



School start times and teenage driver motor vehicle crashes

Robert D. Foss^{a,*}, Richard L. Smith^b, Natalie P. O'Brien^a

^a Highway Safety Research Center, University of North Carolina at Chapel Hill, Chapel Hill, NC, 27599, United States

^b Department of Statistics and Operations Research, University of North Carolina at Chapel Hill, Chapel Hill, NC, 27599, United States



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ABSTRACT

Introduction: Shifting school start times to 8:30 am or later has been found to improve academic performance and reduce behavior problems. Limited research suggests this may also reduce adolescent driver motor vehicle crashes. A change in the school start time from 7:30 am to 8:45 am for all public high schools in one North Carolina county presented the opportunity to address this question with greater methodologic rigor.

Method: We conducted ARIMA interrupted time-series analyses to examine motor vehicle crash rates of high school age drivers in the intervention county and 3 similar comparison counties with comparable urban-rural population distribution. To focus on crashes most likely to be affected, we limited analysis to crashes involving 16- & 17-year-old drivers occurring on days when school was in session.

Results: In the intervention county, there was a 14% downward shift in the time-series following the 75 min delay in school start times ($p = .076$). There was no change approaching statistical significance in any of the other three counties. Further analysis indicated marked, statistically significant shifts in hourly crash rates in the intervention county, reflecting effects of the change in school start time on young driver exposure. Crashes from 7 to 7:59 am decreased sharply (-25% , $p = .008$), but increased similarly from 8 to 8:59 am (21% , $p = .004$). Crashes from 2 to 2:59 pm declined dramatically (-48% , $p = .000$), then increased to a lesser degree from 3 to 3:59 pm (32% , $p = .024$) and non-significantly from 4 to 4:59 (19% , $p = .102$). There was no meaningful change in early morning or nighttime crashes, when drowsiness-induced crashes might have been expected to be most common.

Discussion: The small decrease in crashes among high school age drivers following the shift in school start time is consistent with the findings of other studies of teen driver crashes and school start times. All these studies, including the present one, have limitations, but the similar findings suggest that crashes and school start times are indeed related, with earlier start times equating to more crashes.

Conclusion: Later high school start times ($> 8:30$ am) appear to be associated with lower adolescent driver crash rates, but additional research is needed to confirm this and to identify the mechanism by which this occurs (reduced drowsiness or reduced exposure).

1. Introduction

Driving while sleepy or fatigued can result in decreased alertness, slowed reaction times, failure to notice developing emergency situations and, in the extreme, falling asleep. Experimental studies suggest that even moderate sleep deprivation, of the sort experienced by the end of a long day, can impair drivers' cognitive abilities comparably to having a blood alcohol concentration (BAC) at the legal limit of 0.08% (Faletti et al., 2003; Williamson & Feyer, 2000). Accurate data on the role of fatigue or drowsiness in crashes are difficult to obtain from crash data bases, and it is suspected that analyses of such data underestimate the incidence of drowsy driving crashes. The most compelling documentation of the role of drowsiness in crashes comes from a recent

analysis of naturalistic driving data acquired in the SHRP-2 study of almost 3600 drivers, from late 2010 through 2013 (Antin et al., 2015; Dingus et al., 2015). Owens et al. (2018) analyzed continuous video recording of crash-involved drivers during the 60 s preceding the crash and classified more than 10% of drivers as drowsy, using a standard measure (eyes closed $\geq 12\%$ of the time prior to the crash).

One of the original studies of drowsy-driving crashes found that individuals younger than 25 accounted for a majority of such crashes in North Carolina (Pack et al., 1994). More recent analysis of a nationally representative sample of crashes that were thoroughly investigated from 1999 to 2008 found that 7% of all crashes involved a drowsy driver. Crash-involved drivers ages 16–24 were 80% more likely than those age 40 and older to have exhibited signs of drowsiness (Tefft,

* Corresponding author at: Highway Safety Research Center, University of North Carolina, 730 Martin Luther King Jr Blvd, Chapel Hill, NC, 27599-3430, United States.
E-mail address: rob.foss@unc.edu (R.D. Foss).

2012). This over-involvement by young drivers may result, in part, from an interaction between driving experience and hazard perception. Smith et al., 2009 suggest that more experienced drivers are less susceptible to degradation of their hazard perception abilities when they are sleepy.

Developments in understanding human sleep needs during the past two decades may provide further explanation for the over-involvement of younger drivers in drowsy driving crashes. Circadian rhythms change during adolescence, leading teenagers to fall asleep later than when they were younger (Wolfson and Carskadon, 1998, 2003). As a consequence of this “sleep phase shift,” to obtain sufficient rest adolescents need to be asleep in the early morning hours (e.g., 6–7 am) (National Sleep Foundation, 2000). Although developments in a wide range of technologies and in social networking have substantially altered the lives of teenagers during the past decade, the shift in circadian rhythm is a biological phenomenon and not simply a matter of teens choosing to go to bed later (Carskadon et al., 2004). With this unavoidable developmental change occurring in the context of a “24-hour world” that now encourages later bedtimes for nearly everyone, the result has been an increasing number of sleep-deprived adolescents.

High school start times that have become progressively earlier over time exacerbate the problem of adolescent sleep deprivation. Yang et al. (2005) reported that whereas 5th & 6th graders cite television-watching and internet activities (in addition to academic pressures) as responsible for their sleep deprivation, 10th–12th graders cite early school start times along with academic pressures as the primary contributors. High school bell schedules typically begin earlier than those of middle and elementary schools. This often results from efforts to minimize the number of buses needed in a school district by sequencing bus runs so that multiple morning runs with the same buses can accommodate all students who need transportation. Hansen et al. (2005), provide stark evidence of how early school start times interfere with teenagers’ sleep. Examining sleep diaries of incoming high school seniors for several weeks before and after school began in the fall, they discovered that even though students began going to bed earlier when the fall term began, they still slept an average of 1.7 fewer hours on nights preceding a school day than on summer nights. Although there was some adaptation as the school year progressed, students continued to experience substantial sleep deprivation on weekdays. Subsequent research has confirmed and extended these findings (Bowers and Moyer, 2017).

As the critical importance of sleep has come to be more fully recognized and adolescent sleep patterns better understood, some school systems in the U.S. have reversed the decades-long trend toward earlier high school start times. These policy changes are designed to avoid causing sleep deficits and the resulting consequences in the teenage population. Moving start times back from 7:30 am or earlier to 8:30 am or later appears to have produced improvements in academic performance and decreases in disruptive behavior (Dexter et al., 2003; Wahlstrom et al., 2014; Wolfson & Carskadon, 1998). In view of the growing evidence about the many undesirable sequelae of adolescent sleep deprivation, the American Academy of Pediatrics has endorsed setting school start times at 8:30 a.m. or later, to remove school schedules as a contributor to these problems (Adolescent Sleep Working Group, 2014). One of the arguments marshalled in support of later school start times is the evidence that they reduce motor vehicle crashes. However, there have been only a few inquiries into this issue and all these studies suffer from methodologic limitations.

Danner conducted the first study of this issue, reporting a reduction in teenage driver crashes after a one hour delay in high school start times (Danner 2002; Danner & Phillips, 2008). After the start time was changed from 8 am to 9 am in Fayette County (Lexington metropolitan area), the crash rate among licensed 17 & 18-year-old drivers declined 16% during the following two years, compared with the previous two years. During the same time period, crashes throughout the rest of the state increased by 8%.

A cross-sectional comparison of two large, adjacent counties in southeastern Virginia with high school start times that differ by 80 min (7:20 vs 8:40 am) reported a 29% lower per capita crash rate among 16–18-year-olds in the county with the later start time (Vorona et al., 2011).

In a comprehensive examination of the effects of altering school start times by 4 communities in Minnesota and Wyoming, Wahlstrom et al. (2014) included an examination of simple crash counts among 16–18-year-old drivers for the year preceding and following the adjustments. There was no notable change in crashes in the two larger communities (decrease from 200 to 196), but substantial decreases (from 40 to 13) were seen in two quite small, rural communities.

In sum the limited body of evidence suggests that later high school start times may lead to fewer crashes, but with so few studies the question is far from settled. No matter how well conceived and executed, no single study can precisely estimate the effect of a policy change, which is why systematic reviews and meta-analyses are so critical (Deeks et al., 2008). Moreover, each of these studies has methodologic limitations. Danner & Phillips (2008) excluded 16-year-old drivers, who represent a substantial proportion of high school age drivers from the analyses,¹ but included 18-year-olds, many of whom would have graduated and consequently been unaffected by high school policies. They included summertime crashes, which would not have been affected by school schedules, and compared crash rates in a large relatively affluent urban/suburban community to those in the remainder of a largely rural, impoverished state. Wahlstrom et al. (2014) appropriately included 16-year-olds, and excluded summer crashes, but they also included 18-year-olds and weekend crashes. They conducted no statistical analyses, merely comparing crash counts for a single year before and after a change in school start times, employing no comparison groups. They also had difficulty matching crashes to the population exposed to the change in start times. The intervention was school-based, but the analysis looked at teen driver crashes that occurred within city boundaries, regardless of whether the driver was a student. And crashes involving students subject to the school start policy that occurred outside the city were not included in the analyses. Along with Danner & Phillips they made no attempt to adjust for secular trends, which are commonly found when examining teen driver crashes over time (Masten et al., 2011).

Vorona et al. (2011) conducted far more detailed and comprehensive analyses, comparing crashes in two demographically similar, geographically adjacent eastern Virginia counties with substantially differing school start times. They examined 16-17-year-old crashes during the school year. However, they did include weekend crashes, which are probably differentially affected—or completely unaffected—by school start time. Cross-sectional comparisons can never be safely assumed to estimate intervention effects (Hauer, 2010) because it’s difficult to know all the relevant ways in which two groups may differ beyond the matter of interest (school start time in this case). Cognizant of this issue, and in view of the fact that crash rates were higher in one county among drivers of all ages, Vorona et al. did attempt to examine whether the two counties differed in traffic congestion—which could account for the difference, but that was not the case. Vorona et al. (2014) examined teen driver crashes in another pair of geographically adjacent Virginia counties, where school start times differed markedly (8:45 vs 7:20 a.m.). The findings were highly similar to the results of their previous study; 16–17-year-old weekday crash rates per licensed driver were about 30% higher in the county with the earlier school start time.

A more refined analytic approach to this issue would help to more effectively rule out alternative explanations for the apparent beneficial

¹ Although Danner & Phillips provide no explanation for this exclusion, it may have been to avoid the possible contaminating effect of coincident changes in Kentucky’s young driver licensing system. These changes reduced crashes among 16-year-olds by nearly one-third by increasing the mandatory learner period from one month to 6-months duration (Agent et al., 2001).

effect on young driver crashes of delaying the high school start time. The present study is an attempt to do this, examining an age group and time periods more directly subject to effects of an altered high school start time. Beginning in August 2003, Forsyth County, North Carolina (2003 population = 317,430)

moved the high school start time from 7:30 am to 8:45 am. The present study is a conceptual replication of the Danner & Phillips (2008) study, employing a study design that allows adjustment for pre-existing trend, focuses more tightly on when (school days only), and the population in which (16–17-year-olds), the effect would be expected.

2. Method

2.1. Crash data

Data were obtained from the North Carolina Crash Data System, for crashes involving drivers ages 16 and 17 who held a North Carolina driver license, from January 2000 through June 2007. This data base includes all police-reported crashes occurring on a public roadway and involving either injury or more than \$500 damage. North Carolina is a relatively rural state, with a substantial proportion of the population living in rural areas. This results in a great deal of driving on rural roads, where crash risks differ substantially from urban/suburban driving. Accordingly, we chose not to use the entire state for comparison to limit the range of factors that contribute to young novice driver crashes in the intervention and comparison counties. Analyses were limited to crashes that occurred in Forsyth County and the three larger counties in North Carolina (Guilford, Mecklenburg and Wake). These three counties are fairly comparable to Forsyth in terms of urbanization and homogeneity of driving environment. The 2003 population densities in Forsyth, Guilford, Mecklenburg and Wake Counties were 747, 648, 1322, and 755 persons per square mile, respectively. The population density for North Carolina as a whole was 165 persons per square mile.

The starting date of January 2000 was selected because a new crash reporting form was adopted at that time, creating a number of inconsistencies with data recorded using the previous form. Moreover, the young driver licensing system in North Carolina was altered to create a multi-stage graduated driver licensing (GDL) system in December 1997. This produced some dramatic changes in the nature of the young driver cohort and in crash rates among high school age drivers (cf., Foss et al., 2001). The young driver licensing system had returned to a state of equilibrium by July 1999, but the crash rate has remained substantially lower among high school age drivers. Use of three comparison counties for the present analyses should control for any possible unknown, longer term after-effects of this change in the licensing process. We examined crash data only through the end of the 2007 school year, to avoid the complicated contaminating effects of the Great Recession, whose effects on teenage employment, hence driving exposure and crashes, began to appear in late 2007 (Bureau of Labor Statistics, 2017).

2.2. School data

Table 1 summarizes information about the schools in the counties studied. Two of the comparison counties—Guilford and Mecklenburg—had uniform county-wide start times for all public high schools. Start times in the Wake County schools were not uniform, varying from 7:25 am to 8:05 am, but most started at 7:25 am; the mean start time was 7:36 am in 2003. These start times have remained largely constant since 2000 although they occasionally shifted by a few minutes from year to year, especially in Wake county. In Forsyth County the uniform start time for all public high schools was 7:30 am until August 2003, when it shifted to 8:45 am There are private high schools in all four counties, whose start times often differ from those of public schools. Information about start times was not available for most private schools. Many of these schools are quite small, with fewer than 50 students.

Table 1
Number of schools, enrollment and daily school start times for four studied counties.

County	N	Fall 2003 Enrollment	Original start time	New start time
Forsyth	8	12,500	7:30 am	8:45 am
Guilford	14	18,150	8:40 am	Same
Mecklenburg	15	27,950	7:15 am	Same
Wake	16	28,150	7:36 am ^a	Same

^a Start times were not uniform across Wake County. 7:36 am was the mean start time in 2003.

Table 2
16- and 17-year-old population in the intervention (Forsyth) and three North Carolina comparison counties for the years of study.

Year	County			
	Forsyth	Guilford	Mecklenburg	Wake
2000	7,514	10,141	17,156	15,440
2001	7,716	10,349	18,084	16,745
2002	8,060	10,943	19,230	17,964
2003	8,368	11,379	20,076	18,808
2004	8,621	11,477	20,811	19,651
2005	8,946	11,864	21,530	20,847
2006	9,688	12,580	22,741	22,461
2007	10,311	13,041	24,117	23,906

Details about the school calendars of all four school systems were compiled from official school records and by speaking with school system officials in each county. This information included the days that school was scheduled to be in session, days when school was canceled due to inclement weather and make-up days when school was actually in session though not originally scheduled as a class day. In combination with the crash data, this information was used to calculate crash rates per school day in session.

2.3. Population data

The population grew substantially in all four NC counties during the period under study, with total population increases between 2000 and 2007 ranging from 8.7% to 30.9%. The number of 16- and 17-year-olds grew at an even faster rate in all counties (see Table 2). To account for the effect of population increase on crashes, annual census estimates of the number of 16- and 17-year-old residents of each county were obtained from the office of the North Carolina State Demographer. These were used to adjust for population changes.

2.4. Construction of time series

We examined monthly crash counts from January 2000 through June 2007.² However, because school was not in session on weekends or during the summer, these days/periods were excluded from the analysis. Rather than using calendar month as the unit of analysis, we created “pseudo-months” to capture as many school-in-session days as possible, while simultaneously excluding the summer recess period. Accordingly, as examined here each year contained 10 pseudo-months. Month 1 of each year runs from January 10 through February 9; Month 2 from February 10 through March 9; ... Month 10 from December 10 through January 9 the following year. Table 3 shows the periods covered by each time unit (month) in the analysis (January 1–9, 2000, are

² A new crash reporting system was implemented in January 2000, rendering data for prior years somewhat incomparable. The analysis begins with January, rather than August, 2000 to obtain the maximum number of pre-intervention months.

Table 3
Definition of data series time periods (“months”).

Month	Begin date		End date	
1	January 10	2000	February 9	2000
2	February 10	2000	March 9	2000
3	March 10	2000	April 9	2000
4	April 10	2000	May 9	2000
5	May 10	2000	June 9	2000
6	August 10	2000	September 9	2000
7	September 10	2000	October 9	2000
8	October 10	2000	November 9	2000
9	November 10	2000	December 9	2000
10	December 10	2000	January 9	2001
11	January 10	2001	February 9	2001
12	February 10	2001	March 9	2001
13	March 10	2001	April 9	2001
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73	March 10	2007	April 9	2007
74	April 10	2007	May 9	2007
75	May 10	2007	June 9	2007

not included in the analysis). As thus defined, the dataset covers a total of 75 months, 10 each in years 2000-2006 and 5 in 2007.

The number of crashes per school-in-session day involving drivers age 16 or 17 was calculated for each month. Using age-specific population estimates for each county, we calculated a population-adjusted series as the number of crashes per school day, per 10,000 16-17-year-old county residents during the year of the crash.

The initial time series were constructed by aggregating all hours of the day. However, since the time of the crash is important in some analyses, we also computed time series restricted to specific periods of the day (6 am–9 am, 9 am–noon, Noon–3 pm, 3 pm–6 pm, 6 pm–6 am), and for individual hours (6 am–7 am, 7 am–8 am, etc.).

2.5. Statistical analyses

To obtain an initial assessment of a possible change point, we fitted the following regression model to each time series:

$$x_t = \beta_0 + \beta_1 t + \beta_2 I(t > 35) + \sum_{j=1}^9 \beta_{2+j} (m_{tj} - \bar{m}_j) + \varepsilon_t \tag{1}$$

Here, β_0 is an intercept, β_1 is a linear time trend, β_2 is the size of the change point after time 35 (i.e. month 35 of the data, which corresponds to the month of the school start time change in Forsyth County), and $\beta_3, \dots, \beta_{11}$ are monthly coefficients. The variable m_{tj} is an indicator: 1 if time point t is in month j , 0 otherwise. We define this for $j = 1, \dots, 9$: the value for $j = 10$ is by default assumed to be 0. The variable \bar{m}_j is the mean of m_{tj} over all t , and we assume the standard linear regression model that the errors ε_{tj} are uncorrelated with mean 0 and common variance. The model (1) is fitted by ordinary least squares regression and the fitted line without monthly mean terms, i.e., $\hat{\beta}_0 + \hat{\beta}_1 t + \hat{\beta}_2 I(t > 35)$, is shown in the plots of the time series given below. In this way, we are able to visualize the separate effects of the change point and the overall trend. We did not calculate standard errors for this regression, because those are derived through a more detailed ARIMA analysis, which is described next.

The general strategy behind intervention analysis based on ARIMA time series models has been described in numerous places. Box and Tiao (1975) first suggested the approach, while Brockwell and Davis (2003) provide a good introductory overview of the methodology. A recent application of this approach to assess the effect of a traffic safety intervention—an evaluation of speed enforcement cameras in Charlotte, NC—is provided by Moon and Hummer (2001).

Given that initial plots of the time series show clear visual evidence of both trend and seasonality, it is natural to start by differencing the

series at a lag of one year (10 months, since 2 summer months are excluded from analyses):

$$y_t = x_t - x_{t-10}, \quad t = 11, \dots, 75. \tag{2}$$

Ignoring for the moment the possibility of a change point, we fit a seasonal ARIMA time series model to y_t :

$$\varphi(B)\Phi(B)(y_t - \mu) = \theta(B)\Theta(B)\varepsilon_t. \tag{3}$$

Here:

- $\varphi(B) = 1 - \sum_{i=1}^p \varphi_i B^i$ is the autoregressive operator of order p ,
- $\Phi(B) = 1 - \sum_{i=1}^P \Phi_i B^{is}$ is the seasonal autoregressive operator of order P and seasonality $s = 10$,
- $\theta(B) = 1 + \sum_{i=1}^q \theta_i B^i$ is the moving average operator of order q ,
- $\Theta(B) = 1 + \sum_{i=1}^Q \Theta_i B^{is}$ is the seasonal moving average operator of order Q .

B is the backshift operator ($B^k y_t = y_{t-k}$) and μ is the overall mean. If $\mu < 0$, then there is an overall decrease in crash rates over the time period of the study, but this conclusion in itself does not imply that the decrease is due to the change in school start times; for that we need a more specific, intervention analysis.

To extend model (3) to the case with an intervention (or change point), we write

$$\varphi(B)\Phi(B)(y_t - \beta_0 - \beta_1 z_t) = \theta(B)\Theta(B)\varepsilon_t. \tag{4}$$

Thus the constant mean μ in (3) is replaced by a regression function $\beta_0 + \beta_1 z_t$, where z_t is the following indicator function: $z_t = 1$ for $t = 36, 37, \dots, 45$, otherwise $z_t = 0$. The rationale for this definition of z_t is that model (4) has been derived from (1) by differencing at lag 10: z_t is precisely the differenced version of the function $I(t > 35)$. However, by including the autoregressive and moving average operators in (4), we allow correctly for time series dependence.

A key step for the application of (3) or (4) is the selection of model orders p, P, q, Q . Here, p and q refer to the non-seasonal part of the model—larger values of p and q would indicate a higher degree of autocorrelation over consecutive months within a year, while the values of P and Q relate to autocorrelations at multiples of one year (in this case, 10 months) and therefore reflect the seasonal effects in the data. There is no universally agreed upon procedure for selecting these model orders. There are various semi-automated methods such as the Akaike Information Criterion (AIC; Akaike 1973), the Bayesian Information Criterion (BIC; Akaike 1978) or the bias-corrected Akaike Information Criterion (AICC), introduced for time series by Hurvich and Tsai, 1989). We used each of these criteria to help guide the model choice, but without regarding any of them as absolute. We also tried out various time series models using the test of Ljung and Box (1978). This is a test for autocorrelation among the residuals of a time series model; if the hypothesis of uncorrelated residuals is accepted, then the time series model is taken to be a reasonable fit to the data. All of these methods are described in standard time series texts, such as Brockwell and Davis (2003). In most of the following analyses, we use $p = P = q = 0, Q = 1$, in which case the model (4) reduces to

$$y_t - \beta_0 - \beta_1 z_t = \varepsilon_t + \Theta_1 \varepsilon_{t-10}. \tag{5}$$

In this model, the parameter Θ_1 accounts for the autocorrelation at lag 10, which is a measure of seasonal effect. This has the advantage of being a relatively simple model, which appears to fit most of the time series examined and passes the Ljung-Box test in most cases.

The analyses were conducted using the statistical package R (R Core Development Team, 2010), in particular using the ARIMA function in R.

3. Results

3.1. Initial identification of changes in crash rates

The following figures show plots of the adjusted series for the four North Carolina counties studied. The vertical dashed line is at month

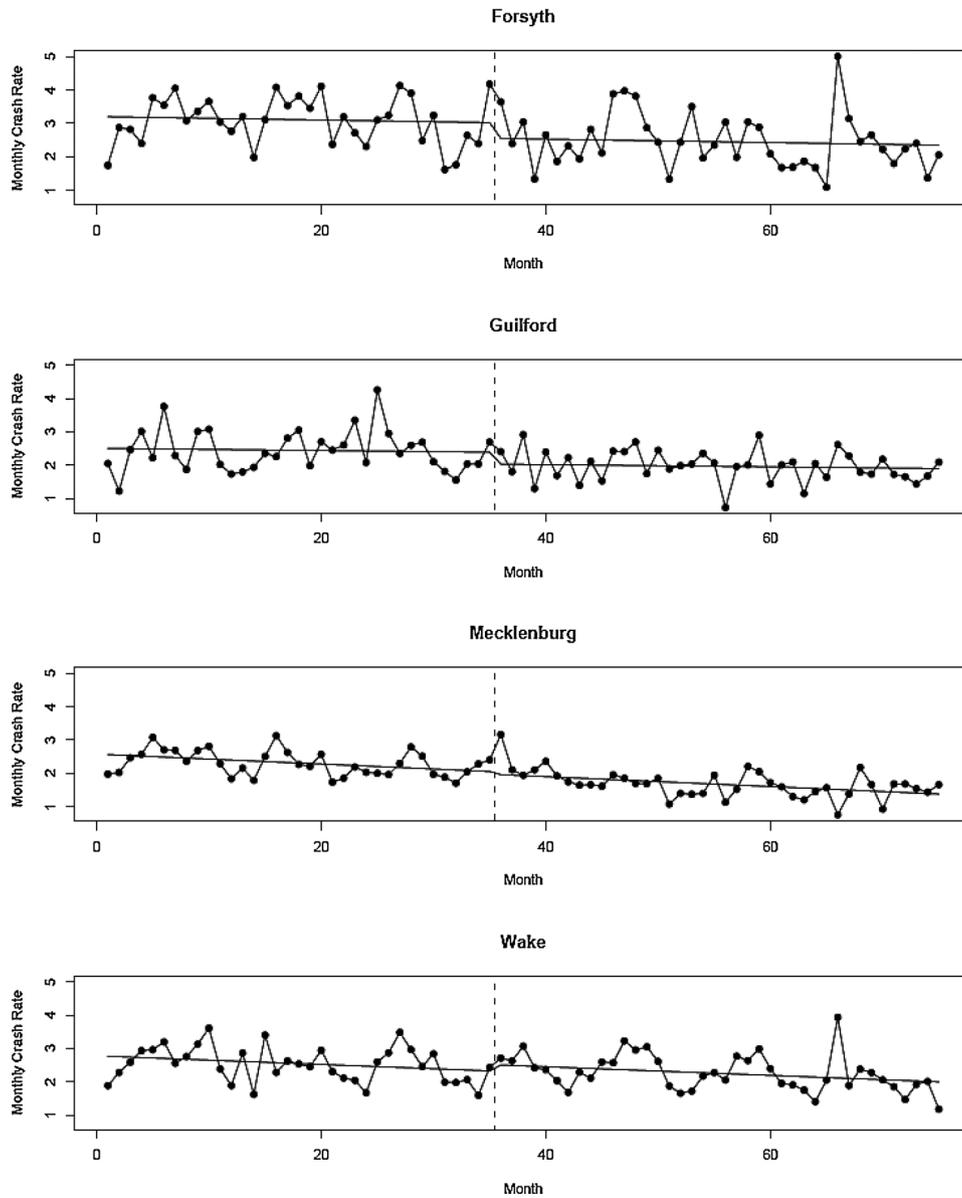


Fig. 1. Adjusted monthly daytime (6 am to 6 pm) crash rates in four NC counties, from January 2000 through June 2007.

35, i.e., before August 2003, the month in which the later school start time was introduced in Forsyth County. Each plotted data point represents the crash rate per school day in session during the month, per 10,000 16- and 17-year-olds in the county, as described above. Thus, for example, if there were 36 crashes on the 18 days that school was in session during a month, the unadjusted crash rate per school day for the month would be $36/18 = 2.00$. If the county had a population of 8400 16- and 17-year-olds, the mean population-adjusted monthly crash rate per school day in session would be $(36/18) / (8,400/10,000) = 2.00/.84 = 2.38$.

Fig. 1 shows a plot of the population-adjusted daytime crash series (6 am to 6 pm). It is apparent that there is seasonality in the data, with more crashes during the autumn months and fewer in the springtime. There are also downward trends of varying strengths in all four counties. The overall trend is especially strong in Mecklenburg County.

Prior to conducting a formal time-series analysis, the model

described in Eq. (1) was fitted to each data series, and the resulting trend drawn on the monthly crash plots to take an initial look for a possible change in the level of the series. As is shown in Fig. 1, there is a small, but perceptible, downward shift in daytime crashes at the time of the school policy change for Forsyth County. However, when the same regression model is fitted, there is also a downward shift for Guilford County. The other two counties, Mecklenburg and Wake, show no evidence of a shift in crash rates. There is also no evidence of a shift in nighttime crashes—which would be expected if drowsiness was reduced by the change in school start time—in Forsyth County (Fig. 2). Note the differing scale on the vertical axes, compared to Fig. 1, indicating that there are roughly 4 times as many crashes in this age group during the daytime vs. nighttime hours.

We used ARIMA time series analysis to quantitatively assess the observed shifts and estimate their statistical reliability.

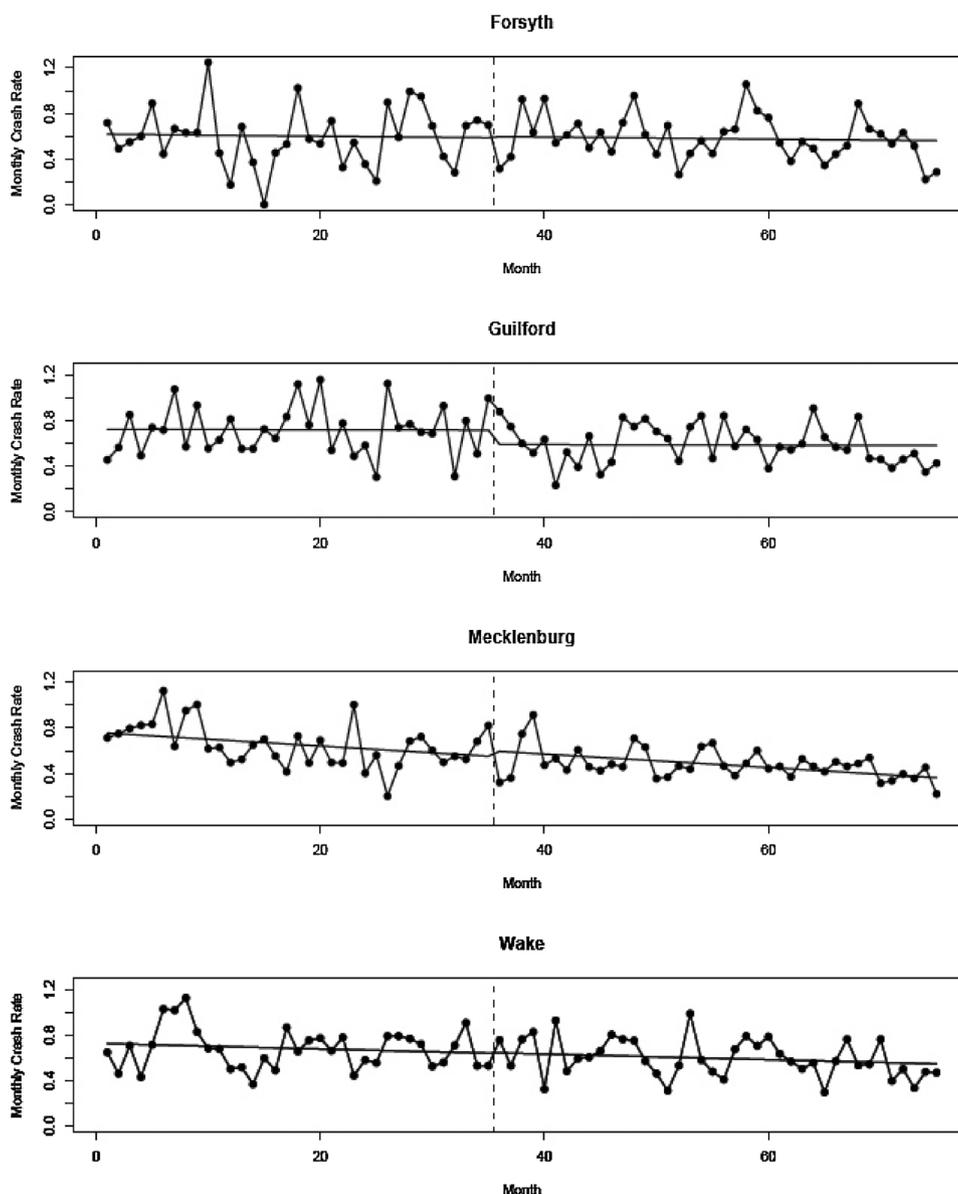


Fig. 2. Adjusted monthly nighttime (6 pm to 6 am) crash rates in four NC counties, from January 2000 through June 2007.

Table 4
Model (5) parameter estimates for the time series in Forsyth County, NC.

Model	Parameter	Estimate	Standard Error	95% CI (LL, UL)
No Intervention	θ_1	-0.855	0.276	(-1.396, -0.314)
	β_0	-0.145	0.033	(-0.21, -0.08)
	AIC	142.2		
Intervention	θ_1	-0.826	0.229	(-1.275, -0.377)
	β_0	-0.050	0.063	(-0.173, 0.073)
	β_1	-0.475	0.267	(-0.998, 0.048)
	AIC	141.1		

3.2. Intervention analysis for Forsyth County

Parameter estimates for the model shown in Eq. (5), applied to the full dataset (all hours of the day) for Forsyth County, are shown in Table 4.

Thus, the model with no intervention shows a statistically significant overall downward trend (β_0), but the one with an intervention shows a negative β_1 (-.475)—indicating a clear drop following the

change in school start time—accounting for nearly all of the overall decline. The AIC statistic also indicated that the model including an intervention parameter fit the data better.³

Reduced drowsiness resulting from adequate sleep might have produced differing effects by time of day. Although the effects of sleep deprivation are complex, the effect of reduced drowsiness would most likely be seen in the early morning, late night and perhaps early afternoon hours. To look for evidence of differential effects by time of day, the same model fitted to the full day was applied to separate daily time blocks for each of the four counties.

Table 5 provides a summary of the results of these more detailed analyses. For simplicity we report only the β_1 parameter estimates, which measure the size of the shift under the intervention model, and

³ Plots of the autocorrelation function (/ACF) and partial ACF for the differenced series y_t showed significant autocorrelations at lag 10 (which is natural, since this corresponds to the seasonal effect) and also at some other lags, notably 4 and 6. The corresponding plots for the residuals from the time series model still showed a slightly significant autocorrelation at lag 4. However the Ljung-Box test (which combines the ACF at lags 1, 2, ..., J into a single test statistic) is not significant for any value of J up to 20. Therefore, we concluded that the model is a reasonable fit to the data.

Table 5

The $\hat{\beta}_1$ (intervention effect) parameter estimates for model (5) fitted to full day and five different daily time blocks in Intervention (Forsyth) and comparison counties.

Time period	$\hat{\beta}_1$	Standard Error	95% CI (LL, UL)
Forsyth County			
Full day	-0.475	0.267	(-0.998, 0.048)
6 am–9 am	-0.152	0.115	(-0.377, 0.073)
9 am–noon	-0.151	0.077	(-0.302, 0.000)
Noon–3 pm	-0.686	0.129	(-0.939, -0.433)
3 pm–6 pm	0.511	0.183	(0.152, 0.870)
6 pm–6 am	0.011	0.083	(-0.152, 0.174)
Guilford County			
Full day	-0.358	0.250	(-0.848, 0.132)
6 am–9 am	-0.059	0.082	(-0.220, 0.102)
9 am–noon ^a	-0.005	0.038	(-0.079, 0.069)
Noon–3 pm	-0.013	0.079	(-0.168, 0.142)
3 pm–6 pm	-0.265	0.150	(-0.559, 0.029)
6 pm–6 am	-0.127	0.087	(-0.298, 0.044)
Mecklenburg County			
Full day	-0.064	0.147	(-0.352, 0.224)
6 am–9 am	-0.021	0.071	(-0.160, 0.118)
9 am–noon	0.003	0.024	(-0.044, 0.050)
Noon–3 pm	-0.028	0.078	(-0.181, 0.125)
3 pm–6 pm	-0.027	0.080	(-0.184, 0.130)
6 pm–6 am	0.048	0.063	(-0.075, 0.171)
Wake County			
Full day	0.177	0.178	(-0.172, 0.526)
6 am–9 am	0.024	0.084	(-0.141, 0.189)
9 am–noon	0.005	0.041	(-0.075, 0.085)
Noon–3 pm ^b	0.015	0.057	(-0.097, 0.127)
3 pm–6 pm	0.137	0.084	(-0.028, 0.302)
6 pm–6 am	0.005	0.072	(-0.136, 0.146)

^a The time series model for 9 am–noon in Guilford, is Eq. (4) with $P = q = 0$, $p = Q = 1$. We included an autoregressive non-seasonal component of order 1, as well as the moving average seasonal component of order 1, because this model provided a better fit for this series.

^b The model for noon–3 pm in Wake is based on Eq. (4), with $P = q = 0$, $p = Q = 1$, which provided a better fit to the data.

their 95% confidence intervals, for the full day and five daily time blocks in each of the four counties.

The Forsyth County results show a marked decrease in crash rates from noon to 3 pm, and a substantial increase from 3 pm to 6 pm, with small decreases from 6 am to 9 am and 9 am to noon. These results are consistent with a change in the pattern of crashes corresponding to the times when high school age drivers are on the road during school days. Following the shift in start time, the school day ends at 3:40 pm in Forsyth County high schools. Prior to the policy change the instruction day ended at 2:25 pm. High school parking lots clear out quickly after the final bell, putting a large number of teenage drivers on the roadways within 15–20 min. This change in the peak exposure time for high school age drivers resulting from the shift in school start (and ending) times provides a parsimonious explanation for the decrease in crashes from noon to 3 pm and the increase after 3 pm. Note that the policy did not shift the peak morning drive time out of the 6 am–9 am time block, so a change there as well as during the nighttime block could be viewed as evidence of decreased drowsiness. The lack of any notable effect in either of those suggests the change in school start did not materially affect drowsy-driving crashes.

However, the question of whether there was an overall decrease in crashes after the policy was implemented, is most relevant for assessing the effect of the school policy change. The substantial decrease in crashes from Noon to 3 pm was only partially offset by the increase from 3 to 6 pm. The decrease in all crashes following the change in school start time ($\hat{\beta}_1 = -0.475$) represents a notable decrease ($p = 0.076$). Although this does not reach conventional levels of statistical significance, p-values are only one of several important

considerations in interpreting the meaning of empirical findings (Wasserstein & Lazar, 2016), and the reliance on null-hypothesis significance tests based on arbitrary thresholds (e.g., $\alpha = 0.01$ or 0.05) as the preferred—or only—criterion of scientific value is increasingly viewed as inappropriately regimented, especially in observational, as opposed to experimental, studies (Nickerson, 2000; Savitz, 2003; Trafimow & Marks, 2016).

3.3. Guilford County

The results for Guilford County (Table 5) suggest a modest decline in overall crashes coincident with the August 2003 policy change in Forsyth County ($\hat{\beta}_1 = -0.358$, $p = .152$). The pattern, however, is quite different, with most of the change occurring in the after school hours ($\hat{\beta}_1 = -0.265$, $p = .078$) and, to a lesser extent, the nighttime hours ($\hat{\beta}_1 = -0.127$, $p = .14$). In both cases the models excluding an intervention parameter fit the data as well as those assuming an intervention effect.

3.4. Mecklenburg and Wake counties

There was no evidence of an intervention effect (i.e., change in August 2003), overall or at any particular time of day for either of these counties (Table 5).

3.5. Hour by hour analysis of Forsyth County data

To better understand the variation by hour of day, the data from Forsyth County were broken up into single-hour analyses, from 6 am (meaning the hour between 6 am and 7 am) through to 11 pm.⁴ These series are plotted in Fig. 3. The estimated changes in population-adjusted crash rates at the time of the school schedule change ($\hat{\beta}_1$), together with associated standard errors, and confidence intervals, are shown in Table 6.

For the 7–8 am hour, there is a statistically significant decrease, which is only partly balanced by an increase in the 8 am hour. These clearly reflect altered driving times resulting from the schedule change. They do not suggest that students overall are safer as a result of the schedule change, that is, that improved sleep reduced crashes overall. Likewise, there is a statistically significant decrease during the 2 pm hour, matched by increases in the 3 pm and 4 pm hours, but note that the 2–3 pm decrease is by far the biggest change in magnitude during the entire day and it is not offset by the increases from 3 to 5 pm. Thus, shifting the school day 75 min later did not appear simply to shift the timing of crashes. There does appear to be an overall decrease as well. Summing all the $\hat{\beta}_1$ values in Table 6, we find the result -0.46 , is essentially identical to the result reported above for the full daytime crash series (-0.475). Since the overall mean population-adjusted crash rate is 3.34, this represents about a 14% decrease in the overall crash rate as an apparent result of the schedule change.

The notable decrease from 10 to 10:59 am is quite puzzling. Most students would have been in class at that time, both before and after the start time was pushed back. The anomaly here is the greater heterogeneity in crash rates during this one hour block before the shift in start times, which is inconsistent with other hours during which students are typically in class. We explored a few possible explanations for this decrease, but none proved viable.

The analyses reported here for the single hour crash series used the same ARIMA model as in the main, full-day analysis. Because of the smaller number of crashes during one-hour windows, it is less certain that such a model is appropriate (the normal distribution is more likely

⁴ Outside those hours, there are too few crashes in total for the analysis to be meaningful. Even during the 6 am and 11 pm hours, a large proportion of the observed monthly crash rates are 0.

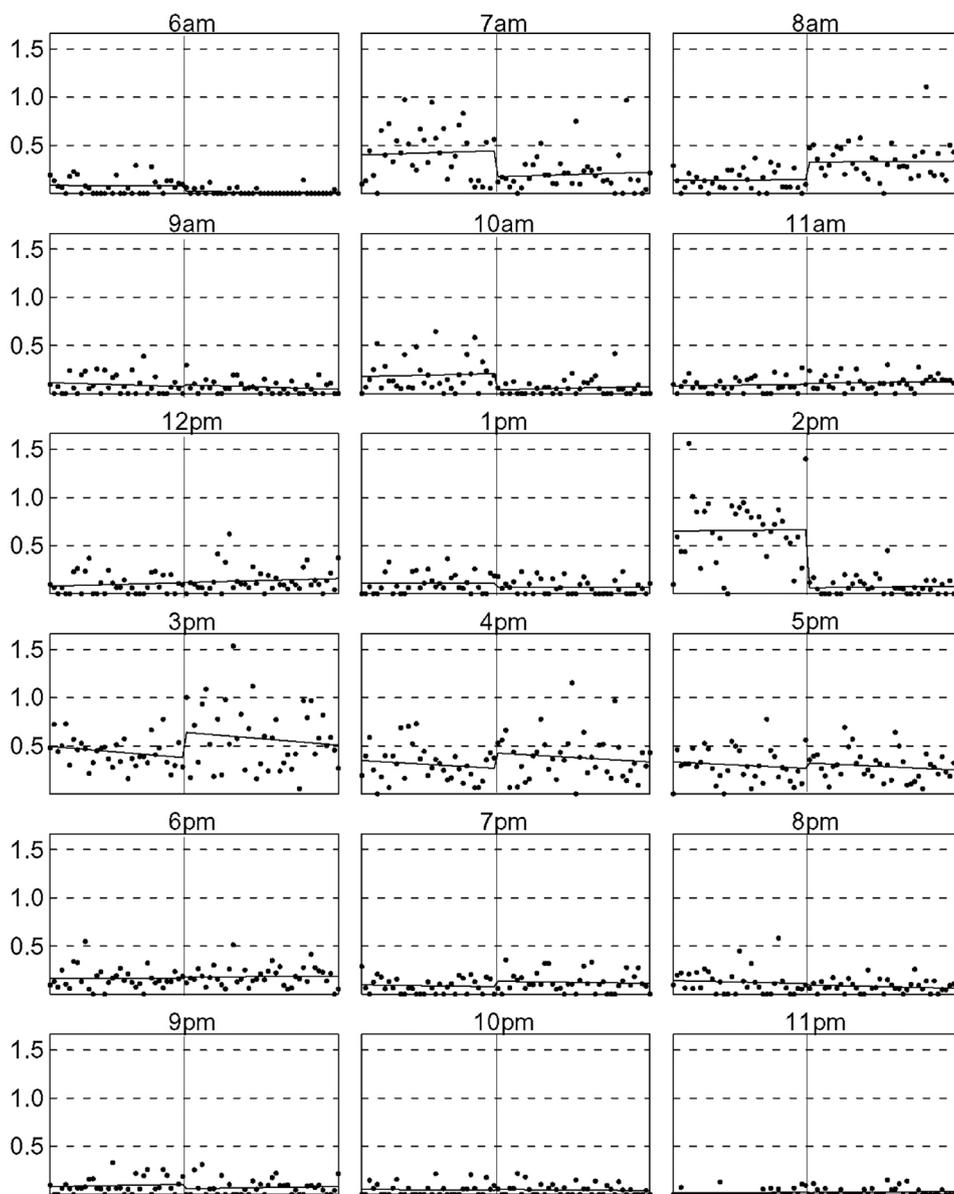


Fig. 3. Adjusted monthly crash rates, by single hour, January 2000 to June 2007, Forsyth County, NC.

Table 6
Hour by hour intervention parameter estimates for model (5), Forsyth County.

Hour	$\hat{\beta}_1$	Standard Error	95% CI (LL, UL)
6 am	-0.060	0.031	(-0.121, 0.001)
7 am	-0.287	0.107	(-0.497, -0.077)
8 am	0.194	0.066	(0.065, 0.323)
9 am	0.020	0.043	(-0.064, 0.104)
10 am	-0.182	0.062	(-0.304, -0.06)
11 am	0.012	0.038	(-0.062, 0.086)
Noon	0.003	0.055	(-0.105, 0.111)
1 pm	-0.044	0.043	(-0.128, 0.040)
2 pm	-0.645	0.118	(-0.876, -0.414)
3 pm	0.277	0.123	(0.036, 0.518)
4 pm	0.171	0.106	(-0.037, 0.379)
5 pm	0.061	0.069	(-0.074, 0.196)
6 pm	0.017	0.048	(-0.077, 0.111)
7 pm	0.061	0.044	(-0.025, 0.147)
8 pm	-0.016	0.049	(-0.112, 0.080)
9 pm	-0.049	0.041	(-0.129, 0.031)
10 pm	0.010	0.028	(-0.045, 0.065)
11 pm	-0.003	0.020	(-0.042, 0.036)

justified as an approximation when sample sizes are large). However, these analyses were checked using the Ljung-Box test for residual autocorrelation and looking for outliers as a test of the normal distribution; there is no evidence from those tests that the analyses are unreasonable.

4. Discussion

The present study was conducted to complement previous studies and avoid the methodologic shortcomings that limit the strength of their findings regarding the effect of school start times on teen driver motor vehicle crashes. To that end we conducted time-series analyses to adjust for enduring trends and the cyclic nature of crashes, used multiple comparison groups, and focused precisely on age groups (16-17-year-olds) and crash times (weekdays during the school year) most likely to be affected by high school schedules. The results show an estimated overall decrease in per capita crash rates of about 14% in Forsyth County, NC following the 75 min change in the countywide high school start time. Whether this reflects an actual effect of the policy remains somewhat unclear. A similar though smaller step change was observed

in the most similar of the 3 comparison counties (Guilford), which is also geographically adjacent to the intervention county. The latter decrease did not approach statistical significance, but is nonetheless unsettling as it could suggest there were other forces at work that produced the decrease in crash rates at around this time in central North Carolina. On the other hand there was no evidence of any shift in crash rates in the other two comparison counties.

The patterns of change in crash rates across time of day were different in Guilford and Forsyth Counties. This suggests that if there was an actual change in Guilford County, it reflects something unique to that county rather than a general decline of crash rates among high school age drivers in urbanized regions of central North Carolina. One possible explanation for this puzzling decrease, which was not seen in either of the other two comparison counties examined, is that a county-wide high-visibility enforcement program focusing on teenage drivers was conducted in Guilford County from August through December 2004 (Goodwin et al., 2006). This involved 25 law enforcement checkpoints in the vicinity of high schools as school was dismissed, focusing on compliance with young driver license restrictions (limits on carrying multiple passengers, requirement of belt use). There were also stepped up nighttime patrols, to address compliance with a limit on night driving by teens with an intermediate driver license. These enforcement activities were accompanied by extensive publicity. The combination of enforcement and heavy publicity of the enforcement has repeatedly been shown to produce changes in high risk driving (Lacey et al., 1999; Reinfurt, 2004; Williams & Wells, 2004). Moreover, the overall decline in the Guilford County crash rate was due almost exclusively to a decrease between 3 pm and 6 pm, whereas Forsyth crashes increased sharply during this time of day. This is the time period when enforcement activities in Guilford County were most visible to high school students, with the checkpoints conducted in the vicinity of schools. The initiation of this program followed the school start intervention point by a year. Hence, this explanation for the possible shift in Guilford County is quite speculative, though it was a factor during part of the post-August 2003 assessment period. Nonetheless, the absence of any evidence of a marked crash rate reduction about that time in the other two counties considered suggests that the Forsyth County decrease is not merely the result of a general decrease in young driver crashes in urbanized North Carolina counties that happened to coincide with the shift in school start time in Forsyth County.

More detailed analyses of Forsyth County crash rates, breaking the day into three-hour time blocks, were conducted to see if there were changes consistent with a reduction in student drowsiness. If this were the case, crashes early in the morning, late in the evening and perhaps the early afternoon, would have been most likely to decline following the later start time. However, there was no overall change in crashes in the earliest time block (6 am–9 am), or at night (6 pm to 6 am). Crashes later at night evening should be even more sensitive to improved sleep, but there were too few late night crashes to detect any pattern. The changing crash pattern throughout the day following the shift in school start time more clearly reflects the altered driving exposure associated with later arrival and departure from school than it does a possible reduction in drowsy driving. The more detailed hour-by-hour analysis of crashes clearly underscores this conclusion.

The important policy question at issue is whether a later school start time produces an overall decrease in the rate of school-age driver crashes, regardless of the underlying causal mechanism. The preponderance of evidence, especially considering the recent findings of Vorona et al. in Virginia (Vorona et al., 2011; 2014), seems to point to a modest crash-reducing effect of this policy change. It may be that a later school start time decreases crashes by compressing the after-school part of the day, thereby reducing teens' overall driving exposure. Such an effect of a later school start is no less important, even if the mechanism (reduced exposure) is different from the one originally hypothesized (fewer sleepy high school age drivers).

Other studies have reported that a later start time does reduce

sleepiness among high school students, but the effect on crashes of an increase in sleep may simply be too small to detect in a population of the size studied here, given the many other factors that influence crashes. Drowsy-driving crashes in general are most common during the post-midnight hours, but a minuscule proportion of 16- and 17-year-old driver trips (and crashes) occur between midnight and 6 am. Moreover, not all 16- and 17-year-old drivers in Forsyth County would have been influenced by the public high school start time. A small percentage were private school students, and others would have dropped out of school entirely.

5. Conclusions

It appears that the 75 min shift to a later school start time produced a small overall decrease in crashes among 16-17-year-old drivers, but the results are not definitive. The decrease in crash rates coincident with the altered start time was clear, but was only marginally statistically significant. The fact that no similar shift was observed in the other large urbanized counties suggests this change was unique to the intervention county. It is clear that the timing of crashes shifted, matching the later times when high school students would be driving to school and to various locations after school, but there was a 14% overall decline in crashes as well, not merely a shift in their timing. The lack of any notable decrease in crashes during the nighttime hours, nor any overall decrease during the early morning when students would be driving to school, suggests either that the decline in crashes was not the result of reduced sleepiness or that such an effect was too weak to detect.

Additional longitudinal studies of crashes in other jurisdictions that have altered their start times, and where the teenage driving population is sufficiently large to provide the needed statistical power to detect an effect, would be highly useful in bringing clarity to this issue.

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