Road Illumination and Nighttime Pedestrian Deaths: Evidence from Moonlight

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Abstract

Of the 7,500 pedestrian road deaths recorded in the US in 2022, 79% took place during the night. Low lighting reduces visibility, potentially increasing the frequency and severity of vehicle-pedestrian collisions. I use complete US data on 193,000 nighttime pedestrian deaths, spanning 1975 to 2022. Nightly variation in moonlight provides a natural experiment that exogenously impacts road illumination. Across the US, nighttime pedestrian deaths are 5% lower when the moon is at its brightest, compared to a night with no moonlight. Under cloud-free conditions, peak moonlight causes a 17% drop in pedestrian deaths. In rural areas with low artificial lighting, the effect is 39%. I establish a clear causal relationship between road illumination and pedestrian safety. A small increase in ambient light causes a large improvement in pedestrian outcomes. The finding has policy implications for road safety and the artificial lighting of roadways.

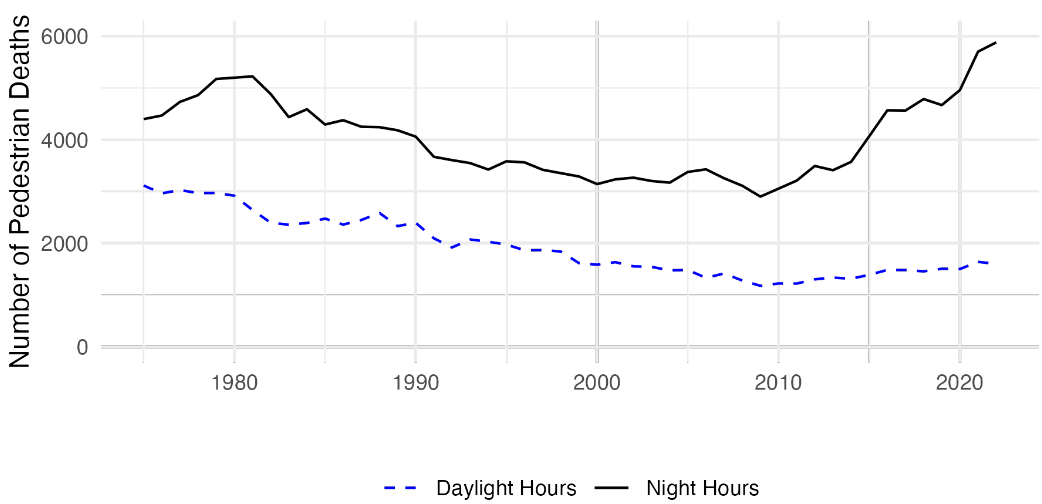
Transportation; Safety; Health; Traffic fatalities; Pedestrians

I1; R41; R42; R48

1 Introduction

US roadways present significant dangers for pedestrians, particularly at night. In 2022, 7,500 pedestrians were struck and killed by vehicles, with four out of five of these deaths occurring during nighttime hours (Figure 1). Low ambient light during the night reduces visibility and could increase pedestrian deaths. Artificially lighting roadways could alleviate the issue. However, estimating the causal effect of ambient light on road safety is complicated by endogeneity issues. Using nightly variation in the phase of the moon, I provide novel causal estimates demonstrating that small increases in ambient light significantly improve pedestrian safety. Using satellite data on nighttime lights, I demonstrate how the effect is strongest in areas with low levels of artificial lighting.

Figure 1: Number of Pedestrian Fatalities per Year by Time of Day



Of the 7,500 pedestrians who died in 2022, 5,900 died during nighttime hours (between sunset and sunrise). The number of nighttime pedestrian deaths has risen dramatically since 2009. Source: FARS; 0.5% of deaths are missing because they did not record a time of day.

Street lighting and vehicle headlights are meant to allow for safe driving at night. While low ambient light levels could explain the frequency of nighttime crashes, other factors could make roads more dangerous at night. For example, intoxicated driving may be more common at night, vehicle speeds may be higher (Huang et al., 2018), drivers may be tired and less alert (Vanlaar et al., 2008), and icy or wet conditions may be more common. Understanding why US roadways are so dangerous for pedestrians at night is an urgent public health question. As shown in Figure 1, nighttime pedestrian deaths increased 103% from 2009-2022. This shift has multiple causes, but it is clear that changes in road conditions have been specifically detrimental during times of low-lighting. The contribution of this paper is to estimate the causal effect of ambient light on pedestrian safety by using exogenous variation in nighttime light. Establishing the relationship between lighting and pedestrian road safety is important for designing safer streets.

Two common methodologies in the literature attempt to estimate a causal relationship between lighting and pedestrian safety. First, a large set of papers specifically use daylight savings time (DST) clock changes as a source of variation in natural light that is orthogonal to the time of day. Second, a set of studies compare safety outcomes at night between locations with and without artificial lighting.

The discrete clock changes caused by the DST system provide quasi-randomness in natural light, where lighting conditions during a particular hour change discretely on the date that clocks are changed. Sullivan and Flannagan (2002) examined US crash data from 1987-1997, finding darkness triggered by daylight savings clock changes led to more crashes, particularly vehicle-pedestrian crashes. Smith (2016) found that US fatal crashes rose 6% in the six days following the spring DST change but found no effect in the fall change. The asymmetric effect is attributed to the spring change reducing sleep hours for drivers. The change in ambient light exposure appeared to have no effect on crashes. Uttley and Fotios (2017) examined vehicle-pedestrian collisions in the UK, finding a higher collision rate when DST reduced sunlight. James (2023) used Australian data and found no effect of daylight savings transitions on overall road collisions; however, the study found a shift in crash timing consistent with more crashes during nighttime hours.

Using DST clock changes as a source of exogenous variation in light may suffer from causal inference limitations. First, driver and pedestrian behavior may change because of DST changes. For example, people may forget to adjust their clocks, resulting in them running late and being more rushed while traveling. Prior research has shown clock changes significantly affect sleep hours, and cause negative health outcomes in the following days (Jin and Ziebarth, 2020). People may intentionally adjust their travel to minimize the time they spend around roadways after dark, reducing exposure to crashes. The prior studies are aware of these limitations and are generally unable to disentangle the effect of ambient lighting specifically from the other disruptive effects of changing clocks. A second limitation of the DST identification strategy is limited statistical power. The approach can utilize only two events per year, using only a fraction of annual data. Overall, the conclusions of these papers suggest DST changes contribute to vehicle crashes, but the specific role of ambient lighting is not disentangled from other DST effects.

With an approach related to DST papers, Johansson et al. (2009) used seasonal differences in daylight across northern European countries to compare crashes during the same hour, with varying daylight exposure, finding darkness increases vehicle crash injuries by 30% in urban areas and 40% in rural areas. Bünnings and Schiele (2021) applied a similar method in the UK, finding that vehicle accident frequency and severity increase in the dark, with darkness raising hourly accident counts by 7%. By using a full year of data, the identification strategy of these studies relies less on the abrupt change in light around DST thresholds, and results are less likely to be affected by behavioral changes associated with DST clock changes.

An alternative method to identify the effect of ambient lighting on pedestrian safety is to compare areas with differing levels of artificial lighting at night. However, locations with street lighting are likely to be denser, have different urban design characteristics, and have more pedestrian infrastructure, which limits the causal interpretation of the comparison. Siddiqui et al. (2006) and Haleem et al. (2015) both examined data from Florida and found nighttime pedestrian crashes were significantly more severe when they occurred at a location without artificial street lighting. Also using Florida data, Li et al. (2023) found that raising road lighting from their lowest category (< 2.2 lux[1]) to the next category (2.2-5.4 lux) reduced pedestrian-involved crashes by 78%, while additional increases in lighting provided small additional improvements in pedestrian safety.

I do not use DST changes or artificial road lighting comparisons as my source of identifying variation. Rather, I use changing moonlight as a source of exogenous variation in road illumination. I provide the first comprehensive study using this source of variation. Sivak et al. (2007) compared mean pedestrian deaths in the US on full moon nights to nights with no moon, noting that pedestrian fatalities were 22% higher when there was no moon. I significantly expand the analysis by using a larger sample, accounting for cloud cover, and demonstrating heterogeneity across artificial lighting

[1]Lux is a measure of the illumination of a surface. One lux is equal to one lumen cast over a square meter, where a lumen is a metric unit of visible light emitted from a source. For context, a 60-watt household bulb produces 800 lumens. A 60-watt bulb casting light over a 400 m^2 surface would illuminate that surface to two lumens.

conditions and road types. I also estimate policy-relevant partial effects of ambient lighting. Unlike a DST clock change, drivers and pedestrians are unlikely to account for, or even be aware of, nightly fluctuations in moonlight when planning travel. While moonlight displays significant variation across nights, it is unlikely to affect trip behavior. The lunar phase is also unlikely to affect human sleep patterns, whereas DST changes have been shown to alter sleep and health. Regarding sample size and statistical power, lunar luminosity provides a source of variation that applies to every night of the year, allowing for a much larger data set.

This paper also connects to a growing literature related to understanding the high rate of pedestrian deaths in the US. Ferenchak and Abadi (2021) provided detailed descriptive evidence of nighttime crashes in the US, finding nighttime vehicle-pedestrian crashes have risen disproportionately on arterial roads, and have disproportionately involved Sport Utility Vehicles. Other recent work has highlighted the dangers of highways bisecting communities (Nehiba and Tyndall, 2023) and examined the impact of rising vehicle size (Edwards and Leonard, 2022; Tyndall, 2021, 2024).

The paper will proceed as follows. Section 2 describes the crash, lunar light, satellite nighttime lights, and satellite cloud cover data sets. Section 3 provides the regression methodology. Section 4 provides results. Section 5 discusses policy implications and Section 6 concludes.

2 Data

2.1 Vehicle-Pedestrian Crashes

I use the US Fatality Analysis Reporting System (FARS) as the primary data source for vehicle-pedestrian crashes. The data is compiled by the National Highway Traffic Safety Administration (NHTSA) and released annually. I use all years available, which span 1975 to 2022. The data includes a detailed set of covariates, which cover the time, location, and circumstances of the crash, as well as characteristics of the pedestrians and drivers.

The FARS data includes every instance of a vehicle crash on a public roadway where there was at least one fatality. I selected all crashes where at least one pedestrian was killed. Across the 48 years of data, I observed 287,023 pedestrians who died in a crash. For every observed pedestrian death, I calculate the position of the sun for that time and location.[2] Night is defined as the period starting when the sun falls below the horizon and ending when the sun rises above the horizon. I sum pedestrian fatalities so that one observation is equal to one night, where a night is coded with the calendar date when the night began.

The data set of nightly pedestrian deaths covers each of the 17,532 nights occurring from 1975 to 2022. Table 1 provides summary statistics. The average night had 11.0 pedestrian deaths. Figure 2 provides the distribution of nightly pedestrian deaths. There are only 13 nights in the data where no pedestrians died. The maximum value is the night of December 31, 1981, when 64 pedestrians died.

Table 1: Summary Statistics for Nightly Pedestrian Deaths and Lunar Activity

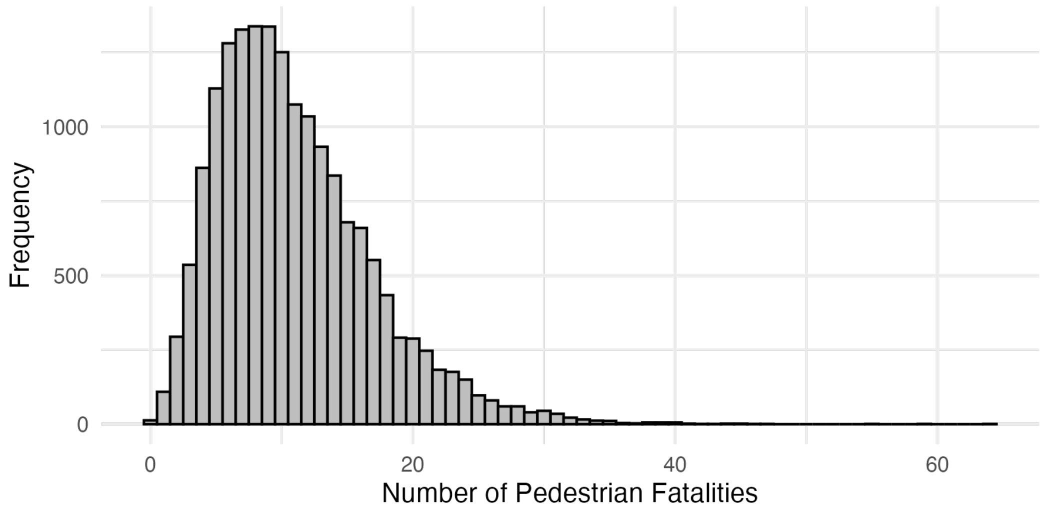
Variable	Mean	Std. Dev.	Min.	Max.
Pedestrain Deaths	10.996	5.972	0	64
...In CBSA County (Urban)	10.362	5.657	0	62
...In Non-CBSA County (Rural)	0.634	0.904	0	9
...Child	0.864	1.163	0	15
...Age 18-65	8.399	4.820	0	50
...Senior	1.733	1.664	0	15
...Male	8.059	4.665	0	49
...Female	2.922	2.147	0	22
...Artificial Road Lighting	4.964	3.225	0	33
...On Interstate Highway	1.231	1.265	0	10
...On Non-Interstate Highway	4.233	3.042	0	24
...On County Road	1.407	1.772	0	24
...On Local Road	3.080	2.274	0	20
Lunar Illumination	0.112	0.166	0	1
Lunar Phase	0.500	0.354	0	1
National Cloud Cover†	0.516	0.108	0.161	0.922
N		17532		

Pedestrian death data is from FARS. Each observation corresponds to one night, where the sample spans every night from 1975-2022.
†Share of the US that is under cloud at midnight CST.

On the average night, 94% of pedestrian deaths occurred in a Core Based Statistical Area (CBSA) rather than a rural county; 76% of victims were aged 18-65, while 8% were children and 16% were over 65; and 73% of victims were male. I also consider road

[2] I use the R package *suncalc* to calculate sun positions. I drop 0.5% of observations, where information is missing on either crash date or time.

Figure 2: Number of Pedestrian Fatalities per Night Across the US



Across 17,532 nights of data, there was an average of 11.0 pedestrian deaths per night with a range of 0-64.

type and streetlight conditions in the analysis. On the average night, 50% of pedestrian deaths occurred on an Interstate or non-Interstate highway and the majority of deaths (55%) occurred on a roadway where the reporting officer recorded that the road had no artificial street lighting.

2.2 Moon Phase and Luminosity

Nightly moonlight will provide an exogenous source of variation in road illumination. As the primary measure of moonlight, I estimate the average lunar luminosity in the US for every night in my sample using the methods outlined in Śmielak (2023).

For each of the 17,532 nights in the sample, I estimate the relative luminosity of the moon. Śmielak (2023) provides a detailed methodology and accompanying statistical package[3] to estimate the luminosity of any particular night and location. The moon's brightness on a particular night is the consequence of many factors. The largest determinant is the phase of the moon. It takes 27.3 days for the moon to complete one orbit of the Earth. However, because the Earth is in its own orbit around the sun, it takes 29.5 days for the moon to complete a full lunar cycle. Full moons therefore occur every 29.5 days. On a given night, the lunar phase is roughly the same for every

[3] I use the moonlit statistical package in R.

location on Earth. This fact motivates the identification strategy, as lunar illumination varies across nights, but does not have significant spatial variation on the same night. The 29.5-day cycle is also helpful to my causal identification strategy. Because the Gregorian Calendar does not consider the lunar cycle, the day on which a full moon falls is constantly changing with respect to the day of the week and day of the month. From one year to the next, the moon's phase is orthogonal to other elements of the calendar.

Other factors affect the moon's brightness. The moon is only above the horizon for an average of 12 hours per day, and the timing of the moon's rise and set varies across days, meaning some nighttime hours have no moonlight because the moon is below the horizon.

The moon's elliptical orbit around the Earth is such that the distance from the Earth to the moon ranges from 357,000 to 407,000 km. The moon's brightness is higher when the moon is nearer to the Earth.

Lunar brightness also follows a seasonal pattern. During winter months, the moon follows a higher path in the sky in the northern hemisphere. The high angle of the moon means that the moonlight travels through less distance of earth's atmosphere before reaching the ground. Moonlight is reduced by the atmosphere through a process called atmospheric extinction. Because of the earth's tilt, the distance between the earth's surface and the moon during the night is also less during the winter. These mechanisms give moonlight seasonal variation, with higher levels of moonlight in the winter months. Observing the moon from a higher elevation can also increase lunar brightness because it reduces the amount of atmospheric extinction.

The algorithm provided by Śmielak (2023) accounts for all of the above determinants of the moon's brightness. I estimate the average moon brightness experienced across the US for each of the 17,532 nights. For a particular night, I calculate brightness at the centroid of every US state, at one-hour intervals, between sunset and sunrise. I then calculate a nightly national average by using state-level population weights. The method provides one number for the average moon luminosity, assigned to each night. The method accounts for times when the moon is below the horizon by assigning a zero value to moonlight during these hours. I normalize the measure so that 0 equals no moonlight at all and 1 equals the US average moonlight that occurred on the brightest night in the sample (January 20, 2019).

In the methodology section, I propose an instrumental variable strategy that makes use of the lunar phase as an instrument for lunar luminosity. I therefore also construct a variable for the lunar phase of each night. The variable is continuous and constructed so that 0 equals a new moon, where 0% of the moon's surface is illuminated on that night, and 1 equals a full moon, where 100% of the moon's surface is illuminated.

Table 1 shows summary statistics for nightly lunar illumination and lunar phase. While the illumination level ranges from 0-1, the average night experienced an average illumination level of only 0.11, or 11% of the light level that occurred on the brightest night. Figure 3 provides histograms for the frequency of the moon's phase and the illumination measure across the 17,532 nights of data. Figure 4 shows the relationship between the phase of the moon and the amount of moonlight. Because the moon's brightness is determined by several factors, some full moon nights have moon luminosity as low as 14% of the brightest night.

Figure 5 shows the aseasonality of the moon's phase and the seasonality of average nightly moonlight. Average moon luminance in the US is twice as high in December as it is in June.

2.3 Nighttime Lights

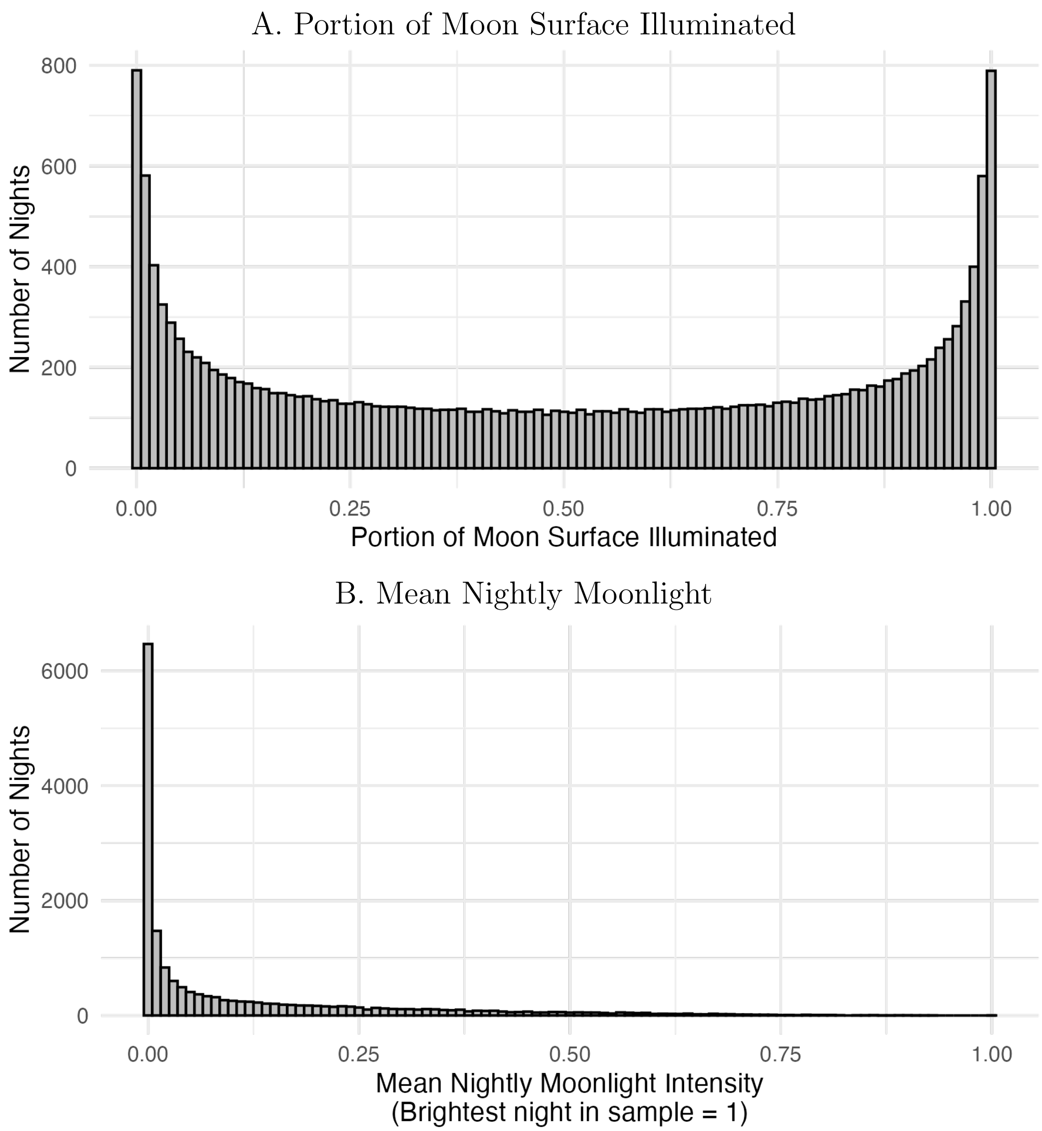
A marginal increase in moonlight is likely to have a larger effect in areas where artificial light levels are low. To identify areas in the US with low vs high artificial light levels I rely on satellite data on nighttime lights.

I use the Visible Infrared Imaging Radiometer Suite nighttime lights data product, maintained by The Earth Observation Group (Elvidge et al., 2021). The data is a cleaned version of satellite data collected from visible and near-infrared satellite sensors. I use annual data, which provides median light levels on the ground after correcting for cloud cover as well as moonlight. The resolution of the data is 15 arc-seconds, which generates pixels with an average width of roughly 350 meters.

FARS crash observations include latitude and longitude information for years 2002 and later. Therefore, heterogeneity analysis that uses nighttime lights data will only span 2002-2022. I use 2013 nighttime lights data, which is the earliest year available, and corresponds to roughly the center of my study period. Figure 6 provides a national map of the nighttime lights data and also displays the portions of the US that are outside of CBSAs.

I assign a nighttime light level to pedestrian deaths by overlaying the crash location with the nighttime lights map. I normalize the nighttime lights measure to range from 0-1, with 0 representing no light detected and 1 representing the brightest location. I

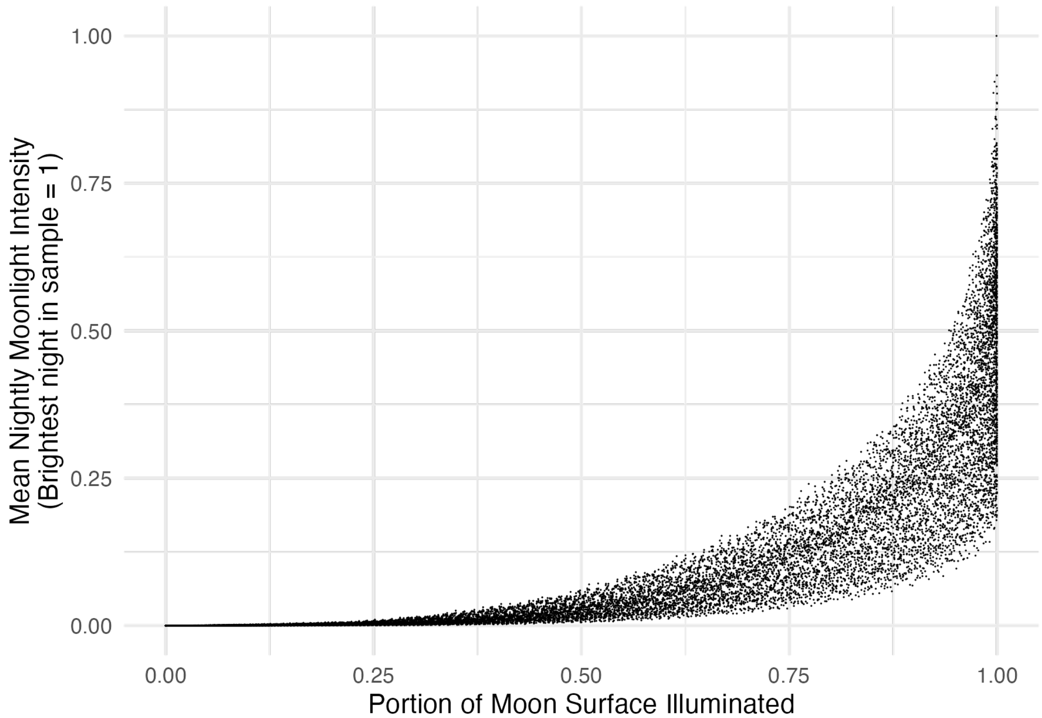
Figure 3: Nightly Variation in Moonlight over Study Period



There are 17,532 nights of data across 48 years. In both panels, an x-axis value of 0 indicates a night with no visible moon. In panel A, a value of 1 indicates a full moon night, while in panel B a 1 indicates the night in the sample with the highest lunar illumination level.

classify all pixels into percentiles according to light detected, so that values of 0-0.01 represent the 1% of US land that has the least light, and values of 0.99-1 represent the 1% of US land that has the brightest nighttime lights.

Figure 4: Relationship Between Moon Phase and Moonlight



There are 17,532 nights of data across 48 years. Each point represents one night.

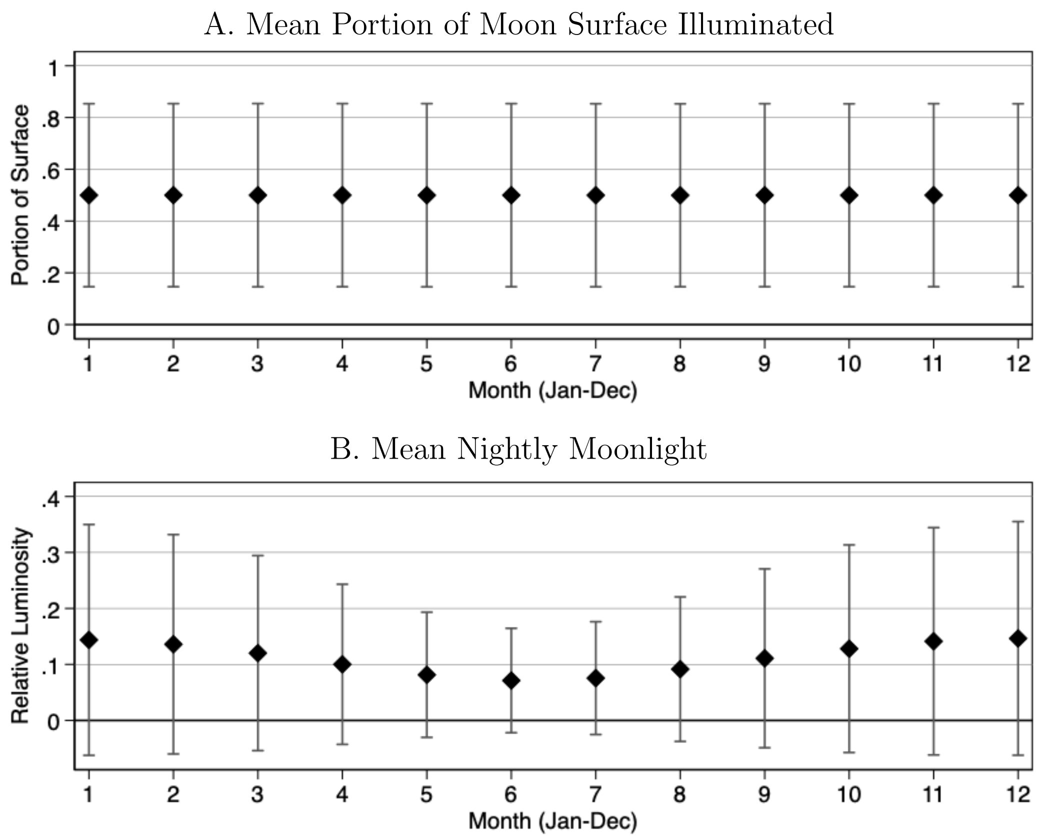
2.4 Satellite Cloud Cover

The luminosity of the moon is determined by the relative positions of the moon, sun, and earth, as well as other factors described above. However, the presence of clouds could completely eliminate the amount of moonlight actually illuminating the ground. I use hourly satellite data on cloud coverage to account for the presence of clouds.

I use the ERA5 (European Centre for Medium-Range Weather Forecasts Reanalysis Version 5) satellite data. The data is provided in a grid of points, separated by 0.25 degrees of latitude and longitude. For each grid cell, the data records local cloud conditions, as a percentage of sky coverage. The data is recorded hourly and is available for my entire study period (1975-2022).

I use the cloud cover data in two ways. First, I calculate nightly national cloud cover by recovering the share of US land that was under cloud at midnight Central Standard Time (CST) every night. Across the 17,532 nights, 53% of US land is under

Figure 5: Monthly Variation in Average Moonlight Conditions



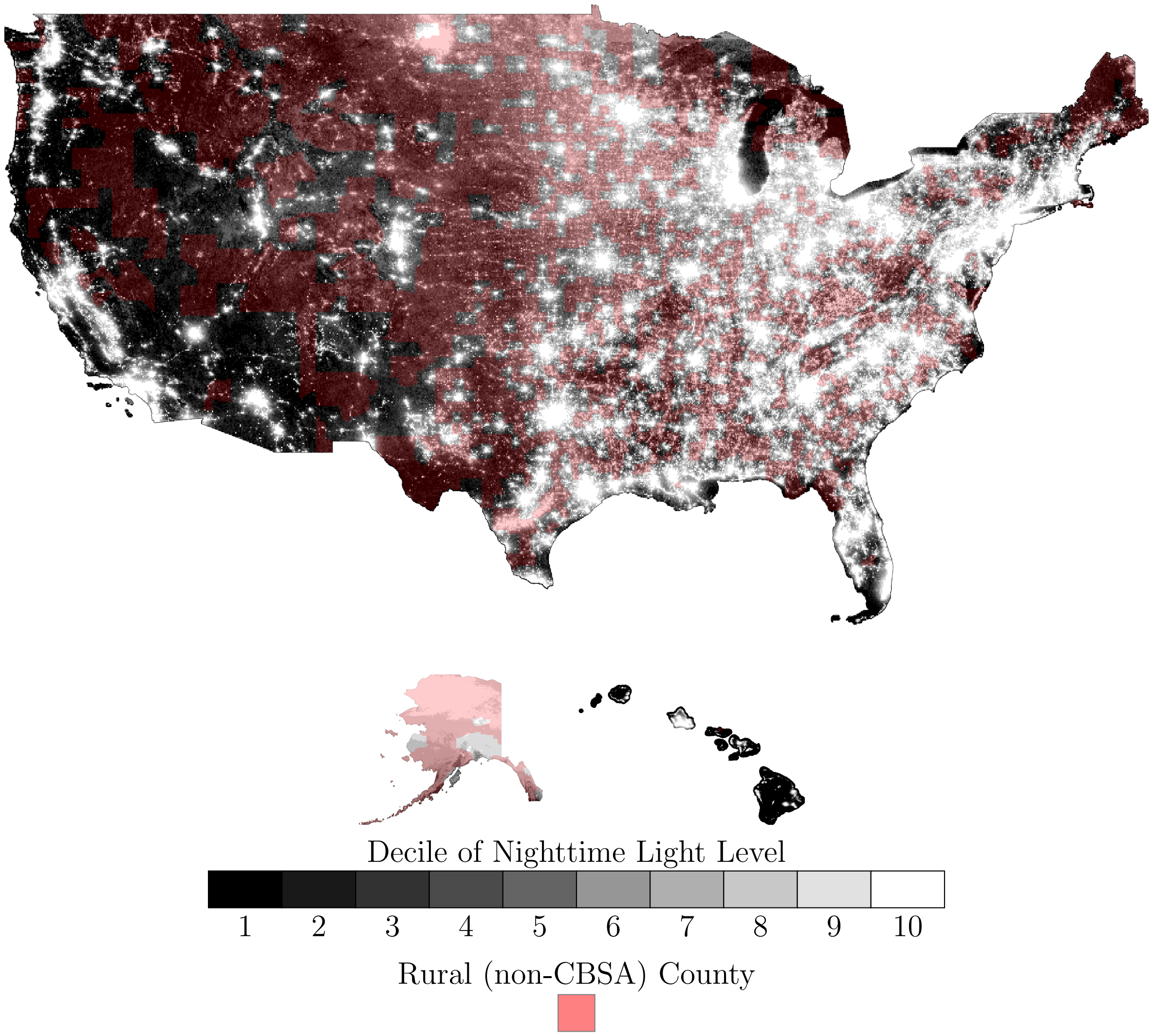
There is no seasonal variation in the phase of the moon. There is seasonal variation in the moon's brightness, with average moon brightness being higher in winter months. For panel B, relative luminosity on a given night ranges from 0 (no moon) to 1 (brightest night observed). Standard deviations are shown.

cloud, on average. This measure will serve as a control variable. Second, I assign local cloud conditions to every crash based on the precise location of crashes that are recorded in the 2002-2022 observations. In some specifications, I look exclusively at areas without cloud cover to recover moonlight effects under cloud-free conditions.

3 Methodology

Using nightly data on pedestrian deaths and moonlight, I estimate the causal effect of a marginal increase in ambient light on the number of pedestrians who die each night. I first introduce a basic Poisson estimation equation. I then discuss measurement error

Figure 6: Nighttime Lights and Non-CBSA Areas



The full nighttime lights layer is shown, overlayed with non-CBSA areas.

as a potential source of bias and describe an instrumental variable strategy.

Equation 1 provides the main regression equation. I estimate a Poisson model to account for the outcome variable being a count variable. D is a count variable capturing the number of pedestrian deaths that occurred during a particular night (n) in the US. M is a measure of moonlight. In the main specification, M equals the mean lunar luminosity as calculated in the prior section. The variable ranges from 0 (no moonlight) to 1 (moonlight level on the brightest night of the study period). C is the share of the US sky covered by cloud on night n. Φ is a year fixed effect, where year is indexed by y, to control for the general change in the frequency of pedestrian fatalities over time. Ψ is a calendar date fixed effect to control for seasonal effects or any effects that occur on a particular date (d). Because a night (n) spans two calendar dates I assign each night the date of the day leading into nightfall. Ψ includes 366 terms, one for each day of the year including a leap year day. θ is a day-of-the-week fixed effect to control for different behavior on different days of the week, where day of the week is indexed by w. ε is an error term. I cluster errors at the year level.[4]

$$D_n = \beta_0 + \beta_1 M_n + \beta_2 C_n + \Phi_{y(n)} + \Psi_{d(n)} + \theta_{w(n)} + \varepsilon_n \tag{1}$$

The main parameter of interest is β_1, which captures the partial effect of moon luminosity on nightly pedestrian deaths. A negative estimate of β_1 would imply that more moonlight leads to fewer pedestrian deaths at night.

The level of moon luminosity M is seasonal. On average, the moon is brighter in winter months. Pedestrian death figures are also seasonal, with higher rates in winter months. Therefore, pedestrian deaths and moon brightness on a given night have a positive correlation for reasons that may be unrelated to ambient light. For example, poor weather in the winter may cause more vehicle crashes. The inclusion of a full set of calendar date fixed effects absorbs any effect of seasonality in deaths, which should eliminate this source of bias.

A separate source of bias may occur due to measurement error in M. I use a national average for moon luminosity on a given night, which imperfectly captures actual moon brightness for several reasons. The method to calculate M is an approximation of actual moon luminosity for a sample of points across the US. The presence of clouds, and their spatial distribution, also affects the amount of light actually provided by the moon.

To cure the specification of attenuation bias from measurement error I propose instrumenting moon luminosity (M) with the phase of the moon (P). Chen et al. (2011) outlines how instrumental variables can correct for measurement error in non-linear regression settings. P is measured from 0 ("new moon") to 1 ("full moon")

[4] Year clusters can account for possible error correlation that would occur from long-run changes in road safety conditions. However, the number of clusters is relatively small (21-48 depending on the sample used), which could plausibly bias error estimates. I reran the paper's main specifications under alternative error clustering and found error estimates are robust. For example, the standard error estimated for the variable of interest in Table 3, column 1 is 0.0152 using yearly clusters, 0.0153 using monthly clusters, and 0.0158 using weekly clusters.

with the number varying in proportion to the phase. For example, a half-moon takes a value of 0.5. I use a two-step Generalized Method of Moments (GMM) instrumental variable Poisson regression, where M is instrumented by P. The moon's phase is the most important property that determines brightness. I show pseudo-first-stage OLS regression results in Table 2. The moon's phase (P) is a strong instrument for luminosity (M). I estimate the average full-moon night raises the normalized (0-1) brightness measure M by 0.36. The R^2 for the phase term (P) alone is 0.63. Because the relationship between P and M is nonlinear (Figure 4), forcing a linear relationship reduces the model fit. In Table 2 columns 2 and 3, I introduce a squared and cubed term for P, which improves the model fit. The cubic fit model yields an R^2 of 0.86.

Table 2: Quasi First-stage, Effect of Lunar Phase on Lunar Illumination

	(1)	(2)	(3)
Lunar Phase	0.364**	-0.451**	0.411**
	(0.001)	(0.002)	(0.004)
Lunar Phase Squared		0.815**	-1.484**
		(0.003)	(0.012)
Lunar Phase Cubed			1.533**
			(0.009)
National Cloud Cover	0.015	-0.006	-0.007
	(0.015)	(0.010)	(0.009)
Year fixed effects	N	Y	Y
Day of year fixed effects	Y	Y	Y
Day of week fixed effects	Y	Y	Y
R^2	0.63	0.82	0.86
N	17532	17532	17532

Significance levels: $*$: 5% $**$: 1%. Standard errors are clustered by year and are shown in parentheses. The measure of lunar phase ranges from 0 (no moon) to 1 (full moon). The outcome variable is lunar illumination, which ranges from 0 (no moonlight) to 1 (brightest night observed).

The instrument's exclusion restriction is fulfilled as long as the moon's phase does not affect pedestrian deaths for reasons other than improved road visibility from increased ambient light. An issue would exist if pedestrians walk near roadways more on full moon nights, potentially because it is easier or safer to navigate roadways with the additional light.[5] If this behavioral response exists, it would mean pedestrians experi-

[5]Colino-Rabanal et al. (2018) used data on the phase of the moon to show that some vehicle-wildlife collisions become more common when there is a full moon; for example collisions with deer in the US.

ence more roadway exposure on nights with more moonlight. If pedestrians are more active on bright moon nights my β_1 estimates are conservative.[6]

4 Results

Table 3 provides Poisson regression results showing the effect of moon luminosity on nightly pedestrian deaths. Column 1 estimates the effect for the entire US. I estimate pedestrian fatalities fall 4.7% nationally on a night with the brightest moon compared to a night with no moonlight. Columns 2 and 3 estimate effects in CBSA and non-CBSA counties respectively, roughly contrasting urban and rural areas (Figure 6). For CBSA areas, I estimate a significant moonlight effect of -4.2%. For non-CBSA areas, pedestrian deaths fall by -13.3% when the moon is at its brightest.

Table 3: Effect of Moon Illumination on Nightly Pedestrian Fatalities

	Full US	Urban	Rural
Lunar Illumination	-0.048**	-0.043**	-0.143**
	(0.015)	(0.015)	(0.052)
National Cloud Cover	0.180**	0.181**	0.176
	(0.035)	(0.035)	(0.103)
Year fixed effects	Y	Y	Y
Day of year fixed effects	Y	Y	Y
Day of week fixed effects	Y	Y	Y
N	17532	17532	17532

Significance levels: $*$: 5% $**$: 1%. Standard errors are clustered by year and are shown in parentheses. The measure of lunar illumination ranges from 0 (no moonlight) to 1 (brightest night observed).

The large effect in rural areas is likely because these areas are darker to begin with, meaning the marginal increase in ambient light represents a relatively larger improvement in visibility. Table 4 tests for a heterogeneous effect across different local

The authors attribute the effect to an established influence of moonlight on nocturnal animal activity. This mechanism is unlikely to be important in my setting as few (if any) people plan their trips around the moon's phase.

[6]I tested for a potential relationship between moonlight and nighttime pedestrian activity using the American Time Use Survey (ATUS). ATUS is a nationally representative time use survey. I pooled responses from 2003-2023. The data contains the date and time of each activity, allowing me to link the data to moon illumination. Looking at activities from 8pm-8am, I find no relationship between moonlight and time spent out of the house or time spent walking. On nights with below average moon illumination, respondents report 0.24% of nighttime hours walking. On nights with above average moon illumination, the figure is 0.23%.

lighting conditions. Across all years of FARS data, there is a variable recorded for whether the crash occurred at a location with artificial street lighting–55% of pedestrian deaths occur on sections of roadway without artificial street lighting. The variable relies on the reporting police officer to accurately record lighting conditions, which could introduce some misclassification error. I expect the moonlight effect to be relevant in locations without street lighting because the marginal effect of moonlight would be too small to meaningfully affect visibility on artificially lit roadways. Table 4, column 1 estimates the effect of moonlight on pedestrian deaths that occurred in locations with artificial lighting. I find an insignificant effect that is estimated close to zero. The 95% confidence interval spans -5% to +5%. Column 2 tests for a moonlight effect on pedestrian fatalities on stretches of road with no artificial lighting. For unlit roadways in the US, I estimate a highly significant 10.5% decrease in pedestrian fatalities caused by moonlight. The result shows that the effect of moonlight is specific to locations without road lighting.

Table 4: Effect of Moon Illumination on Nightly Pedestrian Fatalities, Heterogeneity by Lighting Conditions

	Artificial Lighting	No Artificial Lighting	Full US 2002 onwards	Brightest 2%	Darkest 98%
Lunar Illumination	-0.002	-0.111**	-0.057*	-0.025	-0.181**
	(0.024)	(0.022)	(0.028)	(0.029)	(0.050)
National Cloud Cover	0.254**	0.137**	0.174**	0.185**	0.134
	(0.051)	(0.040)	(0.054)	(0.060)	(0.103)
Year fixed effects	Y	Y	Y	Y	Y
Day of year fixed effects	Y	Y	Y	Y	Y
Day of week fixed effects	Y	Y	Y	Y	Y
N	17532	17532	7670	7670	7670

Significance levels: $*$: 5% $**$: 1%. Standard errors are clustered by year and are shown in parentheses. The measure of lunar illumination ranges from 0 (no moonlight) to 1 (brightest night observed).

Table 4 also tests for a heterogeneous effect by dividing the US according to the nighttime lights data. I divide the US into two areas: the 2% of US land with the most nighttime light and the 98% with the least.[7] Because the US population is heavily concentrated in cities, the brightest 2% of land area covers 78% of fatal vehicle-pedestrian crashes. Precise crash locations are only recorded in 2002 and later so I limit the sample to the 7,670 nights observed in these years. Column 3 estimates the effect for the en-

[7] I show results for other thresholds in Appendix A.

tire US during the abbreviated study period, showing a shift from no moonlight to the brightest night reduces pedestrian deaths by 5.5%, slightly higher than the full study period estimate. Column 4 limits the study area to only the 2% of the country that is brightest at night. I estimate a statistically insignificant 2.3% reduction in deaths. Studying only the 98% of the country that is the darkest, I estimate a drop in pedestrian deaths of 16.6%. The results are consistent with the urban/rural results in Table 3, and demonstrate that small changes in lighting are specifically important in areas that have low levels of artificial lighting.

As discussed in the methodology section, using moon phase as an instrumental variable for moon lumination could help correct for attenuation bias from measurement error. In Appendix B, I provide main results under an instrumental variable specification. I find nearly identical results when using the instrumented approach, suggesting that measurement error does not introduce significant bias, and the main Poisson estimates are well identified. In Appendix C, I provide more alternative results under a conventional OLS estimator and a linear instrumental variable estimator. I also find very similar results using these specifications. The consistent findings show that model selection is not driving the results. In Appendix D, I provide reduced form evidence showing a clear correlative relationship between the lunar cycle and pedestrian deaths.

The above analysis estimates the average effect of moonlight, regardless of local cloud conditions. Under significant clouds, moonlight might be completely obscured, suggesting the above results could understate the effect the moon has on a cloudless night. To draw policy lessons regarding the likely effect of comparable street lighting, it is useful to estimate the lunar light effect under cloudless conditions. Using the satellite data on cloud cover, Table 5 estimates the effect of moonlight on crashes occurring in areas with full, partial, or zero cloud cover. For locations that were experiencing full or partial cloud, I find no effect of moon lumination on pedestrian deaths (columns 1 and 2). Column 3 limits the analysis to crashes that occurred under cloudless conditions. I find pedestrian deaths fall by 17.2% nationally in areas where the sky was clear. On nights with generally more cloud cover, there are mechanically more fatal crashes under clouds and fewer under cloud-free skies. However, general differences in national cloud cover are conditionally orthogonal to lunar illumination and therefore should not affect results. I control directly for the national level of cloud cover on a particular night to improve estimate precision. Day-of-year fixed effects remove any seasonality in cloud cover.

Focusing only on areas without cloud cover can better isolate the true effect of

Table 5: Effect of Moon Illumination on Nightly Pedestrian Fatalities, By Local Cloud Conditions

	Full Cloud	Some Cloud	No Cloud
Lunar Illumination	-0.033	-0.020	-0.189**
	(0.076)	(0.035)	(0.070)
National Cloud Cover	3.336**	0.394**	-3.100**
	(0.107)	(0.064)	(0.118)
Year fixed effects	Y	Y	Y
Day of year fixed effects	Y	Y	Y
Day of week fixed effects	Y	Y	Y
N	7670	7670	7670

Significance levels: $*$: 5% $**$: 1%. Standard errors are clustered by year and are shown in parentheses. The measure of lunar illumination ranges from 0 (no moonlight) to 1 (brightest night observed).

moonlight on fatal pedestrian crash frequency. In Table 6, I again check for a heterogeneous effect between roadways based on artificial lighting conditions, but limit the study area to cloudless areas. I find an insignificant effect of moonlight on artificially lit roads under cloudless conditions, though the point estimate is large (-7.6%). For roadways with no artificial lighting under cloudless skies, I find pedestrian deaths fall by 28.8% when the moon is at its brightest. I similarly contrast lunar effects under cloudless skies but compare the brightest and darkest areas of the US based on nighttime lights data. While I find an insignificant effect within the brightest 2% of land, within the darkest 98% of the US, when there is no cloud cover, I estimate that pedestrian fatalities fall by 38.9% under the brightest moonlight.

The very large effect of moonlight in areas with low artificial lighting suggests that road lighting may be an underappreciated determinant of pedestrian road safety. A standard streetlamp provides roughly 30 times as much illumination as the brightest moon. I find that moonlight can reduce pedestrian deaths by nearly 40% in areas without significant artificial lighting, which suggests the proper lighting of roadways with artificial lights could lead to a dramatic reduction in pedestrian-involved crashes and deaths.

I can also contrast effects across different road types. Table 7 provides results separately for local roads, county roads, non-Interstate highways, and Interstate highways.[8]

[8] The FARS variable identifying road type was not recorded in 1981, meaning 1981 is excluded from this analysis.

Table 6: Effect of Moon Illumination on Nightly Pedestrian Fatalities, By Artificial Lighting Conditions, No Clouds

	Full US	Artificial Light	No Artificial Light	Brightest 2%	Darkest 98%
Lunar Illumination	-0.189**	-0.079	-0.328**	-0.116	-0.465**
	(0.070)	(0.095)	(0.096)	(0.078)	(0.106)
National Cloud Cover	-3.100**	-2.751**	-3.498**	-2.984**	-3.520**
	(0.118)	(0.150)	(0.161)	(0.130)	(0.195)
Year fixed effects	Y	Y	Y	Y	Y
Day of year fixed effects	Y	Y	Y	Y	Y
Day of week fixed effects	Y	Y	Y	Y	Y
N	7670	7670	7670	7670	7670

Significance levels: $*$: 5% $**$: 1%. Standard errors are clustered by year and are shown in parentheses. The measure of lunar illumination ranges from 0 (no moonlight) to 1 (brightest night observed).

I find no evidence of a moonlight effect on local roads, this is likely due to these roads having artificial street lighting in most cases. For non-Interstate and Interstate highways, I find full moonlight reduces pedestrian deaths by 5.8% and 5.6%, respectively, though only the non-Interstate estimate is statistically significant.[9] I find the largest effect, a 9.5% decrease in deaths, occurs on county-operated roads. County roads are likely to pass through populated areas, but often do not have artificial street lighting.

Table 7, panel B provides results by road type but limits the analysis to areas without cloud cover. Panel C further limits the sample to areas without artificial street lighting, and Panel D analyzes areas in the darkest 98% of the US according to night-time lights data. Estimated lunar light effects increase when the sample is limited to cloud-free locations, and increase further when analysis is limited to areas with low artificial lighting. However, the frequency of observed pedestrian deaths begins to become sparse in these small sample cells, creating large standard errors. I find particularly strong effects on non-Interstate highways, under low artificial lighting. Under cloud-free conditions, maximum moonlight reduces pedestrian deaths on non-Interstate highways by 29.6% on stretches without street lighting, and by 32.7% for areas in the darkest 98% of the US.

Table 8 provides additional heterogeneity analysis. Panel A provides the results

[9] Although the Interstate system is not meant to accommodate pedestrian crossings, past research has found pedestrian deaths are common where Interstate highways bisect populated areas, including on Interstates themselves (Nehiba and Tyndall, 2023).

Table 7: Effect of Moon Illumination on Nightly Pedestrian Fatalities, By Road Type

A. Full National Sample

	Local Road	County Road	Non-interstate Highway	Interstate Highway
Lunar Illumination	-0.010	-0.100**	-0.060**	-0.058
	(0.025)	(0.035)	(0.022)	(0.041)
National Cloud Control	Y	Y	Y	Y
Year fixed effects	Y	Y	Y	Y
Day of year fixed effects	Y	Y	Y	Y
Day of week fixed effects	Y	Y	Y	Y
N	17167	17167	17167	17167

B. Areas Under Cloud Free Conditions

	Local Road	County Road	Non-interstate Highway	Interstate Highway
Lunar Illumination	-0.077	-0.190	-0.255**	-0.157
	(0.089)	(0.152)	(0.081)	(0.160)
National Cloud Control	Y	Y	Y	Y
Year fixed effects	Y	Y	Y	Y
Day of year fixed effects	Y	Y	Y	Y
Day of week fixed effects	Y	Y	Y	Y
N	7670	7670	7670	7670

C. Areas Under Cloud Free Conditions with No Artificial Street Lighting

	Local Road	County Road	Non-interstate Highway	Interstate Highway
Lunar Illumination	-0.278	-0.238	-0.351**	-0.177
	(0.155)	(0.191)	(0.136)	(0.198)
National Cloud Control	Y	Y	Y	Y
Year fixed effects	Y	Y	Y	Y
Day of year fixed effects	Y	Y	Y	Y
Day of week fixed effects	Y	Y	Y	Y
N	7670	7670	7670	7670

D. Areas Under Cloud Free Conditions in the Darkest 98% of US

	Local Road	County Road	Non-interstate Highway	Interstate Highway
Lunar Illumination	-0.442	-0.420	-0.396**	-0.351
	(0.359)	(0.243)	(0.117)	(0.292)
National Cloud Control	Y	Y	Y	Y
Year fixed effects	Y	Y	Y	Y
Day of year fixed effects	Y	Y	Y	Y
Day of week fixed effects	Y	Y	Y	Y
N	7670	7670	7670	7670

Significance levels: $*$: 5% $**$: 1%. Standard errors are clustered by year and are shown in parentheses. The measure of lunar illumination ranges from 0 (no moonlight) to 1 (brightest night observed).

by age cohort and gender. I find no effect of moonlight on the pedestrian death rate of children (column 1), or seniors (column 3). The effect of moonlight on pedestrian deaths is driven by the non-senior adult population. Across the US, I estimate pedestrian deaths among 18-64-year-olds fall by 6.1% on nights with full moonlight relative to no moonlight.[10] I find the light effect is also specific to male pedestrians. I estimate a

[10]Uttley and Fotios (2017) also tested for differences across age groups, using the daylight savings

reduction in male pedestrian deaths of 6.9%, while the estimate for female pedestrians is not statistically significant. Males are more likely to be victims of fatal pedestrian crashes in the US and are more likely to be struck at higher speeds (Tyndall, 2024). Low lighting appears to exacerbate this gender gap. A larger impact among adult males may be due to higher rates of exposure brought on by more nighttime walking.

Table 8 Panel B performs separate regressions for the four US Census Regions. I find negative point estimates for every region, consistent with fewer deaths on brighter nights. However, only the result for the South is statistically significant. I estimate pedestrian deaths fall 6.3% in the South on the brightest night. The insignificant effects of the other regions may be due to reduced statistical power from splitting the sample of deaths.

I estimate effects across nights, but the strength of the moonlight effect could vary within nights. In the main analysis, I define the night as whenever the sun is below the horizon. However, dawn and dusk hours experience some indirect sunlight due to the earth's atmosphere reflecting sunlight. Moonlight can also vary over the course of a night. Table 8 tests for differences in the effect of moon illumination on pedestrian deaths across different segments of the night. I divide each night into three segments of equal time and test for an effect within each segment. I find the strongest effect of moonlight on pedestrian deaths occurs during the middle-third, or darkest portion, of the night. I do not find statistically significant results for the other portions. The result is consistent with the moon having a larger effect during the portion of the night that is otherwise darkest.

I perform two placebo tests (Table 9) to further establish the main result. First, I test for an effect of moonlight on the number of pedestrian deaths that occurred during daylight hours. If the estimated moonlight effect was unrelated to ambient lighting but was capturing some change in behavior specific to those days, I would expect to see an effect during daylight hours. I find no such relationship (Table 9, column 1). Second, I test for the effect of moonlight on nighttime motorist deaths. Because vehicles operate at night with headlights, moonlight is unlikely to significantly change the visibility of a vehicle to other road users. I find moonlight has no effect on the number of nighttime motorist deaths (column 2). The finding provides more evidence that marginal increases in ambient light are particularly important for pedestrian safety because they increase the visibility of pedestrians. The finding agrees with Sullivan and Flannagan (2007)

identification strategy. They found improved lighting was specifically beneficial for mid-age and senior pedestrians.

Table 8: Effect of Moon Illumination on Nightly Pedestrian Fatalities, Heterogeneous Effects

A. Effect by Demographic Cohort

	Under 18	18-64	65+	Male	Female
Lunar Illumination	0.066	-0.063**	-0.026	-0.072**	0.019
	(0.050)	(0.020)	(0.032)	(0.019)	(0.024)
National Cloud Control	Y	Y	Y	Y	Y
Year fixed effects	Y	Y	Y	Y	Y
Day of year fixed effects	Y	Y	Y	Y	Y
Day of week fixed effects	Y	Y	Y	Y	Y
N	17532	17532	17532	17532	17532

B. Effect by US Region

	West	Midwest	Northeast	South
Lunar Illumination	-0.050	-0.029	-0.011	-0.065**
	(0.027)	(0.043)	(0.035)	(0.022)
National Cloud Control	Y	Y	Y	Y
Year fixed effects	Y	Y	Y	Y
Day of year fixed effects	Y	Y	Y	Y
Day of week fixed effects	Y	Y	Y	Y
N	17532	17532	17532	17532

C. Effect by Portion of Night

	Dusk	Middle Night	Dawn
Lunar Illumination	-0.026	-0.092**	0.029
	(0.022)	(0.021)	(0.038)
National Cloud Cover	0.176**	0.200**	0.125
	(0.040)	(0.056)	(0.083)
Year fixed effects	Y	Y	Y
Day of year fixed effects	Y	Y	Y
Day of week fixed effects	Y	Y	Y
N	17532	17532	17532

Significance levels: $*$: 5% $**$: 1%. Standard errors are clustered by year and are shown in parentheses. The measure of lunar illumination ranges from 0 (no moonlight) to 1 (brightest night observed). In Panel C, dusk is defined as the first third of the night, "Middle Night" is the middle third, and dawn is the last third.

that found pedestrian risk at night rose far more than motorist risk.[11]

Table 9: Effect of Moon Illumination on Road Fatalities, Placebo Tests

	Daytime Pedestrian Deaths	Nighttime Motorist Deaths
Lunar Illumination	0.007	-0.001
	(0.024)	(0.008)
National Cloud Cover	-0.211**	-0.085**
	(0.041)	(0.025)
Year fixed effects	Y	Y
Day of year fixed effects	Y	Y
Day of week fixed effects	Y	Y
N	17532	17532

Significance levels: $*$: 5% $**$: 1%. Standard errors are clustered by year and are shown in parentheses. The measure of lunar illumination ranges from 0 (no moonlight) to 1 (brightest night observed).

5 Policy Discussion

The above results show that a small increase in ambient lighting on dark roads leads to a large improvement in pedestrian safety. In this section, I provide some connections to public policy. First, I attempt to provide a back-of-the-envelope estimate of how many lives could be saved by nationwide improvements to artificial street lighting. Second, I discuss how the findings could be used to justify targeted investments in street lighting.

In 2022, there were 2,506 nighttime pedestrian deaths on roadways without artificial street lighting. I estimate the number of deaths that would be averted under a hypothetical scenario where all roadways were artificially illuminated to a minimum of 0.3 lux, the level of the brightest moonlight in the sample (Kyba et al., 2017). For every nighttime pedestrian death on an unlit road, I multiply the estimated moonlight effect (Table 6, column 3) by the difference between full moonlight and the moonlight that occurred on that night, at that location, accounting for the presence of clouds.[12]

[11] Cyclist safety could also be diminished in low light conditions. However, nighttime cyclist deaths are less common than nighttime pedestrian deaths. Across the study period, 0.8 cyclist deaths are reported per night, compared to 11.0 per night for pedestrians. Therefore, cyclist results were insignificant due to low variation in the data.

[12] Moving from $M = 0$ to $M = 1$ reduces nighttime pedestrian deaths by an estimated 28.0% on unlit roads with no cloud cover. For every pedestrian death on an unlit road that occurred on a clear night I calculate $(1 - M_n) \times 0.280$, which is the probability that death would have been avoided by

I then sum these averted pedestrian deaths across every night in 2022. The calculation implies that 663 pedestrian lives would have been saved in 2022 in a hypothetical world where every road was illuminated to a minimum of 0.3 lux.

While only a back-of-the-envelope calculation, the estimate highlights the significant impact of lighting on annual deaths. The estimates imply that roughly 11% of nighttime pedestrian deaths or 9% of all pedestrian deaths could be averted if all roads were illuminated to a minimum level of 0.3 lux. The US Department of Transportation, in 2023, considered the value of a statistical life to be $13.2 million. Therefore, insufficient lighting on unlit roadways carries a cost in terms of increased pedestrian fatalities of roughly $9 billion per year. This is the value of lives saved by raising light levels only marginally to a 0.3 lux minimum. A typical streetlamp provides roughly 10 lux and could therefore provide a larger improvement in safety. The calculation also ignores the cost of non-fatal pedestrian injuries, motorist injuries and deaths, and property damage that may be caused by poor lighting.

Providing full street lighting on all roadways would be enormously expensive in terms of infrastructure and energy costs. However, the findings of this paper provide two novel policy lessons. First, an exogenous increase in road illumination significantly reduces pedestrian deaths. Second, the amount of lighting needed to improve pedestrian safety is small. The findings suggest that targeted investments of low luminance lighting in high-risk locations could be cost-effective.

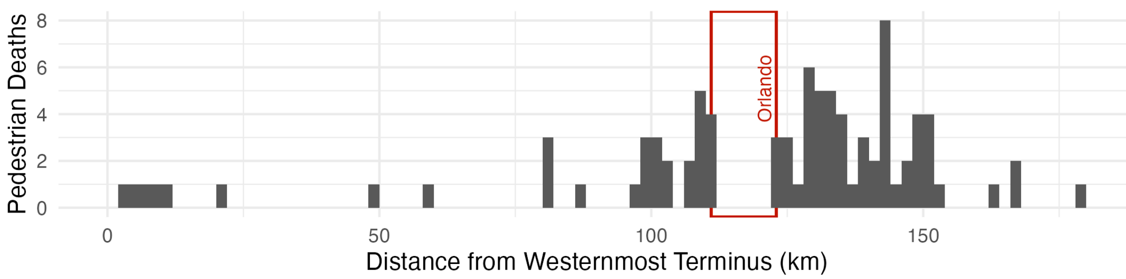
Pedestrian deaths on unlit portions of roads are concentrated near major population centers. In some instances, it is possible to identify locations that present particular dangers to pedestrians at night. I provide an illustrative example. Figure 7 graphs nighttime pedestrian deaths on unlit portions of State Highway 50 in Florida. Highway 50 runs 185 km from the east coast to the west coast of Florida, passing through Orlando. The highway had 89 nighttime pedestrian deaths on segments without artificial street lighting during 2002-2022, the most of any state highway in the country.[13] Some stretches of highway never had a nighttime pedestrian death, so improved lighting would not necessarily reduce pedestrian fatalities at those locations. Some areas experienced significant pedestrian fatalities. On the 31 km stretch of highway to the east of Orlando, there were 53 nighttime pedestrian deaths on unlit sections of Highway

raising ambient lighting to 0.3 lux. For cases with cloud cover, I assume the cloud cover proportionally reduced the moonlight, and scale the estimated effect $((1 - M_n \times (1 - C_n)) \times 0.280)$.

[13]Pre-2002 observations are omitted because they do not consistently record the precise location of the crash.

50 in the 2002-2022 period, an average of 2.5 per year. I estimate the number of these deaths that would have been averted if this stretch of highway maintained 0.3 lux as a minimum amount of road lighting. In expectation, the estimates of this paper (Table 6, column 3) suggest 14.6 of the 53 deaths would have been averted if that 31 km stretch of highway had lighting, averaging 0.69 lives saved per year.[14]

Figure 7: Pedestrian Deaths on Florida State Highway 50 at Locations without Artificial Lighting, 2002-2022



The figure shows pedestrian deaths occurring at night where the record indicates the road had no street lighting. The x-axis ranges from the westernmost point of the highway to the easternmost point. The municipality of Orlando is highlighted in the figure. While I do observe nighttime pedestrian deaths in Orlando, the portion of Highway 50 within Orlando has street lighting, so I do not observe any reported pedestrian deaths on unlit segments of Highway 50.

The DOT adopts a 4% economic discount rate in safety analysis.[15] Assuming a 4% discount rate and the DOT's value of a statistical life implies the present value of saving 0.69 lives per year into the future would be $229 million. Therefore, the installation of road lighting on this 31 km stretch of road could be rationalized by pedestrian lives saved as long as the infrastructure costs do not exceed $229 million in present value terms.

Costs to install conventional street light infrastructure vary widely based on state requirements and local procurement costs. On the stretches of Florida State Highway 50 that do have street lamps, they are spaced roughly 60 meters apart, on both sides of

[14] I reach this estimate by employing the same method used above to estimate the probability that each death would have been averted under improved lighting conditions, accounting for cloud cover, and then summing the expectations of averted deaths.

[15] The suggested discount rate was taken from US Department of Transportation, *Departmental Guidance: Treatment of the Value of Preventing Fatalities and Injuries in Preparing Economic Analyses*, March 2021.

the highway. A $5,000 unit price for lamps would imply a project cost of roughly $5.2 million to light the 31 km stretch of Highway 50. Contrasting present costs and benefits implies a return on investment for installing street lamps of 4,400%. Accounting for injury prevention and motorist safety would imply an even higher return. The rough estimate implies that streetlamp investments could be easily justified by pedestrian safety improvements.

As noted throughout this paper, this method estimates the effect of raising ambient lighting up to 0.3 lux. Conventional street lighting provides much more lighting. The apparent safety improvement from a very small amount of additional lighting suggests that innovative alternatives to conventional street lighting may be cost-effective. While a standard streetlamp can cost several thousand dollars to procure and install, alternatives such as solar-powered LED lights are inexpensive and could be deployed on high-risk roadways to provide small amounts of light at low cost.

6 Conclusion

US traffic deaths represent an enormous public health challenge. Pedestrian dangers are most acute at night, with nearly 80% of pedestrian deaths occurring between sunset and sunrise. Poor lighting on roadways represents one cause of nighttime pedestrian deaths. I contribute to the literature by providing a valid source of exogenous variation in road illumination. I find small increases in light on unlit streets make a large difference to pedestrian safety. Estimates show specific evidence that areas with low levels of artificial lighting could be made significantly safer for pedestrians with even small increases in lighting.

Using moonlight as a source of exogenous variation in ambient light provides estimates that are not subject to the potential biases of prior methods. I confirm the importance of lighting to pedestrian safety, but significantly strengthen the causal evidence, and provide a richer analysis that can show heterogeneity across ambient lighting conditions and road types.

Although using moonlight can overcome endogeneity concerns, the empirical method suffers from some limitations. Most importantly, the variation in light level I can leverage through moonlight is small, and much smaller than what is typically provided by artificial street lighting. The limitation means I estimate a lower bound to the effect of installing artificial street lighting on nighttime pedestrian safety. Importantly, I find even a small increase in ambient light substantially improves pedestrian safety.

Light pollution represents a competing public interest to expanding street lighting. Light pollution has been shown to negatively impact human health (Hölker et al., 2010) and be harmful to ecological systems (Longcore and Rich, 2004). The above results suggest that the marginal pedestrian safety benefits of street lighting are large at low levels of lighting. Improved street lighting could have additional positive societal effects not considered in this study. For example, street lighting improves the sense of safety for pedestrians (Fotios et al., 2015, 2018; Peña-García et al., 2015), which could improve mobility. Determining the optimal level of street lighting would need to account for competing costs and benefits.

Establishing a causal connection between road lighting and pedestrian safety provides an important basis for road design standards. I also provide a framework to consider how the marginal effects of road lighting on pedestrian safety could be incorporated into cost-benefit calculations. Future research could exploit the causal evidence of this paper to support policy recommendations.

US pedestrian deaths at night have risen dramatically since 2009. The cause of this increase remains largely unexplained by the literature. Lighting conditions did not change dramatically in 2009, so lighting effects are unlikely to explain this trend. However, other trends such as increased distracted driving brought on by smartphone adoption and in-car infotainment screens, or the increase in average vehicle size, could interact with poor lighting to contribute to deteriorating safety. Understanding the connection between road lighting and the recent rise in nighttime pedestrian deaths is an important topic for future research.

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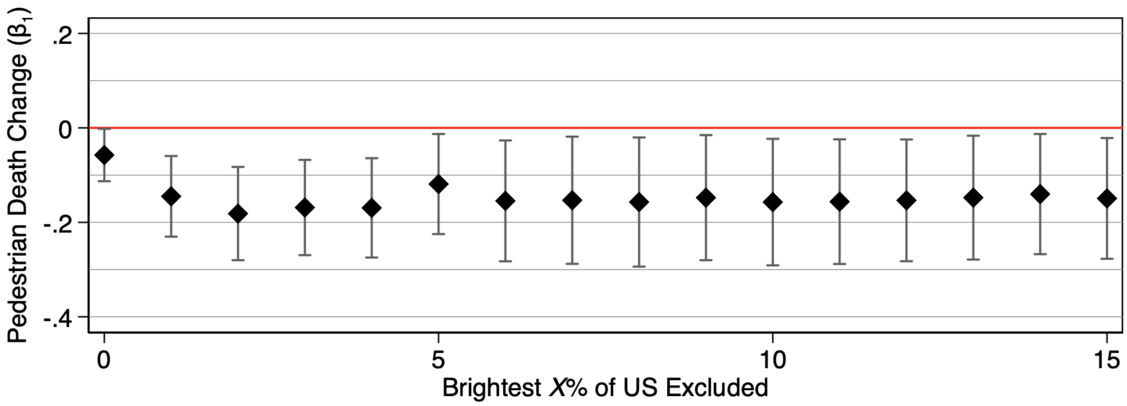
Appendix A: Robustness Across Nighttime Lights Classification Threshold

Figure A1 visualizes the main estimate across various satellite nighttime light conditions. The figure shows the results of 16 separate regressions, utilizing Equation 1. The leftmost point shows the estimated -5.5% effect for the entire US, for 2002-2022 (equal to Table 4, column 3). Moving rightward, I begin excluding the brightest areas. The subsequent point estimate includes the 99% of the US that is the darkest at night. I find that excluding just the brightest 1% of area significantly raises the estimated effect to a 13.5% decrease. As I further restrict the sample to darker areas the effect stabilizes and remains significant.

Figure A1: Heterogenous Effect of Moonlight Based on Local Nighttime Lights



Each point represents the β_1 estimate from a separate regression. The ranges indicate the estimate's 95% confidence interval. The leftmost point estimate is made on the full US sample for years 2002-2022. Each subsequent estimate removes the next brightest 1% of US land according to nighttime lights data.

Appendix B: Instrumental Variable Results

Using lunar phase (P) as an instrumental variable for M in a Generalized Method of Moments (GMM) instrumental variable Poisson regression could provide an estimate of the effect of M on pedestrian deaths while removing the potential attenuation bias introduced by measurement error of M. P is a very strong instrument for M, as shown in Table 2. Table B1 panel i provides the results of the Poisson instrumental variable approach. When M is instrumented with P, I estimate a 6.9% decrease in deaths for the full US, rather than the 4.7% decrease estimated in the original Poisson specification. However, imposing a linear instrument on a relationship that is non-linear and heteroskedastic (Figure 4) may cause bias. In Table B1 panel ii, I instrument M with P as well as P^2, strengthening the first stage. The introduction of the additional instrument lowers the estimated moonlight effect. In Panel iii, I additionally add a cubed (P^3) version of the instrument, which lowers the estimate further. The full US result for the cubic instrument specification shows a 4.9% reduction in deaths, closely matching the uninstrumented Poisson result. Urban and rural-specific estimates are also very similar. Overall, the IV estimates confirm the main Poisson regression results.

Table B1: Effect of Moon Illumination on Nightly Pedestrian Fatalities, IV Poisson Regressions

i. Instrumenting Illumination (M) with Phase (P)

	Full US	Urban	Rural
Lunar Illumination	-0.072**	-0.061**	-0.259**
	(0.020)	(0.020)	(0.079)
National cloud control	Y	Y	Y
Year fixed effects	Y	Y	Y
Day of year fixed effects	Y	Y	Y
Day of week fixed effects	Y	Y	Y
N	17532	17532	17532

ii. Instrumenting Luminosity (M) with Phase (P) and Phase Squared (P^2)

	Full US	Urban	Rural
Lunar Illumination	-0.058**	-0.052**	-0.156*
	(0.017)	(0.017)	(0.067)
National cloud control	Y	Y	Y
Year fixed effects	Y	Y	Y
Day of year fixed effects	Y	Y	Y
Day of week fixed effects	Y	Y	Y
N	17532	17532	17532

iii. Instrumenting Luminosity (M) with Phase (P), Phase Squared (P^2) and Phase Cubed (P^3)

	Full US	Urban	Rural
Lunar Illumination	-0.050**	-0.044*	-0.160*
	(0.017)	(0.017)	(0.066)
National cloud control	Y	Y	Y
Year fixed effects	Y	Y	Y
Day of year fixed effects	Y	Y	Y
Day of week fixed effects	Y	Y	Y
N	17532	17532	17532

Significance levels: $*$: 5% $**$: 1%. Lunar Illumination (M) is instrumented with lunar phase (P). Robust standard errors are shown in parentheses. The measure of lunar illumination ranges from 0 (no moonlight) to 1 (brightest night observed).

Appendix C: Alternative Functional Forms

In the main analysis of this paper, I use a Poisson specification. In Appendix B, I provide results using two-step Generalized Method of Moments (GMM) instrumental variable Poisson regressions. In Table C1, I provide an analogous analysis to the Poisson regression results (Table 3) but rather than a Poisson approach I use a standard OLS regression. The results are very similar. For example, the full US OLS result is a reduction in 0.62 pedestrian deaths per night. The average night had 11.0 deaths, which implies the maximum moonlight effect reduces deaths by 5.6%, which closely matches the 4.7% estimated under the Poisson approach. The urban and rural results are also similar in terms of percentage change.

Table C1: Effect of Moon Illumination on Nightly Pedestrian Fatalities, OLS Results

	Full US	Urban	Rural
Lunar Illumination	-0.620**	-0.527**	-0.094**
	(0.188)	(0.180)	(0.035)
Year fixed effects	Y	Y	Y
Day of year fixed effects	Y	Y	Y
Day of week fixed effects	Y	Y	Y
N	17532	17532	17532

Significance levels: * : 5% ** : 1%. Standard errors are clustered by year and are shown in parentheses. The measure of lunar illumination ranges from 0 (no moonlight) to 1 (brightest night observed).

Table C2 is analogous to Table A1 panel i but uses a standard two-stage least squares estimator rather than the GMM Poisson instrumental approach. Again, I find highly consistent results.

Table C2: Effect of Moon Illumination on Nightly Pedestrian Fatalities, Two-stage Least Squares Results

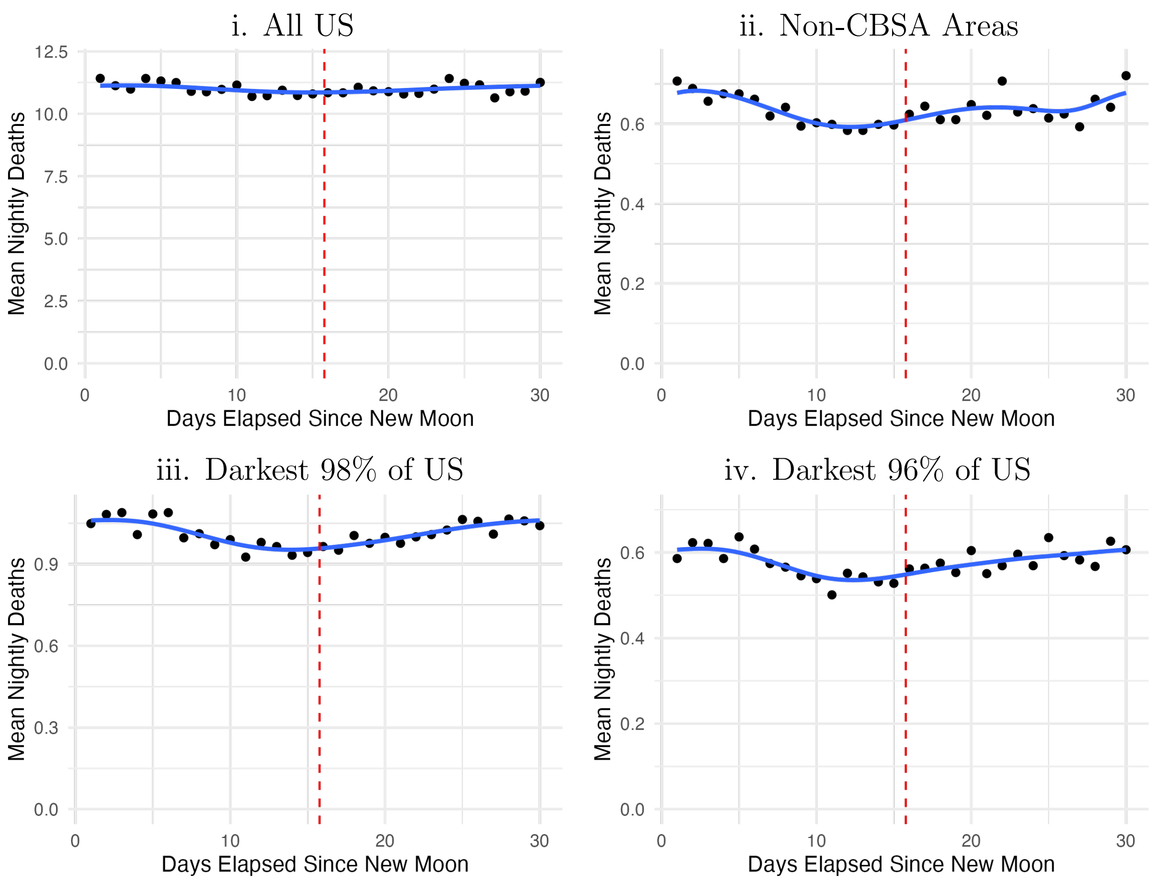
	Full US	Urban	Rural
Lunar Illumination	-0.859**	-0.695**	-0.164**
	(0.220)	(0.211)	(0.047)
Year fixed effects	Y	Y	Y
Day of year fixed effects	Y	Y	Y
Day of week fixed effects	Y	Y	Y
N	17532	17532	17532

Significance levels: * : 5% ** : 1%. Standard errors are clustered by year and are shown in parentheses. The measure of lunar illumination ranges from 0 (no moonlight) to 1 (brightest night observed). The instrumental variable is the measure of lunar phase.

Appendix D: Reduced Form Results

Figure D1 provides raw correlative evidence of the lunar cycle and nighttime pedestrian deaths. I normalize the days of each lunar cycle so that day 1 represents the first day of the cycle where there is no moon ($P = 0$). Because the lunar phase is aseasonal, the pure correlation should capture much of the relationship between the lunar phase and pedestrian deaths. Panel i shows the entire US effect, illustrating a slight dip in nighttime deaths centered on the full-moon phase. Panels ii-iv illustrate the more pronounced correlation for areas with less nighttime light.

Figure D1: Lunar Cycle and Nighttime Pedestrian Deaths



The full moon occurs on day 15-16 of the lunar cycle and is shown with the vertical dashed line. The points represent the average number of nighttime pedestrian deaths for each day in the lunar cycle. Panels i and ii use data from 1975-2022. Panels iii and iv use the nighttime lights satellite data classification and only cover 2002-2022.

The most important determinant of moon luminosity is the phase of the moon. As an additional robustness test, in Table D1 I repeat the main analysis but use the measure of lunar phase (P) as a proxy for moonlight, where the variable ranges from 0 (new moon) to 1 (full moon). Whereas the estimated measure of moon luminosity is subject to some measurement error, the moon phase is not. I estimate consistent results. Full moons reduce pedestrian deaths by 2.7% relative to new moon nights. In urban areas, the estimate is 2.3% and in rural areas the effect is 9.0%. The estimated effects are lower than estimates using lunar luminosity because the measure of the lunar phase fails to capture a significant share of the actual nightly variation in moonlight (Figure 4).

Table D1: Effect of Moon Phase on Nightly Pedestrian Fatalities

	Full US	Urban	Rural
Lunar Phase	-0.027**	-0.023**	-0.094**
	(0.007)	(0.007)	(0.026)
National Cloud Cover	0.179**	0.180**	0.173
	(0.035)	(0.035)	(0.103)
Year fixed effects	Y	Y	Y
Day of year fixed effects	Y	Y	Y
Day of week fixed effects	Y	Y	Y
N	17532	17532	17532

Significance levels: $*$: 5% $**$: 1%. Standard errors are clustered by year and are shown in parentheses. The measure of lunar phase ranges from 0 (new moon) to 1 (full moon).