3	434.7	361.5	60.4	-12.8	50.8	-3.5
1,001 to 50,000 trucks	244.7	272.7	240.4	28.0	-4.3	18.4	5.1

During the strict enforcement period, accidents decreased across the board compared to the light enforcement period. Compared to the pre-mandate period, accident counts for the largest carriers fell by 3.4%, 1.8%, and 12.8% for carriers with 101 to 1,000 trucks, 1,001 to 50,000 trucks, and large asset-based carriers, respectively, while accidents counts for smaller carriers showed the opposite effect, increasing 3.5% for independent owner-operators and 1.8% for carriers with two to six trucks. Figure 4 shows HOS violation percentages and accident counts for independent owner-operators, and Figures 5 and 6 shows the same for carriers with two to six trucks and large asset-based carriers, respectively. For smaller carriers, while HOS violation rates clearly fell post-ELD mandate, the accident counts show positive trends during the same period. On the contrary, accident and HOS violation rates for large carriers show no trend. Collectively, these numbers do not point to any obvious reduction in accidents due to the ELD mandate, and in some cases suggest a possible *increase* in accidents for those carriers most affected by the mandate.

Figure 4. HOS Violations and Number of Accidents for Independent Owner-Operators.

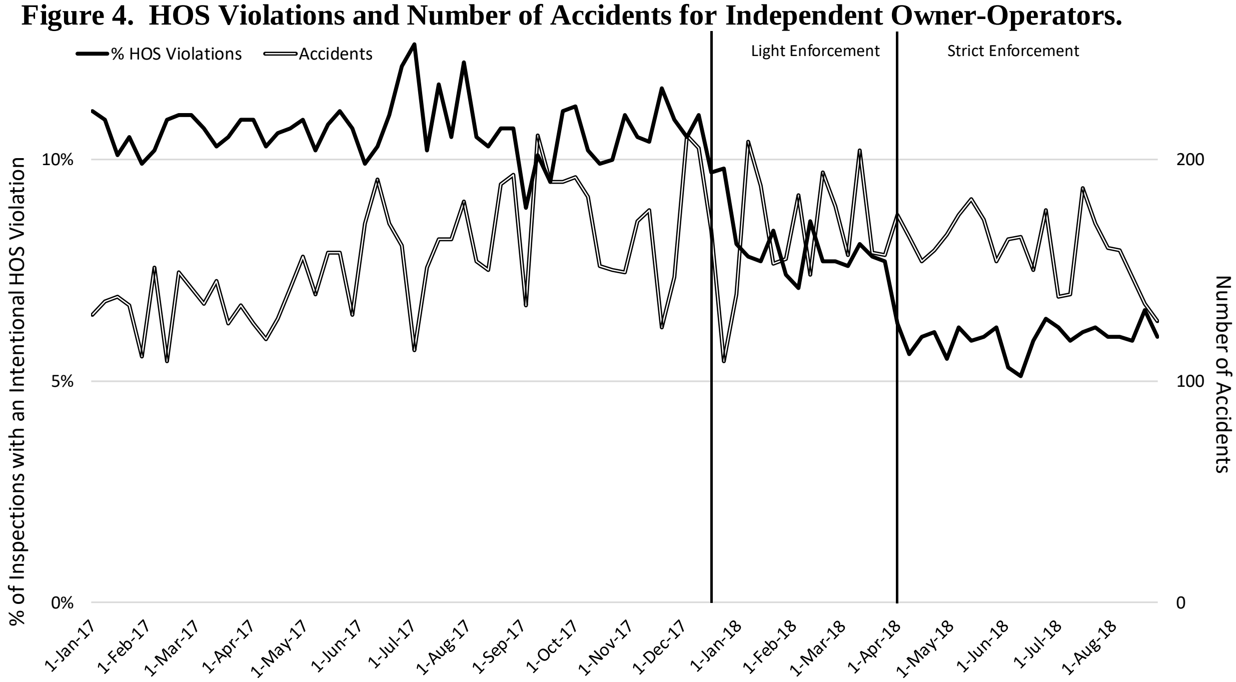


Figure 5. HOS Violations and Number of Accidents for Carriers with Two to Six Trucks.

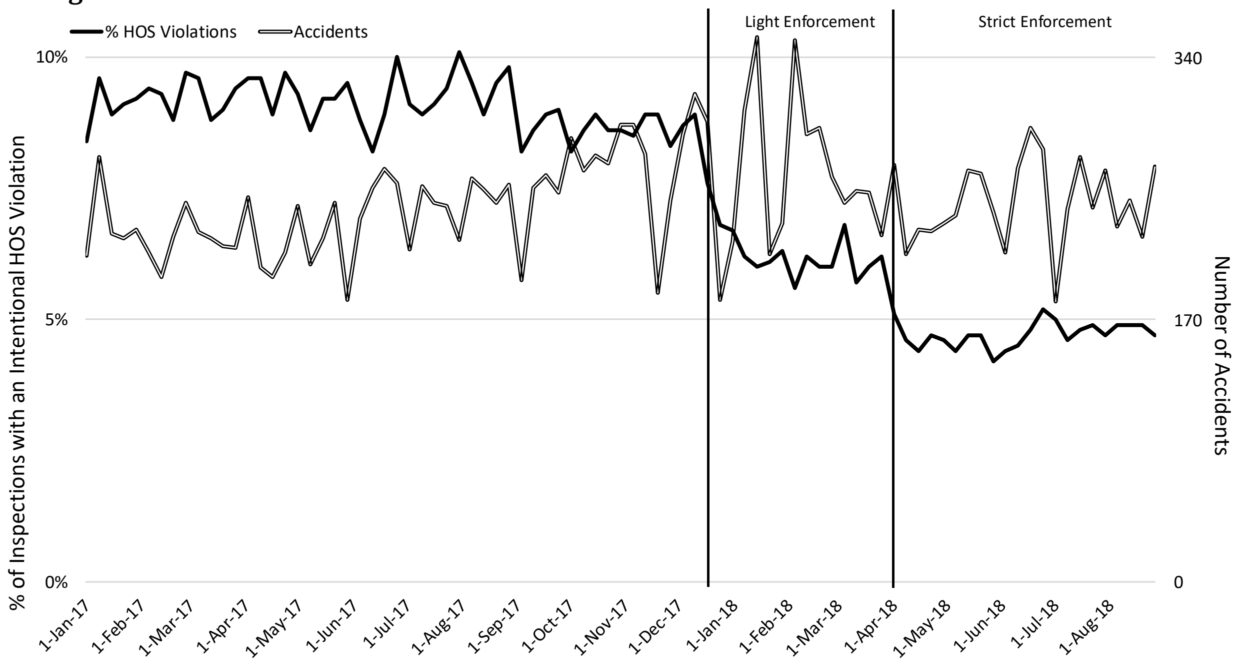


Figure 6. HOS Violations and Number of Accidents for Large Asset-based Carriers.

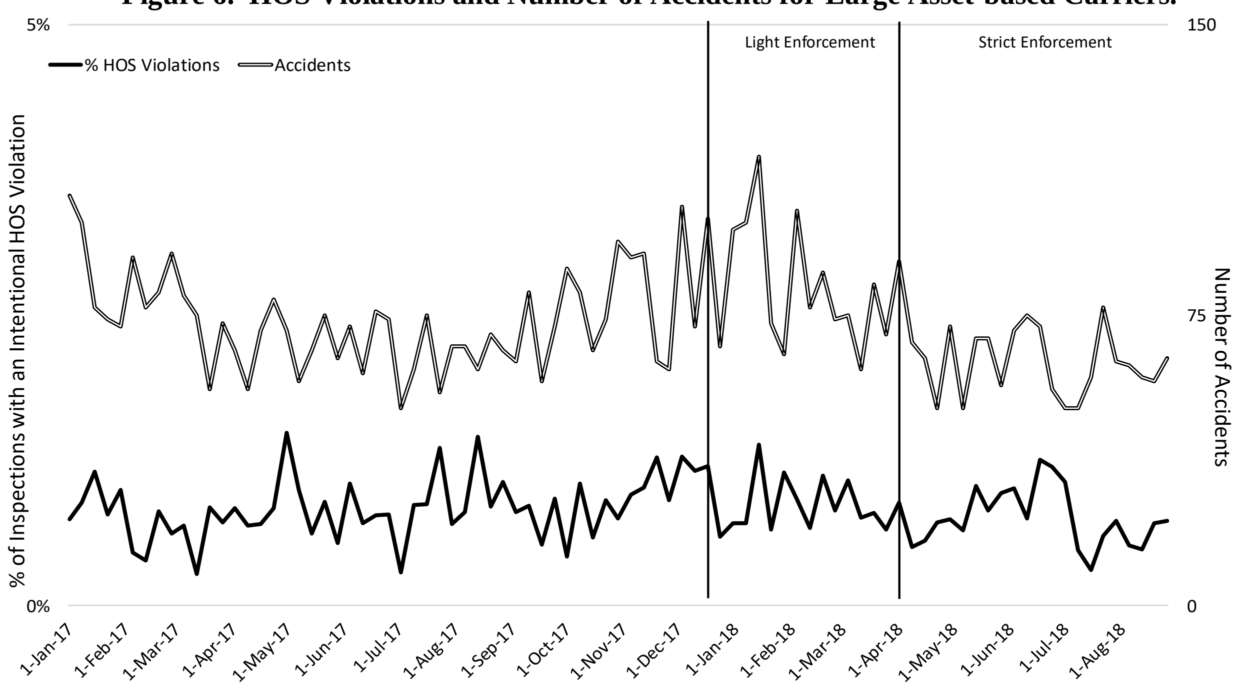


Table 6 reports the results from the difference-in-differences estimation specified in equation 5, where the number of weekly accidents by carrier-size category ($Accidents_{it}$) is the dependent variable. In the light enforcement period, accidents for most types of carriers did not significantly change relative to large asset-based carriers. Carriers with between 101 and 1,000 trucks are the exception, who saw accidents increase by around 50 accidents per week.

Accidents during the strict enforcement period – when HOS compliance increased the most – increased for small carriers relative to large carriers. In most specifications, carriers with between two and six trucks and between seven and 20 trucks had an increased number of accidents ($p < 0.05$ in most cases, and in several cases $p < 0.01$), with practically meaningful numbers, ranging from an increase of 13 to 22 accidents per week. During the strict enforcement period, the only case in which a group of carrier's accident counts fell relative to large asset-based carriers is the most extreme specification, in which we don't include time controls and allow small carriers to increase in both total numbers and productivity per truck. Even in this specification we are able to observe no statistically significant accident reductions. Thus, we cannot conclude that HOS compliance through enforcement of the ELD mandate decreased the number of accidents; H2 is not supported.

Table 6. Difference-in-Differences Estimates of Accidents by Carrier-Size Group and Enforcement Periods.

Dependent Variable: *Accidents*	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Light Enforcement	9.6* (4.51)				12.11 (7.03)	10.1 (6.67)	10.0 (6.82)	13.0* (5.92)	12.6 (6.47)	9.8 (6.05)
Independent owner-operators	2.4 (8.92)	2.4 (12.24)	1.9 (12.26)	-9.0 (12.10)	2.2 (9.88)	-9.2 (10.05)	2.4 (9.23)	12.8 (8.72)	3.0 (9.26)	-6.9 (9.52)
Two to six trucks	13.9 (14.09)	13.9 (10.99)	13.4 (11.00)	21.1* (10.51)	13.7 (12.71)	21.2 (12.42)	13.9 (13.47)	26.4 (14.00)	15.0 (13.50)	14.4 (13.16)
Seven to 20 trucks	18.8 (14.24)	18.8 (10.95)	18.3 (10.97)	27.7** (10.51)	18.6 (12.25)	27.8* (11.85)	18.8 (13.36)	27.8* (13.53)	19.9 (13.24)	20.2 (13.01)
21 to 100 trucks	22.8 (17.67)	22.8 (11.85)	22.2 (11.88)	30.5** (11.36)	22.6 (15.39)	30.7* (15.43)	22.8 (16.15)	38.0* (17.06)	24.5 (16.20)	21.7 (15.83)
101 to 1,000 trucks	50.8** (17.89)	50.8*** (12.38)	50.6*** (12.39)	54.1*** (11.88)	50.7** (16.57)	54.2*** (16.28)	50.8** (17.01)	66.6*** (18.09)	52.2** (16.95)	48.7** (17.00)
1,001 to 50,000 trucks	18.4 (13.63)	18.4 (10.48)	24.9* (11.88)	16.2 (10.18)	20.6 (14.02)	16.2 (12.98)	18.4 (13.56)	25.2 (14.18)	14.0 (14.22)	15.3 (13.68)
Strict Enforcement	-9.4** (2.76)				-1.1 (4.06)	0.60 (4.03)	-13.9* (5.74)	-0.1 (5.89)	-8.63* (3.78)	-9.5* (3.77)
Independent owner-operators	14.7* (5.77)	14.7* (6.08)	14.0* (6.09)	-2.3 (6.98)	14.5* (6.29)	-2.6 (7.67)	14.7* (6.34)	20.7*** (6.41)	15.9* (6.56)	-1.8 (8.23)
Two to six trucks	13.7 (7.73)	13.7* (6.14)	12.9* (6.16)	15.5** (5.92)	13.4* (6.56)	15.5* (6.36)	13.7 (7.37)	22.2** (7.23)	15.9* (7.88)	4.6 (7.72)
Seven to 20 trucks	16.4* (6.44)	16.4** (6.12)	15.7* (6.15)	21.8*** (6.26)	16.2** (6.27)	21.8*** (6.36)	16.4* (6.52)	22.3*** (6.38)	18.6** (6.96)	9.2 (6.79)
21 to 100 trucks	5.1 (9.17)	5.1 (7.25)	4.2 (7.29)	11.0 (7.57)	4.8 (7.91)	11.1 (8.16)	5.1 (8.60)	12.3 (8.65)	8.6 (9.52)	-6.2 (9.22)
101 to 1,000 trucks	-3.5 (7.67)	-3.5 (6.37)	-3.8 (6.38)	-4.0 (6.51)	-3.6 (6.86)	-4.0 (7.07)	-3.5 (7.42)	2.3 (7.52)	0.1 (8.18)	-14.3 (8.01)
1,001 to 50,000 trucks	5.1 (5.84)	5.1 (5.47)	10.5 (7.14)	-1.1 (5.55)	6.9 (7.42)	-1.2 (5.97)	5.1 (6.28)	8.0 (6.12)	4.4 (6.30)	-3.3 (6.74)
Constant	73.4*** (1.80)	77.8*** (9.96)	73.6*** (10.50)	51.6*** (10.33)	85.2*** (7.67)	60.0*** (8.96)	33.7 (38.90)	129.3** (39.28)	81.5*** (4.71)	61.7*** (5.57)
Controls										
Size Category fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Week fixed effects	No	Yes	Yes	Yes	No	No	No	No	No	No
Month-of-Year fixed effects	No	No	No	No	Yes	Yes	No	No	No	No
Holidays	No	No	No	No	Yes	Yes	Yes	Yes	Yes	Yes
Blitz	No	No	No	No	Yes	Yes	Yes	Yes	Yes	Yes
CASS	No	No	No	No	No	No	Yes	Yes	No	No
Registrations	No	No	Yes	No	Yes	No	No	No	No	No
% of Inspections	No	No	No	Yes	No	Yes	No	No	No	No
Registrations × CASS	No	No	No	No	No	No	No	No	Yes	No
% of Inspections × CASS	No	No	No	No	No	No	No	No	No	Yes
R-squared	0.941	0.971	0.971	0.972	0.945	0.947	0.932	0.938	0.932	0.933
N	609	609	609	609	609	609	609	490	609	609

Notes. * p<0.05, ** p<0.01, *** p<0.001. All models use ordinary least squares with robust standard errors reported in parentheses. Column 1 shows the basic difference-in-differences model, columns 2 through 4 include week fixed effects, columns 5 and 6 include month-of-year fixed effects instead of week fixed effects, and columns 7 and 8 do not include time-period controls. Column 8 restricts the sample period to a week-of-year equal to or before week 35, which is the cutoff week for the data in 2018. Columns 9 and 10 include CASS interactions. Large asset-based carriers are the omitted category in all models.

5.3 Unsafe Driving Violations

Increased compliance with HOS regulations reduces the output of a driver who occasionally cheats by decreasing available working hours and flexibility. One behavioral response to offset some of the lost output and associated income could be to increase work intensity per unit time. For example, a driver can drive faster to make up for lost time or change lanes more frequently to get around slow traffic. If drivers increase their unsafe driving actions (such as speeding), this will manifest itself in an increased number of unsafe driving violations cited by roadside inspectors. For example, because individual owner-operators are most affected by the ELD mandate, they should be pulled over for speeding more frequently than drivers for large carriers after the implementation of the ELD mandate.

Compared to large asset-based carriers, drivers for smaller carriers were cited in much higher numbers after the ELD mandate went into effect, shown in Table 7. Individual owner-operators committed 22.7% more unsafe driving violations in the light enforcement period and 35.3% more in the strict enforcement period, compared to a -1.8% decrease and 5.5% increase in unsafe driving infractions for drivers for large asset-based carriers in the respective enforcement periods. The percentages for carriers with between two and six trucks show a similar pattern, increasing by 3.9% and 17.5% in the respective enforcement periods. Figure 7 shows the number of unsafe driving violations over time for individual owner-operators and for large asset-based carriers.

Table 7. Average Number of Weekly Unsafe Driving Violations by Carrier-size in the Enforcement Periods.

Size Category	Pre-mandate	Light Enforcement	Strict Enforcement	Diff (Light)	Diff (Strict)	DD (Light)	DD (Strict)
Large asset-based carriers	98.3	96.5	103.7	-1.9	5.4	--	--
Independent owner operators	268.1	328.9	362.7	60.9	94.6	62.7	89.2
Two to six trucks	491.5	510.7	577.6	19.1	86.1	21.0	80.7
Seven to 20 trucks	516.4	532.2	573.9	15.8	57.5	17.7	52.1
21 to 100 trucks	704.9	731.5	805.3	26.5	100.4	28.4	95.0
101 to 1,000 trucks	573.3	572.8	609.1	-0.5	35.8	1.3	30.4
1,001 to 50,000 trucks	275.1	273.9	308.5	-1.2	33.4	0.6	28.1

Figure 7. Unsafe Driving Violations for Independent Owner-Operators and Large Asset-based Carriers.

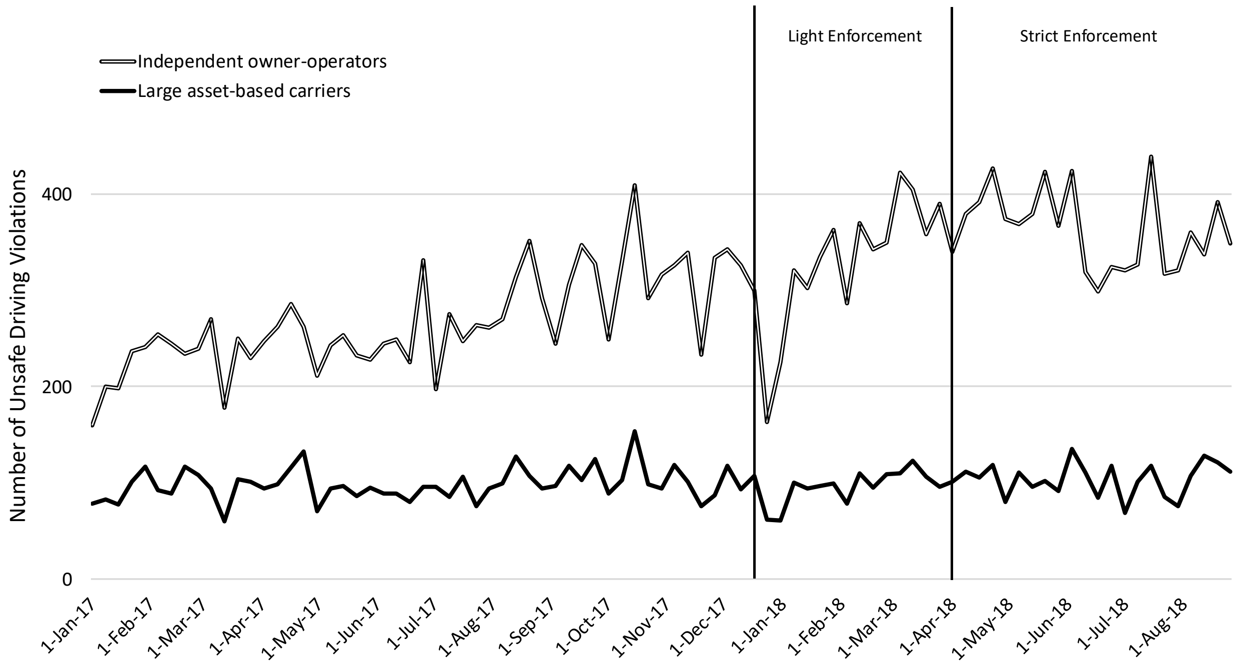


Table 8 reports the results from the difference-in-differences estimation specified in equation 5, where the number of weekly unsafe driving violations (*Unsafe Violations*$_{it}$) is the dependent variable. During the light enforcement period, unsafe driving violations increased significantly for independent owner-operators relative to large asset based carriers. During the period of strict enforcement this pattern becomes more pronounced, with significant increases in unsafe violations in all size classes with fewer than 101 powered units. Independent owner-operators received almost 90 more citations per week (column 1) as a result of the mandate, an increase of more than 33.3% from the pre-mandate level of 268.1 citations per week.

Table 9 shows that speeding violations were a significant contributor to the increase in unsafe driving violations. The same pattern holds as with unsafe driving: independent owner-operators show an increase in speeding relative to large asset-based carriers during the period of light enforcement. When enforcement becomes strict, we observe an increase in speeding for all size classed below 101 powered units. Using figures from column 1, speeding increased by 31.0% for independent owner-operators, 15.9% for two to six truck fleets, 10.6% for six to 20 trucks, and 16.5% for fleets of 21 to 100 trucks, relative to their pre-mandate means. These results support our hypothesis (H3) that drivers who were most impacted by the ELD mandate increased their driving intensity (e.g., by driving faster and changing lanes more often) in response to the decrease in output caused by the mandate.

Table 8. Difference-in-Differences Estimates of Unsafe Violations by Carrier-Size Group and Enforcement Periods.

Dependent Variable: *Unsafe Violations*	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Light Enforcement	-1.9 (5.04)				31.9* (14.15)	27.6* (13.06)	-1.1 (13.33)	-1.38 (8.63)	4.7 (11.11)	12.3 (12.89)
Independent owner-operators	62.7*** (19.33)	62.7*** (19.43)	61.1** (19.45)	39.8* (19.88)	61.6*** (18.47)	39.5* (19.18)	62.7*** (18.02)	93.1*** (14.12)	29.6 (17.23)	59.2*** (18.53)
Two to six trucks	21.0 (26.69)	21.0 (19.99)	19.0 (20.02)	35.5 (18.31)	19.7 (20.60)	35.6 (19.06)	21.0 (20.36)	55.7*** (17.38)	22.7 (18.53)	15.2 (20.84)
Seven to 20 trucks	17.7 (24.40)	17.7 (18.81)	16.0 (18.84)	35.7* (17.17)	16.5 (19.29)	35.9 (18.43)	17.7 (18.84)	47.3** (15.38)	22.7 (17.30)	11.8 (18.94)
21 to 100 trucks	28.4 (35.81)	28.4 (25.00)	26.4 (25.04)	44.0 (24.04)	27.0 (26.94)	44.2 (26.73)	28.4 (27.06)	77.8*** (23.42)	24.4 (26.15)	19.5 (27.55)
101 to 1,000 trucks	1.3 (26.49)	1.3 (20.01)	0.7 (20.05)	8.2 (18.91)	0.9 (20.97)	8.3 (19.92)	1.3 (20.86)	31.7 (17.75)	-6.0 (19.61)	-6.5 (21.09)
1,001 to 50,000 trucks	0.6 (13.91)	0.6 (20.94)	23.2 (22.21)	-3.7 (20.12)	15.9 (23.75)	-3.7 (17.95)	0.6 (18.40)	14.8 (13.20)	-10.4 (16.53)	24.5 (20.66)
Strict Enforcement	5.4 (4.39)				16.3* (7.65)	19.4* (7.56)	-28.1** (8.97)	-5.9 (9.04)	2.2 (5.94)	2.2 (6.07)
Independent owner-operators	89.2*** (12.16)	89.2*** (13.69)	86.8*** (13.62)	54.8*** (13.88)	87.6*** (14.02)	54.3*** (15.43)	89.2*** (12.98)	106.4*** (12.45)	29.9* (14.85)	82.7*** (13.26)
Two to six trucks	80.7*** (15.15)	80.7*** (11.72)	77.7*** (11.72)	84.2*** (11.83)	78.7*** (14.60)	84.3*** (14.35)	80.7*** (15.54)	96.9*** (14.51)	48.0** (16.52)	69.0*** (15.75)
Seven to 20 trucks	52.1*** (16.23)	52.1*** (12.03)	49.7*** (12.04)	63.0*** (12.06)	50.5*** (14.89)	63.1*** (15.23)	52.1*** (15.89)	64.3*** (15.71)	26.2 (16.07)	40.0* (15.98)
21 to 100 trucks	95.0*** (18.69)	95.0*** (13.60)	92.1*** (13.60)	107.0*** (14.13)	93.0*** (16.33)	107.2*** (17.06)	95.0*** (17.90)	119.0*** (16.50)	54.6** (20.01)	75.7*** (19.53)
101 to 1,000 trucks	30.4 (16.13)	30.4** (11.80)	29.3* (11.81)	29.4* (11.83)	29.6 (15.12)	29.4* (14.70)	30.4 (16.14)	40.9** (15.80)	-8.5 (16.72)	11.2 (17.61)
1,001 to 50,000 trucks	28.1** (9.89)	28.1* (11.12)	46.8*** (13.00)	15.5 (11.49)	40.7* (16.53)	15.3 (11.42)	28.1* (11.44)	34.4** (10.87)	-2.2 (11.72)	31.8** (11.40)
Constant	98.3*** (2.42)	-27.3 (27.91)	-41.7 (28.04)	-80.2** (29.53)	64.0*** (11.44)	19.9 (14.49)	-179.9 (55.43)	-0.8 (54.57)	49.0*** (8.81)	86.5*** (7.98)
Controls										
Size Category fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Week fixed effects	No	Yes	Yes	Yes	No	No	No	No	No	No
Month-of-Year fixed effects	No	No	No	No	Yes	Yes	No	No	No	No
Holidays	No	No	No	No	Yes	Yes	Yes	Yes	Yes	Yes
Blitz	No	No	No	No	Yes	Yes	Yes	Yes	Yes	Yes
CASS	No	No	No	No	No	No	Yes	Yes	No	No
Registrations	No	No	Yes	No	Yes	No	No	No	No	No
% of Inspections	No	No	No	Yes	No	Yes	No	No	No	No
Registrations × CASS	No	No	No	No	No	No	No	No	Yes	No
% of Inspections × CASS	No	No	No	No	No	No	No	No	No	Yes
R-squared	0.912	0.977	0.977	0.979	0.951	0.953	0.941	0.957	0.943	0.940
N	609	609	609	609	609	609	609	490	609	609

Notes. * p<0.05, ** p<0.01, *** p<0.001. All models use ordinary least squares with robust standard errors reported in parentheses. Column 1 shows the basic difference-in-differences model, columns 2 through 4 include week fixed effects, columns 5 and 6 include month-of-year fixed effects instead of week fixed effects, and columns 7 and 8 do not include time-period controls. Column 8 restricts the sample period to a week-of-year equal to or before week 35, which is the cutoff week for the data in 2018. Columns 9 and 10 include CASS interactions. Large asset-based carriers are the omitted category in all models.

Table 9. Difference-in-Differences Estimates of Speeding Violations by Carrier-Size Group and Enforcement Periods.

Dependent Variable: *Speeding*	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Light Enforcement	1.4 (3.83)				25.8* (10.04)	23.0* (9.39)	0.9 (9.44)	3.0 (6.22)	5.5 (7.91)	10.6 (9.08)
Independent owner-operators	39.8** (13.02)	39.8** (14.22)	38.5** (14.24)	25.2 (14.94)	38.9** (13.86)	25.0 (14.73)	39.8** (13.30)	60.5*** (10.66)	17.2 (13.18)	37.2** (13.65)
Two to six trucks	25.2 (18.57)	25.2 (14.06)	23.8 (14.08)	34.4** (13.09)	24.2 (14.65)	34.6* (13.76)	25.2 (14.32)	54.3*** (11.29)	26.4* (13.25)	21.1 (14.67)
Seven to 20 trucks	20.9 (18.53)	20.9 (13.96)	19.7 (13.98)	32.4* (12.99)	20.0 (14.50)	32.5* (14.08)	20.9 (14.36)	44.4*** (11.96)	24.3 (13.39)	16.8 (14.42)
21 to 100 trucks	37.2 (27.00)	37.2 (19.26)	35.7 (19.28)	47.1* (18.79)	36.2 (21.09)	47.3* (21.17)	37.2 (21.30)	76.3*** (19.10)	34.5 (20.83)	30.9 (21.75)
101 to 1,000 trucks	12.9 (18.82)	12.9 (14.56)	12.5 (14.59)	17.3 (13.88)	12.6 (14.89)	17.3 (14.20)	12.9 (14.96)	40.1*** (12.21)	7.9 (14.20)	7.3 (15.19)
1,001 to 50,000 trucks	-0.8 (10.30)	-0.8 (15.32)	16.0 (16.21)	-3.5 (14.92)	11.0 (18.22)	-3.6 (13.19)	-0.8 (13.55)	11.6 (9.71)	-8.3 (12.39)	16.1 (15.52)
Strict Enforcement	5.2 (2.90)				17.2** (6.18)	19.1** (6.13)	-17.0* (7.03)	2.5 (6.81)	4.6 (4.64)	4.6 (4.73)
Independent owner-operators	53.7*** (8.52)	53.7*** (10.68)	51.9*** (10.63)	31.8** (11.56)	52.4*** (10.65)	31.5** (12.20)	53.7*** (9.94)	65.5*** (9.41)	13.3 (11.79)	49.0*** (10.16)
Two to six trucks	53.7*** (11.74)	53.7*** (9.40)	51.5*** (9.39)	55.9*** (9.41)	52.1*** (11.27)	56.0*** (11.01)	53.7*** (11.76)	68.6*** (10.41)	31.4* (12.67)	45.4*** (12.14)
Seven to 20 trucks	39.6** (13.53)	39.6*** (10.05)	37.8*** (10.05)	46.5*** (10.18)	38.4** (12.61)	46.6*** (12.92)	39.6** (12.98)	51.1*** (12.49)	22.0 (13.18)	31.0* (13.28)
21 to 100 trucks	84.7*** (15.70)	84.7*** (11.50)	82.5*** (11.48)	92.3*** (11.84)	83.2*** (13.61)	92.5*** (14.11)	84.7*** (14.98)	106.0*** (13.41)	57.2*** (16.47)	71.0*** (16.32)
101 to 1,000 trucks	24.1 (12.69)	24.1* (9.92)	23.3* (9.91)	23.5* (9.86)	23.5 (12.12)	23.4* (11.81)	24.1 (13.00)	36.5** (12.26)	-2.4 (13.69)	10.5 (14.26)
1,001 to 50,000 trucks	17.3* (7.74)	17.3 (9.18)	31.2** (10.47)	9.3 (9.40)	27.1* (13.48)	9.2 (9.04)	17.3* (8.73)	23.9** (8.05)	-3.3 (9.11)	19.9* (8.90)
Constant	59.2*** (1.81)	-23.0 (20.17)	-33.7 (20.30)	-56.6** (21.54)	37.7*** (9.21)	11.0 (11.33)	-139.8** (43.76)	20.0 (41.14)	26.2*** (6.89)	51.1*** (6.24)
Controls										
Size Category fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Week fixed effects	No	Yes	Yes	Yes	No	No	No	No	No	No
Month-of-Year fixed effects	No	No	No	No	Yes	Yes	No	No	No	No
Holidays	No	No	No	No	Yes	Yes	Yes	Yes	Yes	Yes
Blitz	No	No	No	No	Yes	Yes	Yes	Yes	Yes	Yes
CASS	No	No	No	No	No	No	Yes	Yes	No	No
Registrations	No	No	Yes	No	Yes	No	No	No	No	No
% of Inspections	No	No	No	Yes	No	Yes	No	No	No	No
Registrations × CASS	No	No	No	No	No	No	No	No	Yes	No
% of Inspections × CASS	No	No	No	No	No	No	No	No	No	Yes
R-squared	0.910	0.975	0.975	0.976	0.948	0.949	0.935	0.958	0.937	0.934
N	609	609	609	609	609	609	609	490	609	609

Notes. * p<0.05, ** p<0.01, *** p<0.001. All models use ordinary least squares with robust standard errors reported in parentheses. Column 1 shows the basic difference-in-differences model, columns 2 through 4 include week fixed effects, columns 5 and 6 include month-of-year fixed effects instead of week fixed effects, and columns 7 and 8 do not include time-period controls. Column 8 restricts the sample period to a week-of-year equal to or before week 35, which is the cutoff week for the data in 2018. Columns 9 and 10 include CASS interactions. Large asset-based carriers are the omitted category in all models.

6. Discussion

Recapping our main findings, we exploit the difference in ELD adoption rates between different sized carriers before and after the ELD mandate to estimate the effect of ELDs on HOS compliance, roadway safety, and driving behaviors. Whereas larger firms adopted ELDs well before (and irrespective of) the mandate, smaller firms tended to procrastinate (Tita 2017). For example, industry data vendor CarrierLists reported that less than 20 percent of for-hire carriers with 5 to 100 power units had started the ELD compliance process as of mid-September, 2017, but approximately 85 percent of such carriers reported ELD compliance by mid-January 2018 (Lockridge 2018). Consequently, by examining outcomes before and after the mandate by size class, we can estimate the effect of ELD adoption for smaller firms by utilizing large carriers that were known to operate with ELDs before the mandate as a counterfactual control group. While the counterfactual group experiences many of the same market shocks, their ELD compliance did not significantly change as a result of the mandate. Any changes at the large firms must therefore be the result of the shocks, not changes in ELD usage. By differencing out these shocks from the smaller firms, we are able to estimate the effects of ELDs.

We find that the ELD mandate unequivocally enhanced HOS compliance. The percentage of inspections with an intentional HOS violation declined by 43.0% for independent owner operators, and 46.9% for firms operating between two and six trucks. These results are consistent with previous studies of the effects of monitoring on employee behavior (e.g., Pierce, Snow, and McAfee 2015, Staats et al. 2017). However, the ELD mandate did not noticeably improve safety, and we are able to produce no statistically significant evidence that ELD adoption by the smaller firms corresponded to any reduction in accident rates. This result needs to be interpreted carefully, and only holds for the small firms who were induced to adopt ELDs after the mandate went into effect. ELDs are correlated with reduced accidents at larger firms (Cantor et al., 2009; Hickman et al, 2014) and our study is not designed to uncover these benefits. Moreover, our estimate of accident reductions by small firms as a result of the mandate should be interpreted as a lower bound of possible reductions because we do not identify the accident reductions from smaller firms that *anticipated* the mandate and complied early. It is reasonable to expect that carriers with the greatest benefit of ELD adoption complied earlier (Cubitt 2016), and so the accident reductions among early adopting small firms may still be significant. This question warrants further study.

What our results underscore is the heterogeneous response of motor carriers to the mandate. Large carriers and early adopters are managed differently from small carriers and late adopters. As a consequence, the benefits of ELDs measured by larger carriers cannot simply be extended onto small carriers; nor can the benefits of early adopters be extended onto late adopters. Lacking precise information on the heterogeneous benefits of adoptions, previous cost-benefit analyses of the mandate have been forced to use a "one size fits all" methodology, which has likely overstated the potential benefits (1,844 crash per year reduction, Federal Register 2015). Summing the *lower* confidence bound for *all* treatment effect estimates of column 5 of Table 6, the largest possible annual reduction in federally-recordable accidents consistent with our empirical model is between 1,647 (light enforcement) and 1,966 (strict enforcement). Our preferred estimates for the effect of the policy shift is that accidents actually *increased* by between 2,290 and 3,266 per year. The carriers most affected by the ELD mandate—small carriers—show no significant reductions in accidents.

Our research also provides another example of how policy interventions are fraught with uncertainty in complex systems with many interconnections and possible feedbacks. There are many examples of potential policy gains being offset by unintended and often deleterious consequences in these environments: seatbelt usage can potentially increase other unsafe driving behavior (Peltzman 1975), the Endangered Species Act can be detrimental to the species listed (Ferraro et al. 2007), and high-stakes testing increases cheating (Jacob and Levitt 2003). A contributor for our failure to observe significant accident reductions from smaller firms is that the gains from fatigue reduction were offset by increases in unsafe driving behavior. Hardening the HOS constraint reduces per-worker hours and workers may compensate for this lost income by driving more intensively, namely, covering more miles per hour. Unfortunately, this may also incentivize an increase in unsafe driving behavior, which is more tightly correlated to accident rates than hours of service violations (Craft 2010). After the mandate, unsafe driving violations by owner operators increased by 23.4-33.3%, and speeding between 23.0-31.0%.

We close with a few general comments about hours-of-service regulation and mandatory ELD compliance. There are of course many positive aspects of the ELD mandate not considered in our analysis – reduced paperwork, more information availability to both inspectors and carriers due to the electronic capture of a driver's activities, driver work schedules are known with higher certainty (perhaps enabling studies of the effect of different HOS policies on safety outcomes), and increased pressure for more efficient warehouse operations because the cost of delaying drivers at loading and unloading docks increased after the mandate. Nonetheless, with regards to safety, drivers are heavily incentivized to avoid accidents, and this did not change with the ELD mandate. Given the legal liabilities involved with being in a crash when outside hours-of-service limits, drivers are incentivized to be extra cautious when driving beyond limits. The ELD mandate has not done much to change the driver calculus in this respect, and so it is perhaps not surprising that we fail to uncover significant accident reductions.

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