Teens have the highest crash rate of any group in the United States.

Examining the Safety Implications of Later Licensure: Crash Rates of Older vs. Younger Novice Drivers Before and After Graduated Driver Licensing

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Title

Examining the Safety Implications of Later Licensure: Crash Rates of Older vs. Younger Novice Drivers Before and After Graduated Driver Licensing *(October 2014)*

Authors

Robert Foss, Scott Masten, and Carol Martell
University of North Carolina at Chapel Hill Highway Safety Research Center

About the Sponsor

AAA Foundation for Traffic Safety
607 14th Street, NW, Suite 201
Washington, DC 20005
202-638-5944
www.aaafoundation.org

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Abstract

Introduction

Crash involvement by 16- and 17-year-old drivers has decreased substantially over the past 15 years. This is largely due to the widespread adoption of Graduated Driver Licensing (GDL) programs and to the Great Recession, which substantially reduced driving by young teenagers. However, with one exception—New Jersey—GDL systems apply only to new drivers younger than 18, and crash reductions have been smaller among older teenage drivers. A recent study estimated that one third of new young drivers do not obtain a license to drive unsupervised until age 18 or later. Historically, studies of novice drivers in the United States have focused on drivers ages 17 and younger; many have only studied 16-year-olds. Individuals who do not begin driving until age 18 or older have rarely been studied in the U.S. The purpose of this study was to examine the crash involvement of newly licensed young drivers up through age 20 in two states—California and North Carolina—for their first three years of unsupervised driving, to determine how crash rates of these novices are related to the age at which they began driving. This was done before and after each state's GDL system was introduced.

Methods

Crash involvement during the first three years of licensed driving among drivers who were first licensed to drive unsupervised between May 1, 1997 and December 31, 2004 in California and between January 1, 1996 and December 31, 2004 in North Carolina were examined. Crashes occurring after December 31, 2007 were not included, to avoid possible bias associated with the deep economic recession that ensued. The main outcome measures were the proportion of drivers who remained crash free for varying time periods (e.g., 6 months, 12 months, etc.) after they were licensed. These measures were analyzed in relation to the age at which drivers were first licensed. Separate analyses were conducted for all crashes and for crashes that resulted in a reported injury.

Results

Before the implementation of GDL, the youngest drivers (licensed at age 16) consistently were the most likely to be involved in crashes both immediately after licensing and cumulatively over their first three years of driving. Licensing at older ages generally was associated with progressively lower crash incidence rates. In both states, new drivers licensed at age 16 under GDL were less likely to be involved in a crash than 16-year-olds licensed before GDL; pre- vs. post-GDL differences in crash rates of those licensed at ages 17 and older were negligible. New drivers licensed at ages 16, 17, and 18 after the implementation of GDL had similar crash incidence rates during their first year of unsupervised driving, but those licensed at ages 19 and older were less likely to be involved in a crash. A notable exception to this pattern was involvement in injury crashes: drivers licensed at age 18 were more likely than drivers licensed at any other age (younger or older) to be involved in a crash resulting in an injury during their first year of licensed driving. The reasons for this are unclear.

Conclusions

Initial crash rates and their trajectory during the first three years of licensed driving generally are inversely proportional to age at licensing. Following introduction of GDL, however, individuals licensed at ages 16, 17, and 18 had similar incidence of crash involvement for their first several months of driving. Individuals licensed at age 18 improved more quickly, however, and were involved in fewer crashes in their second and third years of driving. The observed relationship between age at licensure and subsequent crash involvement is not necessarily the result of increasing age or maturity; other studies have shown that individuals licensed at younger versus older ages differ in many ways besides age. Finally, given the minimal effects of GDL observed for individuals licensed at age 17 in both states, as well as the findings from several other studies showing a lesser effect of GDL on 17-year-olds, it is not clear what effect could be expected from extending the GDL provisions presently in effect for 16- and 17-year-olds to older novice drivers. The high first-year incidence of injury crashes among individuals licensed at age 18 suggests a potentially important phenomenon that warrants further research.

Introduction

During the past 15 years, motor vehicle crashes involving teen drivers have decreased dramatically, along with the resulting deaths, injuries and associated costs (NHTSA, CDC, Williams, 2014). This progress has been spurred mainly by the implementation of graduated driver licensing (GDL) systems. GDL is an approach to licensing based on the knowledge that learning of complex tasks – like driving – improves dramatically with experience, but takes time (Waller, 2003). Accordingly, GDL systems introduce novices to driving in a series of stages that are designed to provide extensive practical experience under conditions that minimize the risk of crashing attendant to inexperience as new drivers acquire experience (Foss, 2007). Although GDL has almost without exception led to dramatic decreases in crashes among the youngest novice drivers (Foss et al., 2001; Shope et al., 2001; Shope, 2007; Williams & Shults, 2010; Williams, Tefft & Grabowski, 2012), a few relatively recent studies have suggested that GDL may be producing some unintended consequences as well, and that some novice driver crash risks may be widely misunderstood as the result of limitations of earlier studies (Foss et al., 2011). Two national studies, along with one conducted in California, suggest that GDL as implemented in the United States may be contributing to an increase in fatal crash involvement rates of older teens (Masten, Foss & Marshall, 2011; Males, 2007; Fell & Romano, 2013). Because U.S. GDL systems almost exclusively apply only to drivers younger than 18, some researchers speculate the apparent increase in fatal crash involvement among older teen drivers is due to teens voluntarily waiting until age 18 to obtain a license to avoid having to go through the GDL process. If this has been the case, it would have yielded a cohort of newly licensed 18-year-olds who have little-to-no driving experience and yet are exempt from the protective limits that GDL provides by limiting exposure to risky driving conditions for novices. More recent studies prompted by this troubling possibility have not generally found evidence either of an increase in crashes, or of a notable increase in licensing, among 18-year-olds following introduction of GDL (Foss, 2013; Ehsani, Bingham & Shope, 2014; Thompson, 2013, Zhu et al., 2014).

Neither the extent of, nor the reasons for, teens waiting beyond the earliest possible age to obtain a license are completely clear. But it has long been the case that older novice drivers (new drivers licensed after their 18th birthday) are far more common than is widely assumed. A recent AAA Foundation study estimated, from a national survey, that only slightly more than half of young people nationwide obtained a license before turning 18 (Tefft, Williams & Grabowski, 2014). Tefft et al. also report that GDL is rarely named by teens as a reason for waiting beyond the earliest allowable age to obtain a license.

The fact that a substantial proportion of teens do not obtain a license before age 18, regardless of whether this is a new development or what the reasons are, means that many young novice drivers in the U.S. begin driving without the substantial practice under relatively safe conditions that GDL was designed to encourage. This has led many to suggest that U.S. GDL programs should apply to all drivers or at least to a broader age range of young novice drivers, emulating the approach to GDL in other countries.

In the U.S. only New Jersey applies the full GDL process to new drivers aged 18 or older, whereas graduated licensing systems in Canada, Australia and New Zealand generally apply to a wider age range, covering all novices or at least those up to age 25 in most jurisdictions. Only Connecticut, Maryland, and Maine apply any GDL-like requirements to

new drivers past their 18th birthday. Most available research evidence relating to this matter is only tangentially relevant, not focusing directly on questions either of whether U.S. GDL systems create greater risks for 18-year-old novices, or how age at first licensure during the teenage years is related to subsequent crash experience.

One important question that remains largely unaddressed is whether crash rates—especially during the first few months and years of driving—differ significantly as a function of the age at which a person begins driving. In the absence of evidence, the logic of some policymakers has been that by age 18, teens are sufficiently mature that they do not need the extensive training to begin driving that applies to 15-17-year-olds. If 18-year-olds are sufficiently accomplished when they begin driving without the training provided by GDL, then there is little need to extend its coverage to older ages. Previous studies from other countries suggest that there are substantial safety differences between drivers licensed at age 16 vs. those licensed much later (e.g., in their mid- to late-twenties and beyond; cf., Twisk & Stacey, 2007). Studies in a few Canadian provinces have examined differences in crash rates among teens licensed at different ages, finding higher rates among those licensed at 16, but few notable differences between 17-, 18-, and 19-year-olds. Virtually all studies of the association between age at licensure and crash rates were conducted before the implementation of GDL. Almost none of these studies were done in the U.S. Many were done two decades or more ago, when driving conditions were different and the complications arising from the potentially distracting effects of modern electronic technologies did not exist. Hence, they may not be generalizable to the young novice driver population of today. Accordingly, more recent information, from U.S. jurisdictions, reflecting the conditions that hold for young novice drivers licensed under GDL systems would shed useful additional light on this issue.

The goal of the present study was to examine crash rates among newly licensed young drivers, for their first three years of unsupervised driving following licensure, in relation to the age at which they first obtained their license to drive solo (unsupervised). Because of the dramatic differences in the licensing process prior to GDL, we addressed this question both before and after GDL was implemented in two U.S. states whose populations, driving conditions and licensing systems are quite different. To do this we conducted survival analyses (measuring time from initial licensure to first reported crash) for beginning drivers ranging in age from 18 to 54, in both California and North Carolina. We opted to conduct survival analyses, examining time to first crash by novices who began driving at different ages, rather than attempting to directly examine crash rates per licensed driver, because of the substantial complexities involved in estimating the number of licensed drivers of a particular age with a particular amount of driving experience at any point in time.

Method

Data Source and Coding Procedures

California: A 10 percent random sample of all persons ages 16 to 54 who obtained a California non-commercial driver license allowing solo[1] (unsupervised) driving from May 1, 1997[2] to December 31, 2004 was extracted from the licensing database of the California Department of Motor Vehicles (DMV). Drivers with evidence of prior licensure in another jurisdiction were excluded from the sample, because the goal was to identify true novices who did not have prior solo driving experience. Those who subsequently obtained commercial licenses were also excluded, because original license data elements in the CA DMV database are overwritten for such drivers. The sampling timeframe captured samples of drivers licensed both before and after the California GDL program was implemented. The California GDL system is described in Appendix A. Although GDL began July 1, 1998, no driver under age 18 who obtained a license to drive solo before January 1, 1999 could have been licensed through the GDL program (because of the new requirement of a 6-month learner period). Hence, novices (of all ages) licensed from May 1, 1997 until December 31, 1998 were classified as being in the pre-GDL cohort, and those licensed from January 1, 1999 to December 31, 2004 were classified as being in the GDL cohort. The post-GDL study enrollment period was terminated at the end of 2004 in order for all novice drivers to have at least three years of post-licensure driving (hence exposure to crashing) before the beginning of the broad and dramatic U.S. economic decline, which reduced both licensure and driving exposure differentially among drivers of different ages (Longthorne, Subramanian, & Chen, 2010; Williams, 2014). The final sample consisted of 517,440 novice drivers; the age at which they obtained their license is summarized below (Table 1). Just under a quarter (22%) of these individuals were licensed prior to implementation of GDL.

[1]The term "solo driving" can be confusing since most GDL systems address whether a novice is allowed to drive with passengers. Here, we use the term "solo licensure" specifically to refer to a license that allows the driver to drive without adult supervision, regardless of any limit or lack thereof on the number of passengers the driver may be allowed to transport. We examined a sample, rather than the full novice driver population, because the analyses conducted are computer resource intensive and a sample is more than adequate to provide a clear and precise picture of novice drivers in California, which numbered more than 5 million during the study period.

[2]Most crash records prior to May 1997 had been purged from the CA DMV database, as part of normal DMV data management procedures, by the time data were extracted for this analysis.

Table 1. Age distribution of novice drivers in the California sample, initially licensed from May 1, 1997 to December 31, 2004

	Pre-GDL		GDL		Total	
Age at licensure	N	%	N	%	N	%
16	27,039	24%	85,210	21%	112,249	22%
17	9,266	8%	32,780	8%	42,046	8%
18	12,522	11%	62,195	15%	74,717	14%
19	5,960	5%	25,532	6%	31,492	6%
20	4,211	4%	16,963	4%	21,174	4%
21-24	12,741	11%	49,412	12%	62,153	12%
25-54	40,109	36%	133,500	33%	173,609	34%
Total	**111,848**	**100%**	**405,592**	**100%**	**517,440**	**100%**

Crashes during the first 3 years of licensure (ranging from May 1, 1997 to December 31, 2007) were also extracted for each novice driver from the California DMV database. This system contains data on all motor vehicle crashes in California reported by law enforcement, insurance companies, and drivers. Crashes are required to be reported to the DMV if they involve an injury, death, or at least $750 in property damage. Those involving severe property damage or more than minor injuries were typically investigated and reported to DMV by law enforcement, who also made a determination of whether each involved driver was at least partially at-fault for the crash. Three different "survival" (time-to-event) measures were created, representing the time from solo licensure to the first involvement in crashes of the following types:

(a) Crash of any severity (including property-damage only),
(b) Crash involving a fatality or injury to any involved person (a proxy for more serious crashes),
(c) At-fault crash (in which the novice driver was judged to be at least partially at-fault for the crash).

North Carolina: All persons ages 16 to 54 who obtained a North Carolina non-commercial driver license allowing solo (unsupervised) driving from January 1, 1996 to December 31, 2004 were extracted from the licensing database of the North Carolina Division of Motor Vehicles (DMV). Drivers with evidence of prior licensure in another jurisdiction or who subsequently obtained commercial licenses were excluded. This timeframe captured samples of drivers licensed both before and after the North Carolina GDL program was implemented in December 1997. The North Carolina GDL system is described in Appendix B. No novice under age 18 who applied for a license starting December 1, 1997 would have been allowed to drive solo until December 1, 1998. Hence, for purposes of classifying the novices (of all ages) as having been licensed during the pre-GDL or GDL period, those licensed from January 1, 1996 until November 30, 1998 were classified as being in the pre-GDL cohort, and those licensed from December 1, 1998 to December 31, 2004 were classified as being in the GDL cohort. The final North Carolina sample consisted of 1,135,628 novice drivers; the age at which they obtained their license is summarized below

(Table 2). Just over a quarter (27%) of these individuals were licensed prior to implementation of GDL. The proportion of novices licensed in the GDL era is higher than in California because the North Carolina population was growing more rapidly during the study period.

Table 2. Age distribution of novice drivers in the North Carolina study sample, initially licensed from January 1, 1996 to December 31, 2004.

	Pre-GDL		GDL		Total	
Age at licensure	N	%	N	%	N	%
16	144,889	47%	297,168	36%	442,057	39%
17	21,795	7%	64,847	8%	86,642	8%
18	23,021	7%	96,579	12%	119,600	11%
19	13,624	4%	40,012	5%	53,636	5%
20	10,832	4%	31,366	4%	42,198	4%
21-24	31,624	10%	98,748	12%	130,372	11%
25-54	61,412	20%	199,711	24%	261,123	23%
Total	**307,197**	**100%**	**828,431**	**100%**	**1,135,628**	**100%**

Crashes during the first three years of licensure (ranging from January 1, 1996 to December 31, 2007) were also extracted for each novice driver from the DMV database, which contains information on all reported motor vehicle crashes in North Carolina. Crashes are required to be reported to the DMV if they involve an injury, death, or at least $1,000 in property damage. Unlike California there is no indication of driver fault in the crash report. For analysis, three different "survival" (time-to-event) measures were created, representing the time from solo licensure to the first involvement in crashes of the following types:

(a) Crash of any severity (including to property-damage only),
(b) Crash involving a fatality, injury or possible injury to any involved person (a proxy for more serious crashes),
(c) Property-damage only crashes

Analysis Method

The cumulative probabilities of crash-free survival during the three-year period following novice solo licensure were determined by using Kaplan-Meier product limit estimates (Kaplan & Meier, 1958), stratified by cohort (pre-GDL vs. GDL) and age at licensure (16, 17, 18, 19, 20, 21-24, and 25-54 years). The crude survival curves for each Crash type were compared for each age group between the pre-GDL and GDL cohorts using log-rank tests (Kleinbaum & Klein, 2012).

Crude Cox proportional hazards models were first used to estimate unadjusted hazard ratios for each age group, comparing crash incidence between the GDL and pre-GDL

cohorts.[3] Separate models were estimated for each Crash type (i.e., any crash, fatal/injury crash, at-fault crash, etc.). These hazard ratios were then re-estimated using proportional hazards models adjusted for sex and month at licensure (to account for any seasonal differences). The hazard ratios from these crude and adjusted models represent the change in crash incidence for novices licensed after GDL was implemented relative to crash incidence for the same age cohort licensed prior to GDL.

Standard survival analysis using Cox proportional hazards regression assumes that the effect of an intervention (in this case, the introduction of a new approach to licensing) has a similar effect over time–the "proportional hazards" assumption. That is, for example, the assumption in this case would be that the crash likelihood for those licensed under GDL would be proportionately lower (perhaps 10%) than for those licensed under the previous system at all time points after the intervention. If this assumption is incorrect, then the model parameters estimated from the analysis can be misleading. To assess the tenability of the proportional hazards assumption we conducted visual reviews of stratified log-negative-log survival plots and examined Cohort x Time interaction terms in the models. Both categorical and continuous time interactions were explored.

For most Crash types and age groups the proportional hazards assumption was not met. Consequently, we conducted the analyses using continuous Cohort x Time interaction models (i.e., extended Cox models), which do not assume a proportional hazard reduction is produced by the intervention. Hazard ratios comparing the cohorts after six-month increments in experience subsequent to licensure (from 6 months to 3 years) are presented to show the changes over time in the hazard ratios of post- vs pre-GDL licensees. All analyses were conducted using SAS version 9.3.

Results

California Survival Analysis Results

Description of California Cohorts: The percentages of novices experiencing at least one crash during the three years after they were licensed to drive solo decreased as a function of age at licensure. Nearly a third of novices licensed at age 16 or 17 crashed during their first three years driving during the period before as well as after GDL was in place (Table 3). Three-year crash rates were nearly as high for those licensed at age 18, then dropped off notably among those licensed at age 19 and older. Moreover, rates were successively lower at increasingly higher ages of licensure.

Across the various crash types examined (total, fatal/injury, and at-fault) a slightly lower percentage of 16-year-old novices had at least one crash during their first three years driving after GDL was implemented than before its adoption. For all other ages the proportion who crashed within three years either remained stable or increased slightly during the post-GDL period. It is noteworthy that among 25-54-year-olds crashes were somewhat higher after GDL

[3]In survival analysis, hazard refers to the slope of the survival curve over the time period studied. The hazard ratio in this case indicates whether the slope of the curve during the first 3 years of licensure to drive without adult supervision is more or less steep for individuals licensed after GDL compared to those licensed under the previous system. A hazard ratio less than one indicates that on average it took longer for individuals licensed under GDL than it did for persons licensed under the previous system to experience their first crash.

was implemented. This suggests the existence of a historical trend that biases hazard ratios against finding crash incidence to be lower following implementation of GDL. Ideally, statistical adjustments for this trend could be made, but we were unable to find a satisfactory way to do so. Adjustments that were attempted, for example, by standardizing younger novice crash rates to those of older novices, introduced analytic artifacts and produced results that made little sense conceptually. Consequently, we simply present findings for the unadjusted analyses, with the caution that findings need to be interpreted carefully, keeping the apparent general increase in overall crash rates in mind.

During the three years following solo licensure, the total crash incidence rate for novices licensed at age 16 before GDL declined slightly from 12,831 to 12,534 per 100,000 person-years for those licensed after GDL was implemented (Table 4). Total crash rates increased for all other age groups. This same general pattern holds for each of the crash types examined, with declines among 16-year-olds, but increases among all other ages following GDL.

California Kaplan-Meier and Crude Cox Survival Analyses: As an example of the Kaplan-Meier analyses, the crude (unadjusted for covariates) total crash survival curves comparing novices licensed before and after GDL was implemented in California are shown for 16-year-olds in Figure 1. The remaining survival curves – for older age groups and for analyses of crash type subsets – are not shown to conserve space. During the three years after novice solo licensure, a marginally reliable difference in crash-free survival was found between the 16-year-old cohorts ($p = .0616$), reflecting a lower overall crash incidence for those licensed after GDL. Among 17-, 18-, 21–24-, and 25–54-year-old novices, those licensed after GDL had higher total crash incidence during the three years after solo licensure than did those licensed before GDL was implemented (all *p-value*s < .05). No differences in total crash survival were found for 19- and 20-year-old novices (*p*s > .05). These findings are generally consistent with those indicated by the crude hazard ratios shown in Table 4, suggesting lower total crash rates among 16-year-old novices licensed after GDL, but higher total crash rates among all other age groups after GDL. Because GDL did not apply to older novices, the greater crash rates for those licensed after GDL should be interpreted as reflecting an increasingly risky overall driving climate, rather than an effect – either direct or indirect – of moving to a GDL system.

The Kaplan-Meier analyses of fatal/injury and at-fault crashes showed results quite similar to those for total crashes in that only 16-year-old driver crashes decreased. This effect was slightly greater for crashes involving a fatality or injury. These results also parallel those shown in Table 4. In sum, the analyses of varying crash severity subsets consistently shows that crash rates for drivers licensed at age 16 were lower after GDL than beforehand, but there was little or no evidence of crash reductions for drivers licensed at 17 or older.

Additional analyses were conducted to adjust for differences in the sex composition and calendar month licensed between the pre- and post-GDL cohorts and to statistically adjust for the historical increase in crash risk, as reflected by rates for 25-54-year-old novices. These results did not materially alter the patterns shown in Table 4 and are not shown here. They consistently show that the cohort of individuals licensed at age16 was the only one with a notably reduced crash rate following implementation of GDL. This was most clearly exhibited among fatal/injury crashes and at-fault crashes and was minimally apparent among all crashes (suggesting little effect on minor, property damage-only crashes).

Table 3. Cumulative Percentage of California Novices Involved in One or More Total, Fatal/Injury, and At-Fault Crash during the 3 Years after Novice Solo Licensure by GDL Cohort (Pre-GDL vs. GDL) and Age at Solo Licensure

Crash type Age at licensure	Pre-GDL cohort						GDL cohort					
	6 months	12 mos.	18 mos.	24 mos.	30 mos.	36 mos.	6 months	12 mos.	18 mos.	24 mos.	30 mos.	36 mos.
Total crashes												
16	8.0	13.9	19.2	23.9	28.0	31.5	7.6	14.0	19.4	24.0	27.7	30.8
17	7.5	13.0	18.2	22.6	26.7	29.8	7.7	14.5	20.0	24.3	27.9	30.8
18	7.3	12.5	17.4	21.3	24.8	28.0	8.3	14.2	18.9	22.9	26.3	29.2
19	6.3	10.8	15.1	19.0	22.2	25.2	6.7	12.2	16.3	19.7	22.8	25.5
20	5.8	10.1	14.0	17.5	20.1	22.9	6.2	10.8	14.8	18.2	21.3	23.8
21-24	3.9	7.7	10.7	13.4	15.9	18.3	4.8	8.8	12.1	15.0	17.6	19.8
25-54	3.0	5.7	8.3	10.5	12.7	14.7	3.1	6.1	8.6	10.9	13.2	15.2
Fatal/injury crashes												
16	2.2	4.0	5.6	7.1	8.5	9.8	1.9	3.8	5.3	6.7	7.9	9.0
17	2.2	3.9	5.5	7.0	8.5	9.8	2.1	4.2	5.9	7.4	8.7	9.8
18	2.4	4.1	5.8	7.3	8.4	9.7	2.6	4.5	6.2	7.7	9.0	10.1
19	2.1	3.8	5.3	6.6	7.8	9.0	2.1	4.0	5.3	6.6	7.7	8.7
20	1.7	3.0	4.5	5.7	6.7	7.6	1.9	3.4	4.7	5.9	7.0	8.0
21-24	1.2	2.3	3.3	4.3	5.0	5.8	1.4	2.6	3.7	4.7	5.5	6.3
25-54	0.8	1.6	2.3	3.0	3.6	4.2	0.9	1.7	2.5	3.2	3.9	4.5
At-fault crashes												
16	3.9	6.4	8.6	10.6	12.5	14.1	3.3	6.0	8.3	10.3	11.9	13.4
17	3.3	5.7	8.1	10.1	11.8	13.3	3.5	6.7	9.2	11.2	12.9	14.2
18	3.5	6.1	8.2	10.1	11.5	12.9	4.1	6.8	9.1	11.0	12.7	14.1
19	2.7	4.7	6.6	8.3	9.5	11.0	3.1	5.5	7.4	9.1	10.4	11.6
20	2.5	4.4	6.0	7.4	8.5	9.7	2.8	4.7	6.4	8.0	9.4	10.6
21-24	1.5	3.0	4.1	5.0	5.9	6.9	2.0	3.6	4.9	6.0	7.0	7.8
25-54	0.9	1.8	2.6	3.2	3.9	4.5	1.1	2.1	2.9	3.6	4.4	5.0

Note. GDL indicates graduated driver licensing.

Table 4. Total, Fatal/Injury, and At-Fault Crashes per 100,000 Person-years during the 3 Years after Novice Solo Licensure by GDL Cohort (Pre-GDL vs. GDL) and Age at Solo Licensure

Crash type Age at licensure	Pre-GDL cohort			GDL cohort			
	Crashes	Person-years	Rate	Crashes	Person-years	Rate	Crude Hazard ratio[a]
Total crashes							
16	8,517	66,377	12,831	26,242	209,371	12,534	0.98
17	2,758	23,004	11,989	10,097	80,298	12,574	1.05
18	3,505	31,433	11,151	18,151	153,747	11,806	1.06
19	1,499	15,307	9,793	6,521	64,997	10,033	1.02
20	965	10,960	8,805	4,040	43,806	9,222	1.05
21-24	2,333	34,338	6,794	9,800	131,345	7,461	1.10
25-54	5,883	110,797	5,310	20,272	367,429	5,517	1.04
Fatal/injury crashes							
16	2,646	76,739	3,448	7,637	242,748	3,146	0.91
17	904	26,310	3,436	3,214	92,868	3,461	1.01
18	1,219	35,501	3,434	6,263	175,685	3,565	1.04
19	539	16,983	3,174	2,218	72,772	3,048	0.96
20	322	12,091	2,663	1,364	48,598	2,807	1.05
21-24	738	37,014	1,994	3,122	143,019	2,183	1.09
25-54	1,694	117,609	1,440	6,062	390,790	1,551	1.08
At-fault crashes							
16	3,808	74,468	5,114	11,384	235,708	4,830	0.94
17	1,235	25,675	4,810	4,671	90,016	5,189	1.08
18	1,616	34,681	4,660	8,771	170,726	5,137	1.10
19	656	16,763	3,913	2,966	71,300	4,160	1.06
20	408	11,922	3,422	1,795	47,775	3,757	1.10
21-24	873	36,763	2,375	3,867	141,451	2,734	1.15
25-54	1,819	117,384	1,550	6,680	389,438	1,715	1.11

Note. Rates are shown per 100,000 person-years. [a]The referent group for these hazard ratios is novices of the same age during the pre-GDL period.

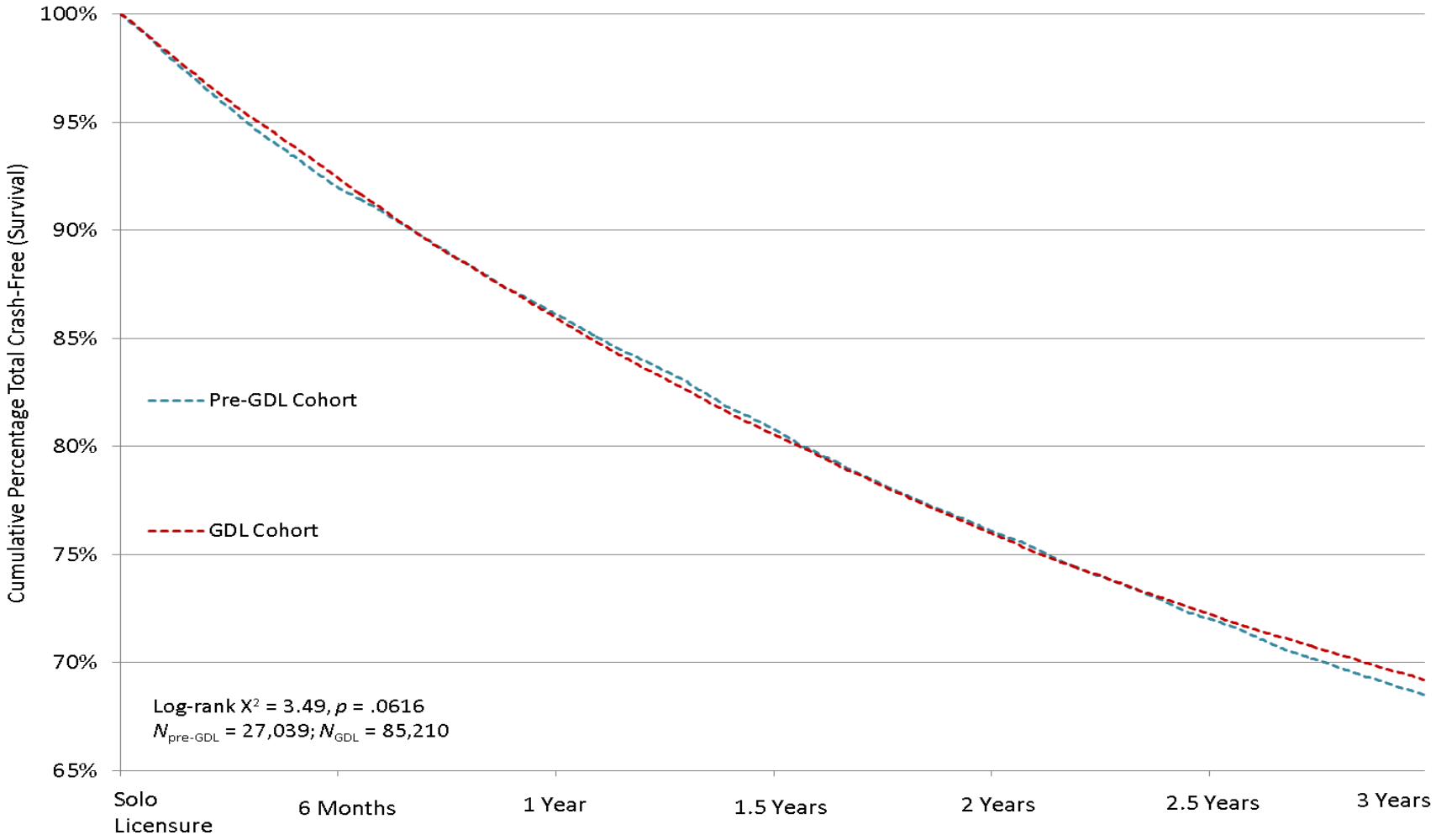

Figure 1. Survival for total crashes (% with no crash) during the 3 years after solo licensure for novices licensed at age 16, before and after the graduated driver licensing (GDL) program was implemented in California.

California Crash Survival by Age at Solo Licensure: The following analyses reflect the same approach used to compare pre- and post-GDL crash incidence rates above, but differ in aim. The goal here is to determine how crash incidence differs by age at which drivers obtained a license to drive without supervision (solo licensure), and further to examine how these relationships varied as a function of time licensed. Because GDL clearly influenced the crash incidence of 16-year-olds, the results are presented separately for novices licensed before GDL was implemented and those licensed under the GDL system. These analyses are adjusted for sex and month of licensure, which differed somewhat for pre- and post-GDL licensees, and to provide hazard ratios that can be compared across ages, the crash incidence for each age group of novices under age 25 is compared to that for 25-54-year-old novices who were licensed contemporaneously.

California Total Crash Survival by Age at Solo Licensure Adjusted for Sex and Month of Licensure: Total crash incidence was generally lower as age of initial novice solo licensure increased (Table 5). This pattern was highly similar before and after the California GDL program was implemented. Total crash incidence was highest for all age groups during their first six months of solo driving and decreased over the next 30 months of licensure for all age cohorts, although even after three years of licensure the incidence of all novices under age 25 remained higher than that for age 25-54-year-old novices. Moreover, the early difference in crash incidence increased as drivers were licensed longer (see Figure 2). Log-rank tests indicate that the survival curves of the different age licensees differ to a statistically significant degree ($p < .0001$).

Although the relative order of crash incidence rates by age at licensing was similar before and after GDL was implemented, there was a somewhat steeper decline in young novice rates relative to 25-54-year-olds after GDL. The hazard ratios of 16-20-year-old drivers declined by an average of 22 percent between six months and 36 months post-licensure prior to GDL, and by 30 percent after GDL was implemented. That is, drivers licensed at younger ages made greater improvements than 25-54-year-old drivers, and this was somewhat more pronounced after GDL was implemented.

In addition to the apparent greater decline in crash incidence with experience after GDL was implemented, the other noteworthy change is that being licensed under GDL brought the hazard ratios of both 16- and 17-year-olds closer to those of 18-year-old drivers, essentially removing the small but clear age differences that existed before GDL (Figures 2 and 3). The ordering of crash incidence was perfectly aligned (inversely) with age at licensure before GDL; after GDL was in place the hazard ratios for persons licensed at age 16, 17 and 18 were quite similar during the initial months of driving. However, by the time drivers had 18 months experience, they had separated and the youngest drivers again had the highest hazard ratios as the age-related differences that were observed among teen novices prior to GDL partially re-emerged.

Table 5. Adjusted Cox Proportional Hazards Survival Results for Total Crashes during the 3 Years after Solo Licensure Comparing Younger Novices to Those Ages 25-54-Years-Old, Before and After the California GDL Program was Implemented

Age at Licensure	Time after solo licensure: adjusted hazard ratio (95% CI)					
	6 months	12 mos.	18 mos.	24 mos.	30 mos.	36 mos.
Pre-GDL						
16	**2.77** (2.59-2.96)	**2.66** (2.51-2.83)	**2.56** (2.41-2.72)	**2.46** (2.31-2.62)	**2.36** (2.20-2.55)	**2.27** (2.08-2.48)
17	**2.47** (2.24-2.71)	**2.35** (2.15-2.56)	**2.24** (2.05-2.44)	**2.13** (1.94-2.34)	**2.03** (1.82-2.26)	**1.93** (1.71-2.19)
18	**2.36** (2.18-2.56)	**2.23** (2.07-2.40)	**2.10** (1.95-2.26)	**1.98** (1.83-2.14)	**1.87** (1.70-2.05)	**1.76** (1.58-1.96)
19	**1.99** (1.78-2.24)	**1.91** (1.72-2.12)	**1.83** (1.65-2.03)	**1.75** (1.56-1.96)	**1.68** (1.47-1.91)	**1.60** (1.38-1.87)
20	**1.93** (1.68-2.22)	**1.82** (1.6-2.07)	**1.71** (1.51-1.95)	**1.61** (1.40-1.85)	**1.52** (1.29-1.78)	**1.43** (1.19-1.72)
21-24	**1.42** (1.28-1.56)	**1.38** (1.27-1.51)	**1.35** (1.24-1.48)	**1.32** (1.20-1.45)	**1.29** (1.16-1.44)	**1.26** (1.11-1.43)
GDL						
16	**2.65** (2.51-2.79)	**2.51** (2.38-2.63)	**2.37** (2.26-2.49)	**2.24** (2.13-2.36)	**2.12** (2.01-2.24)	**2.01** (1.89-2.14)
17	**2.55** (2.36-2.75)	**2.37** (2.2-2.55)	**2.21** (2.05-2.37)	**2.05** (1.90-2.21)	**1.91** (1.76-2.07)	**1.78** (1.63-1.94)
18	**2.50** (2.35-2.66)	**2.28** (2.15-2.42)	**2.08** (1.96-2.21)	**1.90** (1.79-2.02)	**1.74** (1.63-1.86)	**1.59** (1.48-1.70)
19	**2.06** (1.88-2.25)	**1.90** (1.74-2.08)	**1.76** (1.61-1.92)	**1.63** (1.48-1.78)	**1.50** (1.36-1.65)	**1.39** (1.25-1.54)
20	**1.94** (1.74-2.17)	**1.82** (1.64-2.03)	**1.71** (1.53-1.90)	**1.60** (1.43-1.79)	**1.50** (1.33-1.69)	**1.41** (1.24-1.60)
21-24	**1.56** (1.45-1.69)	**1.48** (1.38-1.59)	**1.40** (1.31-1.51)	**1.33** (1.23-1.44)	**1.26** (1.17-1.37)	**1.20** (1.10-1.31)

Note. 95% CI indicates 95% confidence interval for the adjusted hazard ratio. The hazard ratios are adjusted for sex, month of licensure, and historical changes in crash incidence. The referent group for these hazard ratios is 25-54-year-old novices during the same pre or post GDL period. Boldface indicates pre- vs post-GDL hazard ratios were different, to a statistically reliable degree at $\alpha = .05$.

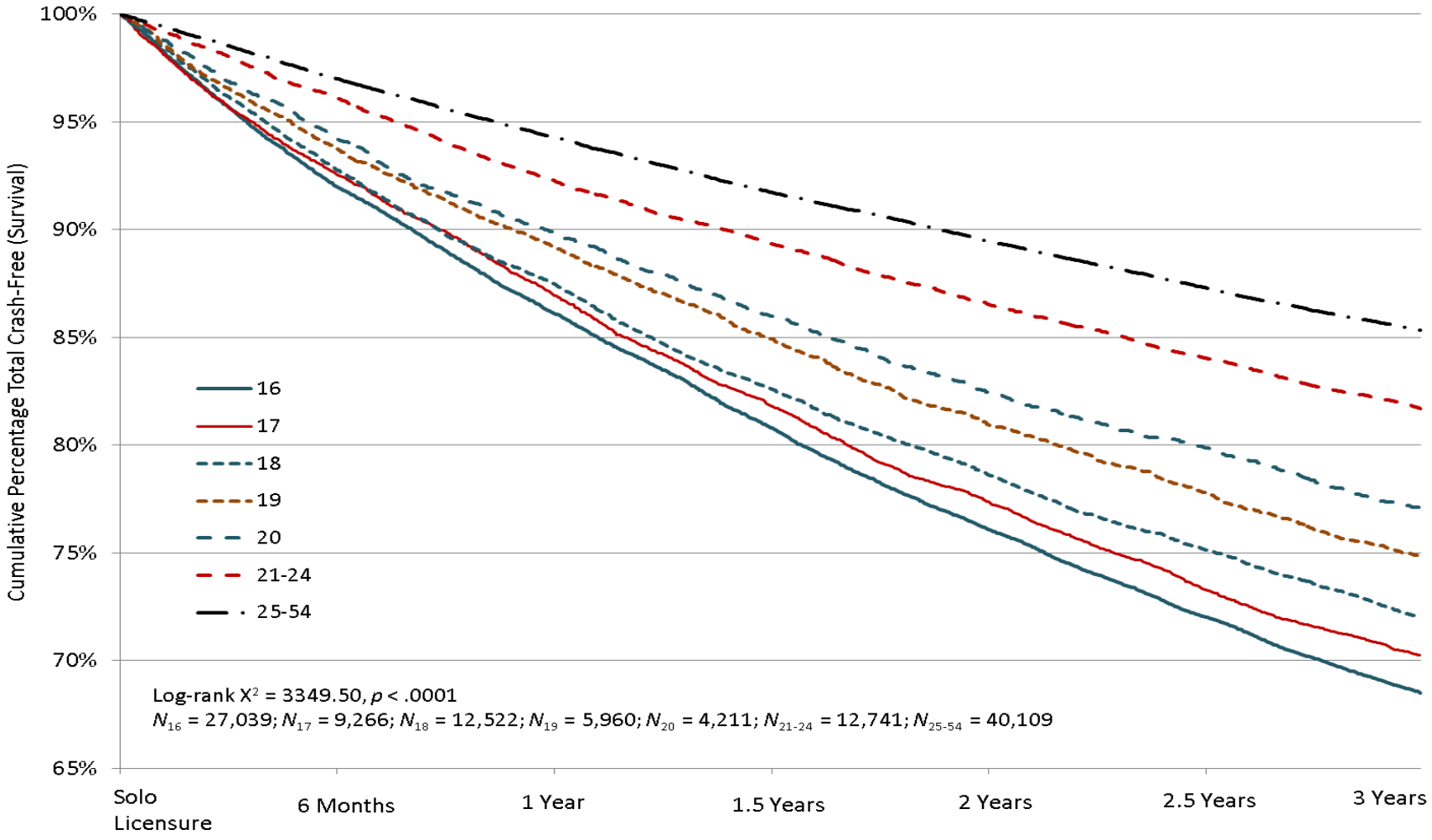

Figure 2. Crash-free survival (time to first crash of any severity) during the 3 years after solo licensure for novices licensed at different ages before the graduated driver licensing (GDL) program was implemented in California.

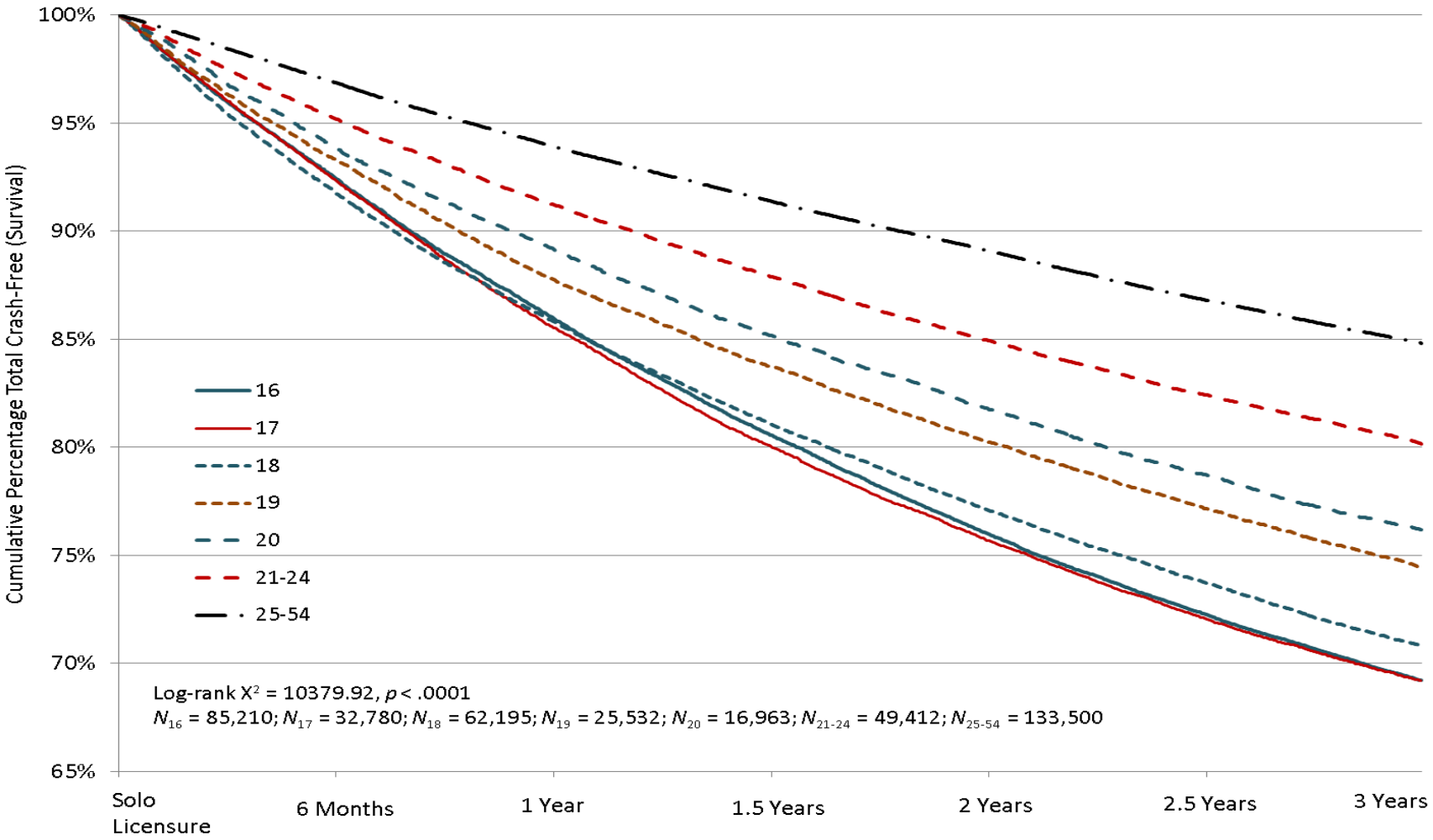

Figure 3. Crash-free survival (time to first crash of any severity) during the 3 years after solo licensure for novices licensed at different ages after the graduated driver licensing (GDL) program was implemented in California.

California Fatal/Injury and At-fault Crash Survival by Age at Solo Licensure Adjusted for Sex and Month of Licensure: Fatal/injury crash incidence was also generally lower as a function of older age of novice solo licensure (Table 6), although the highest point estimates during the first year of solo licensure were actually among 18-year-old novices, both before and after the California GDL program was implemented. Like total crash rates, fatal/injury crash incidence also decreased as a function of time licensed.

It appears that being licensed through the GDL system was particularly beneficial in reducing 16- and 17-year-old fatal/injury crashes (Table 6). Although their crash incidence was somewhat lower than 18-year-olds prior to GDL, it dropped markedly among those licensed after GDL. But as with total crashes, the incidence rates of 16- and 17-year-olds eventually match those of 18-year-olds, as the latter made greater progress in reducing crashes during the first three years of licensure. The pattern for at-fault crashes (Table 7) falls in between that of total and fatal/injury crashes.

In sum, although the details of the levels and overall trajectories differ somewhat, drivers licensed at age 16 or 17 through the California GDL system appear to benefit from the process, but the effect lasts only for a year or two, by which point those licensed at 18 – whose initial crash rates were higher than those of younger licensees – have made more progress than younger drivers in reducing their crashes.

North Carolina Survival Analysis Results

Description of North Carolina Cohorts: As was seen in the California data, crash incidence rates for North Carolina novices were successively lower at increasingly higher ages of initial licensure. However, following implementation of GDL the differences in crash rates between those who began driving at 16, 17, and 18 were compressed to the point they were largely indistinguishable, especially during the initial 18 months of unsupervised driving (Table 8). Unlike California, overall crash rates did not increase among older novices in the years following implementation of GDL. In fact, the percentage of novices who crashed in their first three years declined ($p < .05$) for those who began at any age except 17 and 19. Fatal/injury crashes declined following GDL in all age groups.

The lower crash rates after GDL was implemented among 25-54-year-olds indicate historical changes that, in this case, would bias the hazard ratios towards finding incidence to be lower during the GDL period among younger novices. Again this suggests the importance of standardizing the change in crashes among younger novices to that observed among 25-54-year-olds, to provide a clearer picture of the effects of GDL.

Table 6. Adjusted Cox Proportional Hazards Survival Results for Fatal/Injury Crashes during the 3 Years after Solo Licensure Comparing Younger Novices to Those Ages 25-54-Years-Old, Before and After the California GDL Program was Implemented

Age at licensure	Time after solo licensure adjusted hazard ratio (95% CI) 6 months	12 mos.	18 mos.	24 mos.	30 mos.	36 mos.
			Pre-GDL			
16	**2.68** (2.37-3.03)	**2.62** (2.34-2.92)	**2.55** (2.29-2.85)	**2.49** (2.22-2.80)	**2.43** (2.13-2.78)	**2.38** (2.03-2.78)
17	**2.59** (2.19-3.07)	**2.54** (2.18-2.96)	**2.50** (2.15-2.90)	**2.45** (2.09-2.88)	**2.41** (2.01-2.89)	**2.36** (1.91-2.93)
18	**2.82** (2.45-3.25)	**2.68** (2.37-3.04)	**2.55** (2.26-2.88)	**2.43** (2.12-2.77)	**2.31** (1.97-2.70)	**2.19** (1.82-2.64)
19	**2.25** (1.84-2.75)	**2.18** (1.82-2.61)	**2.11** (1.77-2.52)	**2.05** (1.69-2.48)	**1.98** (1.59-2.47)	**1.92** (1.49-2.48)
20	**1.97** (1.54-2.53)	**1.88** (1.50-2.36)	**1.80** (1.44-2.25)	**1.72** (1.35-2.18)	**1.64** (1.25-2.16)	**1.57** (1.14-2.16)
21-24	**1.31** (1.09-1.57)	**1.28** (1.09-1.51)	**1.26** (1.07-1.47)	**1.23** (1.04-1.46)	1.21 (0.99-1.47)	1.18 (0.94-1.49)
			GDL			
16	**2.37** (2.15-2.61)	**2.25** (2.06-2.47)	**2.15** (1.96-2.35)	**2.04** (1.86-2.24)	**1.94** (1.76-2.15)	**1.85** (1.66-2.06)
17	**2.59** (2.27-2.96)	**2.44** (2.15-2.78)	**2.31** (2.03-2.62)	**2.17** (1.91-2.48)	**2.05** (1.78-2.36)	**1.93** (1.66-2.25)
18	**2.84** (2.56-3.16)	**2.62** (2.37-2.89)	**2.41** (2.18-2.66)	**2.22** (2.00-2.46)	**2.04** (1.83-2.28)	**1.88** (1.66-2.12)
19	**2.15** (1.84-2.51)	**2.00** (1.72-2.32)	**1.85** (1.59-2.15)	**1.72** (1.47-2.01)	**1.59** (1.35-1.88)	**1.48** (1.24-1.77)
20	**1.94** (1.59-2.35)	**1.85** (1.53-2.23)	**1.76** (1.46-2.13)	**1.69** (1.39-2.04)	**1.61** (1.31-1.97)	**1.54** (1.24-1.91)
21-24	**1.39** (1.20-1.60)	**1.33** (1.16-1.52)	**1.27** (1.11-1.46)	**1.22** (1.06-1.40)	**1.17** (1.01-1.35)	1.12 (0.95-1.31)

Table 7. Adjusted Cox Proportional Hazards Survival Results for At-Fault Crashes during the 3 Years after Solo Licensure Comparing Younger Novices to Those Ages 25-54-Years-Old, Before and After the California GDL Program was Implemented.

Age at licensure	Time after solo licensure adjusted hazard ratio (95% CI) 6 months	12 mos.	18 mos.	24 mos.	30 mos.	36 mos.
			Pre-GDL			
16	**3.83** (3.43-4.27)	**3.57** (3.24-3.94)	**3.33** (3.02-3.67)	**3.11** (2.80-3.46)	**2.90** (2.57-3.28)	**2.71** (2.35-3.13)
17	**3.25** (2.80-3.77)	**3.08** (2.69-3.53)	**2.92** (2.56-3.34)	**2.77** (2.40-3.20)	**2.63** (2.22-3.10)	**2.49** (2.05-3.02)
18	**3.49** (3.08-3.96)	**3.17** (2.84-3.55)	**2.88** (2.58-3.22)	**2.62** (2.31-2.96)	**2.38** (2.06-2.75)	**2.16** (1.82-2.57)
19	**2.59** (2.16-3.10)	**2.48** (2.10-2.92)	**2.37** (2.02-2.78)	**2.26** (1.90-2.70)	**2.17** (1.77-2.65)	**2.07** (1.64-2.62)
20	**2.21** (1.77-2.77)	**2.05** (1.67-2.52)	**1.91** (1.55-2.33)	**1.77** (1.42-2.20)	**1.64** (1.27-2.11)	**1.52** (1.13-2.04)
21-24	**1.43** (1.21-1.69)	**1.39** (1.19-1.61)	**1.34** (1.16-1.56)	**1.30** (1.11-1.52)	**1.26** (1.05-1.51)	1.22 (0.99-1.51)
			GDL			
16	**3.13** (2.88-3.41)	**2.99** (2.76-3.24)	**2.85** (2.63-3.08)	**2.71** (2.50-2.95)	**2.59** (2.37-2.83)	**2.47** (2.24-2.72)
17	**3.18** (2.83-3.57)	**2.97** (2.65-3.32)	**2.77** (2.47-3.10)	**2.58** (2.30-2.90)	**2.41** (2.13-2.73)	**2.25** (1.96-2.58)
18	**3.37** (3.07-3.70)	**3.09** (2.83-3.38)	**2.84** (2.6-3.10)	**2.61** (2.38-2.86)	**2.39** (2.17-2.64)	**2.20** (1.97-2.45)
19	**2.58** (2.25-2.97)	**2.39** (2.09-2.74)	**2.22** (1.94-2.54)	**2.06** (1.79-2.36)	**1.91** (1.64-2.21)	**1.77** (1.51-2.07)
20	**2.07** (1.73-2.47)	**1.98** (1.67-2.36)	**1.90** (1.60-2.26)	**1.82** (1.53-2.17)	**1.74** (1.45-2.10)	**1.67** (1.37-2.04)
21-24	**1.56** (1.37-1.78)	**1.47** (1.30-1.66)	**1.38** (1.22-1.56)	**1.30** (1.14-1.48)	**1.22** (1.07-1.40)	1.15 (0.99-1.33)

Table 8. Cumulative Percentage of North Carolina Novices Involved in One or More Total, Fatal/Injury, and Property Damage-Only Crash during the 3 Years after Novice Solo Licensure by GDL Cohort (Pre-GDL vs. GDL) and Age at Solo Licensure

Crash type Age at licensure	Pre-GDL cohort						GDL cohort					
	6 months	12 mos.	18 mos.	24 mos.	30 mos.	36 mos.	6 months	12 mos.	18 mos.	24 mos.	30 mos.	36 mos.
Total crashes												
16	14.1	22.7	29.5	35.0	39.4	43.2	12.3	20.6	27.1	32.2	36.4	39.7
17	13.3	21.2	27.3	32.3	36.6	40.1	13.3	21.8	27.8	32.7	36.9	40.4
18	13.1	20.7	26.1	30.9	35.0	38.5	13.1	20.6	26.3	30.7	34.4	37.6
19	11.3	18.3	23.5	27.8	31.4	34.7	10.9	17.7	23.0	27.3	30.8	34.0
20	10.3	16.7	22.1	26.1	29.7	32.8	9.3	15.5	20.6	24.5	27.8	30.6
21-24	8.2	13.7	18.2	22.2	25.3	28.2	7.4	12.8	16.9	20.3	23.1	25.4
25-54	5.8	10.1	13.7	16.8	19.8	22.4	5.3	9.5	13.0	15.9	18.4	20.5
Fatal/injury crashes												
16	6.7	11.0	14.5	17.3	19.4	21.0	4.0	6.8	9.2	11.2	13.1	14.6
17	6.8	11.1	14.6	17.1	19.3	21.0	4.5	7.7	10.2	12.3	14.3	16.1
18	6.9	11.1	14.0	16.5	18.5	20.1	4.8	7.8	10.1	12.3	14.2	15.9
19	6.1	9.7	12.7	14.8	16.5	18.0	3.7	6.3	8.3	10.3	12.0	13.5
20	4.9	8.5	11.2	13.3	14.9	16.1	2.9	4.9	6.7	8.4	9.9	11.4
21-24	3.9	6.7	9.1	10.9	12.1	13.1	2.3	3.9	5.3	6.6	7.8	8.9
25-54	2.7	4.9	6.7	8.1	9.2	10.0	1.5	2.7	3.8	4.9	6.0	6.9
Property damage-only												
16	7.8	13.1	17.6	21.6	25.2	28.5	8.5	14.7	19.7	23.7	27.0	29.7
17	6.9	11.5	15.3	18.8	22.0	25.0	9.1	15.2	19.7	23.5	26.8	29.5
18	6.8	11.2	14.7	18.2	21.4	24.5	8.9	14.2	18.5	21.8	24.6	27.1
19	5.8	9.7	12.9	16.0	18.8	21.7	7.5	12.5	16.5	19.6	22.3	24.8
20	5.8	9.4	12.7	15.6	18.4	21.2	6.7	11.4	15.2	18.2	20.7	22.9
21-24	4.6	7.7	10.6	13.3	15.9	18.5	5.4	9.5	12.8	15.4	17.6	19.5
25-54	3.2	5.6	7.8	10.1	12.5	14.7	4.0	7.2	9.9	12.1	14.0	15.6

North Carolina Kaplan-Meier and Crude Cox Survival Analyses: Crude total crash survival curves for novices licensed before and after GDL were compared for each beginning licensing age cohort separately for total, fatal/injury and property damage crashes. Results closely paralleled those indicated by the hazard ratios shown in Table 9. Accordingly, results of the Kaplan-Meier analyses are not presented here.

As shown in Table 9, during the three years after novice solo licensure, the crash incidence rate for 16-year-old novices licensed under GDL (17,633 per 100,000 person-years) was 11 percent lower than for those licensed before GDL was implemented (19,794 per 100,000 person-years). Rates were little changed for drivers who began driving at 17, 18, or 19 (indicated by the hazard ratios of about 1.0). Among those who started at 20 or older, the decline during the post-GDL era was similar to that of 16-year-olds.

The rates and crude hazard ratios suggest much lower fatal/injury crash rates among all age groups of novices licensed after GDL (Table 9). However, rather than an effect of GDL, especially on older drivers never exposed to GDL, these large differences almost certainly reflect a change in reporting of injury crashes in North Carolina during the time period shortly after GDL was implemented. A new crash report form was introduced beginning January 1, 2000 that altered the verbal labels of injury codes. As a result, the reporting of more serious injuries plummeted immediately. Analyses at that time indicated that the substantial and immediate drop in the number of reported serious injury crashes was so large and sudden that it could not have been real. Further inspection of reported crash severity by year, in the data analyzed here, identified a three-year period (2000-2002) following introduction of this new form, during which reports of injury crashes were atypically low in comparison to earlier and later years.[4] Because of the complex and confounding effects of the changing reports of crash severity during the study period, great caution is needed in interpreting pre- and post-GDL results for the differing levels of crash severity shown in Table 9. Consequently, no further analyses by level of crash severity are reported.

North Carolina Crash Survival Adjusted for Sex and Month of Licensure: The young novice driver cohorts before and after GDL differed in the proportion of males and in the distribution of months during which solo driving began. The latter resulted from the more cyclical nature of licensing created by GDL. Because crash rates differ by calendar month and males have higher crash rates, it was important to adjust for these differences. After adjusting, total crash incidence of 16-year-old novices licensed under GDL was found to be lower than that for 16-year-old novices licensed beforehand, in the initial months after solo licensure (Table 10). The difference between the pre- and post-GDL 16-year-old license cohorts was constant over time, with post-GDL rates remaining about 10 percent lower than those prior to GDL at each six-month post-licensing increment. Total crash incidence among 17- and 19-year-olds novices licensed under GDL did not differ from those licensed beforehand. Among all other age groups of novices, total crash incidence was lower among those licensed after GDL was implemented, though there was some variation over time. The difference in pre- and post-GDL rates appeared to decrease with increasing experience for those licensed at age 18 and at 21 or older. It is unclear why this would be the case, but

[4]The transition to the new form, as well as a new relational database file structure for the crash data system, created numerous problems, anomalies and inconsistencies between newer and previous data. Many of these were addressed in the new crash data file to align the post-2000 data with those prior to the change. However, some issues appear either not to have been found, or never to have been addressed.

if it is a real pattern and not an artifact of our analytic approach it could not be the result of the change to a GDL licensing system, because most drivers licensed after GDL was in place were too old to ever have been exposed to the GDL process.

Table 9. Total, Fatal/Injury, and Property Damage-Only Crashes per 100,000 Person-years during the 3 Years after Novice Solo Licensure by GDL Cohort (Pre-GDL vs. GDL) and Age at Solo Licensure

Crash type	Pre-GDL cohort			GDL cohort			
Age at licensure	Crashes	Person-years	Rate	Crashes	Person-years	Rate	Crude Hazard ratio[a]
Total crashes							
16	62,587	316,191	19,794	118,073	669,619	17,633	0.89
17	8,829	49,184	17,951	26,657	147,349	18,091	1.01
18	8,745	51,628	16,939	35,832	216,652	16,539	0.98
19	4,731	31,958	14,804	13,573	94,330	14,389	0.97
20	3,557	25,917	13,725	9,606	76,328	12,585	0.92
21-24	8,917	78,651	11,337	25,118	249,862	10,053	0.89
25-54	13,771	160,317	8,590	40,914	526,455	7,772	0.90
Fatal/injury crashes							
16	30,462	376,821	8,084	43,552	814,585	5,347	0.66
17	4,624	57,081	8,101	10,631	179,106	5,936	0.73
18	4,554	59,454	7,660	15,136	258,506	5,855	0.76
19	2,448	36,147	6,772	5,396	110,333	4,891	0.72
20	1,743	29,214	5,966	3,583	88,125	4,066	0.68
21-24	4,133	87,043	4,748	8,814	281,207	3,134	0.66
25-54	6,170	172,905	3,568	13,854	576,697	2,402	0.67
Property damage-only							
16	41,346	362,204	11,415	88,247	729,700	12,094	1.06
17	5,492	56,298	9,755	19,456	161,932	12,015	1.23
18	5,555	58,573	9,484	25,874	237,029	10,916	1.15
19	2,955	35,789	8,257	9,908	101,596	9,752	1.18
20	2,302	28,592	8,051	7,197	80,975	8,888	1.10
21-24	5,848	85,090	6,873	19,219	261,204	7,358	1.07
25-54	9,047	169,824	5,327	31,206	543,874	5,738	1.08

[a]The referent group for these hazard ratios is novices of the same age during the pre-GDL period.

Table 10. Adjusted Cox Proportional Hazards Survival Results for Total Crashes during the 3 Years after Solo Licensure Comparing Novices Licensed after the North Carolina GDL Program was Implemented to those Licensed Beforehand, by Age at Solo Licensure

Age at licensure	Time after solo licensure adjusted hazard ratio (95% CI)					
	6 months	12 mos.	18 mos.	24 mos.	30 mos.	36 mos.
16	**0.89** (0.88-0.90)	**0.90** (0.89-0.90)	**0.90** (0.89-0.91)	**0.90** (0.89-0.91)	**0.90** (0.88-0.92)	**0.90** (0.88-0.92)
17	1.01 (0.98-1.04)	1.01 (0.98-1.03)	1.01 (0.98-1.03)	1.00 (0.97-1.04)	1.00 (0.95-1.05)	1.00 (0.94-1.06)
18	1.00 (0.97-1.03)	**0.98** (0.95-1.00)	**0.95** (0.93-0.98)	**0.93** (0.90-0.96)	**0.91** (0.87-0.95)	**0.89** (0.84-0.94)
19	0.97 (0.94-1.02)	0.97 (0.94-1.01)	0.97 (0.94-1.01)	0.97 (0.92-1.02)	0.97 (0.91-1.03)	0.97 (0.89-1.05)
20	**0.92** (0.88-0.97)	**0.92** (0.89-0.96)	**0.92** (0.88-0.96)	**0.92** (0.87-0.97)	**0.91** (0.85-0.98)	0.91 (0.83-1.00)
21-24	**0.92** (0.89-0.95)	**0.90** (0.88-0.92)	**0.88** (0.86-0.90)	**0.86** (0.83-0.89)	**0.84** (0.80-0.88)	**0.82** (0.77-0.86)
25-54	**0.95** (0.93-0.98)	**0.93** (0.91-0.94)	**0.90** (0.88-0.92)	**0.87** (0.85-0.89)	**0.85** (0.82-0.88)	**0.82** (0.79-0.86)

Note. The hazard ratios are adjusted for sex and month of licensure. The referent group for these hazard ratios is novices of the same age during the pre-GDL period. Boldface indicates pre- vs post-GDL hazard ratios were different, to a statistically reliable degree at $\alpha = .05$.

North Carolina Crash Survival Adjusted for Sex, Month of Licensure, and Historical Changes in Crash Incidence: After standardizing the adjusted hazard ratios of the younger novices to the pre- to post-GDL changes in crash incidence observed for 25-54-year-old novices, total crash incidence for 16-year-old novices licensed under GDL was found to be 3–6 percent lower during the first year of solo licensure than that for 16-year-olds licensed before GDL was implemented (Table 11), but 3–10 percent higher during the second and third years of solo licensure. Similarly the crash incidence rate of all younger novices, in comparison to those of older novices, appears to have increased over time.

Unfortunately, adjusting for older novice crash rates appears to have introduced an artificial effect, as also seemed to occur in the California analyses. This can be seen by comparing the hazard ratios in Table 10, which are not standardized to the 25-54-year-old crash rate, with those in Table 11, which reflect this standardization. A note of explanation is needed here. To serve as a useful control series, the crash incidence rates of older novices should reflect only the effects of changes in the overall driving conditions (or changes in reporting practices) that influence crash rates for drivers of any age. Although it is standard practice to use an older driver series, such as 25-54-year-olds to do this in examinations of teen driver crashes, in the present case the older series is not actually older drivers, but rather older novices. It appears that older novices improved at a faster rate than young novices, even though they don't improve as much (because their initial rates are lower, leaving less room for improvement due to experience). As a result, using the 25-54-year-old novice rate to standardize pre- and post-GDL crash rates produced the appearance that younger novices licensed in the GDL era get progressively worse over time, whereas in fact they simply get worse in comparison to older novices. Additionally, the North Carolina population grew dramatically from the mid-1990s to the mid-2000s, and this included a large number of immigrants from outside the U.S. who would have been novice licensees in

North Carolina. Consequently, the 25-54-year-old novice driver population after GDL may have differed in important, but unknown, ways from the same cohort prior to 1998. In summary, the 25-54-year-old crash incidence rate appears to reflect not only conditions in the overall driving environment that affect crashes and crash reporting, but also factors unique to older novices. This renders the older novice series a less than ideal indicator of overall driving conditions and, as a result, an imperfect measure with which to control for historical trends in crash risk.

As a result of the complicated picture created by adjusting for historical trends using the 25-54-year-old crash rate, the absolute changes in hazard ratios from 6 to 36 months with licensing age cohorts should be interpreted cautiously, as we suspect these represent changes in both the older (25-54) and younger novice licensee crash rates.

Table 11. Adjusted and Standardized Cox Proportional Hazards Survival Results for Total Crashes during the 3 Years after Solo Licensure Comparing Novices Licensed after the North Carolina GDL Program was Implemented to those Licensed Beforehand, by Age at Solo Licensure

Age at licensure	Time after solo licensure adjusted hazard ratio (95% CI)					
	6 months	12 mos.	18 mos.	24 mos.	30 mos.	36 mos.
16	**0.94** (0.91-0.96)	**0.97** (0.95-0.99)	1.00 (0.98-1.02)	**1.03** (1.00-1.06)	**1.06** (1.02-1.11)	**1.10** (1.04-1.15)
17	**1.06** (1.02-1.10)	**1.09** (1.06-1.13)	**1.12** (1.08-1.16)	**1.15** (1.10-1.20)	**1.18** (1.11-1.25)	**1.21** (1.13-1.31)
18	**1.05** (1.01-1.09)	**1.05** (1.02-1.09)	**1.06** (1.03-1.10)	**1.07** (1.02-1.11)	**1.07** (1.01-1.14)	**1.08** (1.00-1.16)
19	1.02 (0.97-1.07)	**1.05** (1.01-1.09)	**1.08** (1.04-1.13)	**1.11** (1.05-1.17)	**1.14** (1.06-1.23)	**1.18** (1.07-1.29)
20	0.97 (0.92-1.02)	1.00 (0.95-1.04)	1.02 (0.98-1.07)	1.05 (0.99-1.12)	1.08 (1.00-1.17)	**1.11** (1.00-1.23)
21-24	0.97 (0.93-1.01)	0.97 (0.94-1.00)	0.98 (0.95-1.01)	0.98 (0.94-1.03)	0.99 (0.94-1.05)	1.00 (0.93-1.07)

Note. 95% CI indicates 95% confidence interval for the adjusted hazard ratio. The hazard ratios are adjusted for sex, month of licensure, and historical changes in crash incidence. The referent group for these hazard ratios is 25-54-year-old novices during the same pre or post GDL period. Boldface indicates pre- vs post-GDL hazard ratios were different, to a statistically reliable degree at $\alpha = .05$.

North Carolina Crash Survival by Age at Solo Licensure Adjusted for Sex and Month of Licensure: These analyses were conducted to determine how crash incidence differs – in level and trajectory over time licensed – by age at the time of solo licensure. For these analyses, the crash incidence for each age group of novices under 25 years is compared to that for 25-54-year-old novices who were licensed contemporaneously. Despite the possible limitations of using older novices to adjust for historical trends mentioned above, the standardized hazard ratios can still be usefully examined as indicators of the relative differences between the young licensing age cohorts, at various points after licensing, because all are standardized to the same 25-54-year-old base at the same point in time.

Crash incidence was generally lower as age of novice solo licensure increased (Table 12), and this pattern was consistent both before and after the North Carolina GDL program was implemented. Crash incidence was highest during the initial months of licensing and it decreased over the course of licensure for novices of all ages. Nonetheless, even after three

years of licensure the incidence of novices who began driving before age 25 was higher than that for age 25-54-year-old novices, with the exception of 21-24-year-olds whose crash incidence approached that of the older group by three years after solo licensure.

As was the case in California, the introduction of GDL brought the crash experience of drivers licensed at ages 16 and 17 in line with that of drivers who began at age 18 during the first year of driving, after which the crash rates of those licensed at 18 began to level off more than those of teens licensed at earlier ages. This can be seen in the hazard ratios comparing younger licensees with 25-54-year-old licensees presented in Table 12. Survival curves for pre- and post-GDL licensees shown in Figures 4 and 5 provide a somewhat different, more detailed picture than Table 12. They highlight how the post-GDL crash experience of 18-year-old licensees is nearly identical to that of 16- and 17-year-olds shortly after licensure, then how 18-year-olds' ability to avoid crashing improves more quickly than does that of those licensed at 16 and 17 (whose survival curves continue to decline more than the curve for 18-year-olds). Log-rank tests indicate that the survival curves of the different age licensees differ to a statistically significant degree ($p < .0001$).

That crash rates of drivers licensed at age 18 following GDL are equal to, or lower than, those of individuals licensed at 16 or 17 indicates that GDL has not created a problem among 18-year-olds. Even though individuals who began at 18 experienced none of the benefits of GDL, their hazard ratios at every time point for the first three years of driving were lower than those of teens who began at earlier ages, with all the benefits of GDL.

Discussion

The primary goal of the present study was to examine the extent to which crash rates differ as a function of the age at which individuals are licensed. Because one of the main reasons for asking this question was to shed some light on whether jurisdictions in the U.S. should perhaps consider extending graduated driver licensing systems to cover drivers older than 17, we addressed the basic question both before and after GDL was implemented (in fairly different forms) in two states – California and North Carolina.

The major findings of this study are that (1) GDL appeared to reliably reduce crash rates per licensed driver among drivers licensed at age 16, but not those licensed at later ages in both states; (2) GDL does not appear to have increased crash rates among 18-year-old drivers in either state, as would be expected if a substantial number of teens wait to begin driving until they are old enough to avoid GDL requirements; (3) prior to GDL, in both states age at licensure to begin driving without adult accompaniment was inversely related to crash rates initially, and this difference persisted for up to three years following licensure; (4) in both states GDL reduced initial crash rates and altered the trajectory of the time-to-crash survival of 16- and 17-year-old licensees such that the rates and trajectories were quite similar among drivers licensed at 16-18 until about a year after licensure.

Table 12. Adjusted Cox Proportional Hazards Survival Results for Total Crashes during the 3 Years after Solo Licensure Comparing Younger Novices to Those Ages 25-54-Years-Old, Before and After the North Carolina GDL Program was Implemented

Age at licensure	Time after solo licensure adjusted hazard ratio (95% CI)					
	6 months	12 mos.	18 mos.	24 mos.	30 mos.	36 mos.
			Pre-GDL			
16	**2.16** (2.09-2.23)	**2.03** (1.97-2.1)	**1.92** (1.86-1.98)	**1.81** (1.75-1.87)	**1.70** (1.63-1.77)	**1.60** (1.53-1.68)
17	**2.07** (1.95-2.19)	**1.93** (1.83-2.04)	**1.80** (1.71-1.90)	**1.68** (1.59-1.79)	**1.57** (1.47-1.68)	**1.47** (1.36-1.59)
18	**1.91** (1.81-2.01)	**1.77** (1.69-1.86)	**1.64** (1.56-1.73)	**1.53** (1.44-1.61)	**1.41** (1.33-1.51)	**1.31** (1.22-1.41)
19	**1.69** (1.57-1.82)	**1.57** (1.47-1.69)	**1.46** (1.37-1.57)	**1.36** (1.26-1.47)	**1.27** (1.16-1.38)	**1.18** (1.07-1.30)
20	**1.58** (1.46-1.72)	**1.49** (1.37-1.61)	**1.39** (1.29-1.51)	**1.31** (1.20-1.42)	**1.22** (1.11-1.35)	**1.15** (1.03-1.28)
21-24	**1.30** (1.23-1.38)	**1.25** (1.19-1.31)	**1.20** (1.14-1.26)	**1.15** (1.08-1.21)	**1.10** (1.03-1.17)	1.05 (0.98-1.13)
			GDL			
16	**2.02** (1.97-2.08)	**1.97** (1.91-2.02)	**1.91** (1.86-1.97)	**1.86** (1.81-1.92)	**1.81** (1.75-1.87)	**1.76** (1.70-1.82)
17	**2.20** (2.09-2.31)	**2.11** (2.01-2.21)	**2.02** (1.92-2.12)	**1.94** (1.84-2.04)	**1.86** (1.76-1.96)	**1.78** (1.68-1.89)
18	**2.00** (1.91-2.09)	**1.87** (1.79-1.95)	**1.74** (1.67-1.82)	**1.63** (1.55-1.70)	**1.52** (1.45-1.59)	**1.42** (1.34-1.49)
19	**1.73** (1.62-1.84)	**1.65** (1.55-1.76)	**1.58** (1.49-1.69)	**1.52** (1.42-1.62)	**1.45** (1.35-1.56)	**1.39** (1.29-1.50)
20	**1.54** (1.42-1.65)	**1.48** (1.38-1.59)	**1.43** (1.33-1.53)	**1.37** (1.27-1.48)	**1.32** (1.22-1.43)	**1.28** (1.17-1.39)
21-24	**1.26** (1.20-1.32)	**1.21** (1.16-1.27)	**1.17** (1.12-1.23)	**1.13** (1.07-1.18)	**1.09** (1.03-1.15)	1.05 (0.99-1.11)

Note. The hazard ratios are adjusted for sex, month of licensure, and historical changes in crash incidence. The referent group for these hazard ratios is 25-54-year-old novices during the same pre or post GDL period. Boldface indicates pre- vs post-GDL hazard ratios were different, to a statistically reliable degree at $\alpha = .05$.

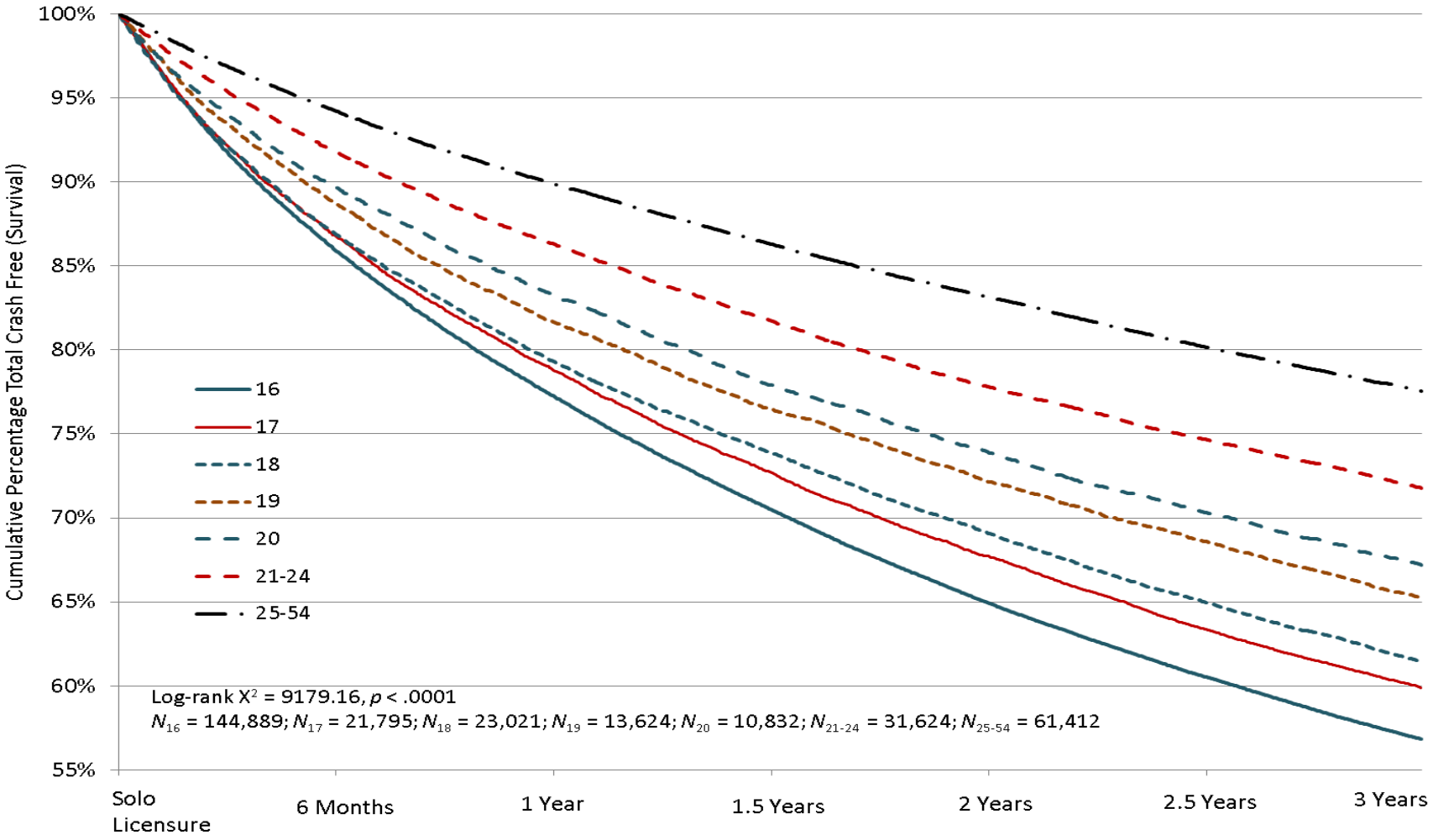

Figure 4. Crash-free survival (time to first crash of any severity) during the 3 years after solo licensure for novices licensed at different ages before the graduated driver licensing (GDL) program was implemented in North Carolina.

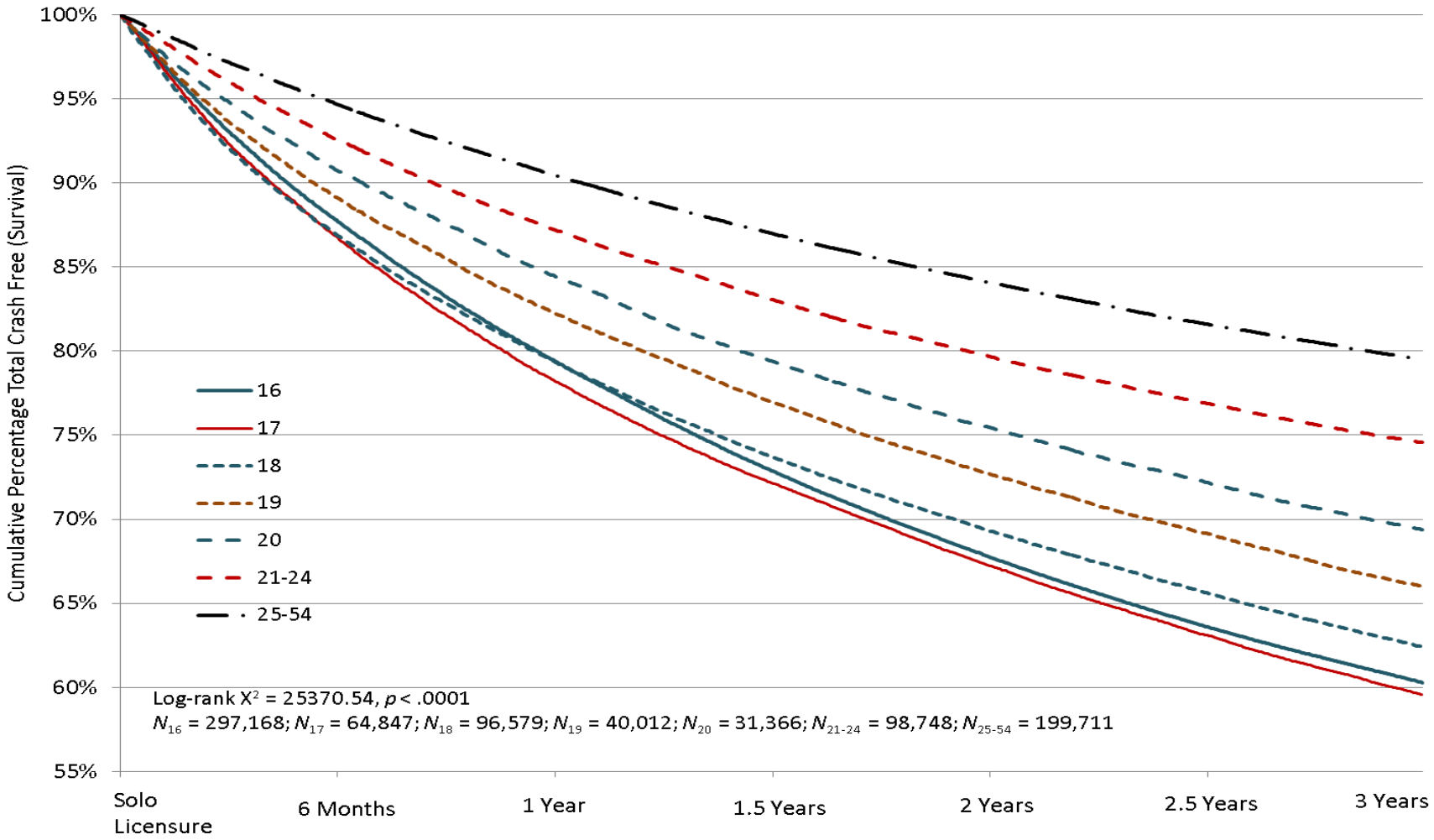

Figure 5. Crash-free survival (time to first crash of any severity) during the 3 years after solo licensure for novices licensed at different ages after the graduated driver licensing (GDL) program was implemented in North Carolina.

Novices licensed at age 16 under the GDL systems in both California and North Carolina consistently had a lower crash incidence rate than their pre-GDL counterparts, for most every crash type and severity analyzed. The patterns for older novice drivers were such that this difference among 16-year-olds can reasonably be attributed to effects of the GDL process. Although the relatively small post-GDL changes may appear inconsistent with the extensive literature documenting substantial crash reductions among young novice drivers (Shope, 2007), they are not. The smaller effects seen here result from using an analytic approach – examining only drivers licensed to drive unaccompanied by an adult – that could not identify one of the two primary ways in which GDL can reduce young novice driver crashes. The large effects documented in many studies of GDL largely reflect reduced driving among the population of teens eligible to obtain a license (that is, fewer young people are licensed to drive solo at the youngest allowable age). The findings here reflect changes that may have occurred in the ability of young drivers to avoid crashing, less driving in the risky conditions limited by intermediate GDL licenses (late at night and with age-peers as passengers) and perhaps less driving overall. But the highly protective effects of not (yet) driving at all and driving only while accompanied by an adult among 16- and 17-year-olds created by GDL are not reflected in the present findings because only licensed drivers were studied. An early study of GDL in Florida also found effects similar to those reported here, for 16-year-old beginners, in an analysis that did not capture the exposure reduction that occurs when a multi-stage GDL system is first introduced (Ulmer et al., 2000). Karaca-Mandic & Ridgeway (2010) also concluded, based on a quite different analysis of crashes in multiple states, that the primary beneficial effect of GDL has accrued through reducing exposure within the 16- and 17-year-old population. However, Zhu et al (2014) recently estimated, for the first time, that about half the reduction in fatal crash involvement of 16-year-old drivers was apparently the result of improved driving. But, as has been the case in many other studies, they found no effect of GDL for 17-year-olds.

The magnitude of effect in the Zhu et al. (2014) findings provide some indication that GDL may be more powerful in producing more competent young drivers, than our findings suggest. However, their failure to find a benefit for 17-year-olds, along with ours and those of numerous other studies, raises the question of what effect could be expected by extending GDL to cover drivers older than 17. Those studies that have found the largest effects of GDL on 17-year-old crash involvement have been conducted in states (Georgia and North Carolina) with a long enough learner period (12 months) and old enough beginning licensing age that a substantial proportion of the 17-year-old population spends at least part of the year driving under the most protective condition of GDL: with an adult supervisor in the vehicle (Foss, 2007; Foss & Masten, 2014; Preusser & Tison, 2007; Rios et al., 2006).

The analyses conduced here cannot address whether GDL may have prompted some teens to wait until age 18 to begin driving. They do indicate, however, that if that is the case these individuals are probably not experiencing high crash risks as a result of having begun driving without the benefit of GDL. In both California and North Carolina, those who began driving at age 18 after GDL was in place had similar or lower crash hazard ratios than teens who began at earlier ages and experienced the benefits of the GDL process.

It has long been a desire of researchers and policymakers alike to address the question of the potential effects of increasing the minimum licensing age. Limited, suggestive evidence has sometimes been interpreted as supporting a later minimum licensing age than is presently the case in the U.S. (Begg & Langley, 2009; McCartt et al., 2009; Williams, 2009;

Williams et al., 2013). The present study provides the kind of detailed data on the association of crash rates with age at licensing, in the context of a GDL program, that has been unavailable in the U.S. until now. In general, individuals who began driving at age 18 had lower crash rates than those who began at 17 or 16, though the differences are not dramatic. Those who began driving at 19-20 did substantially better than those who started at age 18, and those who began even later were markedly less likely to crash during their first, second, or third year driving. This replicates the widely reported pattern found in the Netherlands (Twisk & Stacey, 2007) and elsewhere. The present findings, reflecting crash data for several years in much larger jurisdictions than have previously been studied, provide more detail on this pattern by single year of age from 16 through 20.

One noteworthy exception to the inverse relationship between crash rates and licensing age was the finding in California that drivers licensed at 18 had the highest initial fatal/injury hazard ratios of any licensing age group during the first six months driving. For the next two years the hazard ratios were highly similar for those licensed at 16, 17, and 18. Unexpected patterns like this have been reported by others as well. Waller et al. (2001) found, for example, that being older at licensing was associated with an increase rather than the expected decrease in drivers being at-fault in crashes. As Waller et al. and many others have noted, individuals who decide to begin driving at later ages may differ in several ways from those who begin earlier.

In interpreting the present clear and detailed findings about the inverse association between crash incidence in the early years of driving and age at which individuals begin, it is important to bear in mind that those who decide to begin driving at ages later than the minimum allowed probably differ in meaningful ways beyond calendar age, from those who begin at the earliest possible age. Young teens who wait awhile to begin probably have less, or no, access to a vehicle at age 16 or 17 than those who begin driving as early as possible. Those who wait are less likely to be able to afford the costs of driving (Tefft, Williams & Grabowski, 2014). They probably have less perceived need to drive. They may be more fearful of driving, have more alternative travel options, or may simply be less interested in driving than those who begin at the earliest possible age. Unfortunately, having relied on archival licensing and crash data, the present analyses were incapable of controlling for or investigating these possible differences. We were only able to look at calendar age of individuals. Accordingly, the clear differences in crash incidence found for persons who began driving at later ages cannot be interpreted as simple causal effects of age or age-related factors (e.g., maturity, driving style, etc.). Hence, it is inappropriate to assume that if all individuals who obtained a license at age 16 or 17 were somehow persuaded, or required, to wait until age 19 to begin that they would experience the same crash rates and trajectories identified among those individuals analyzed here who began driving at 19, rather than earlier.

The similarity in findings for the two states studied is encouraging and allows some confidence that they represent general rather than state-specific patterns. Although crash rates differed between California and North Carolina, the states differ in many ways, making it difficult to draw any meaningful conclusions about the different crash rates. In addition to having substantially different GDL programs, driving conditions differ substantially between California and North Carolina. The need to drive, especially at a young age, is distributed differently within the populations of these two states. The data recorded in these states differs notably as well. Whereas North Carolina attempts to record

crash data for all crashes on public roads that exceed the $1,000 damage threshold, California data are less likely to include minor, property-damage only crashes. The result is a higher crash rate, or shorter crash-free survival time, in North Carolina that is at least in part simply an artifact of the information available for analysis.

Study limitations

Overly simplistic studies that fail to take into account the many complexities of data, driving, human abilities and behavior, can produce questionable results. Unfortunately, studies like the present that recognize these issues and try to address them with sophisticated study designs and analyses often find a raft of puzzling or conflicting findings that are hard to interpret. Ever-more complex analytic approaches, for all their promise of greater precision, also bring the risk of introducing design- or analysis-specific artifacts to the findings. That has clearly been the case here. In both California and North Carolina, adjusting younger novice crashes rates using those of 25-54-year-old novices appeared to induce a systematic effect, rather than simply control for possible changes in the driving environment. In many of the analyses, adjusting for older novice crash rates produced the appearance of a systematic, widespread decline in (adjusted) crash rates over the first three years of licensure, with those licensed in the GDL era appearing to become progressively better drivers during this time period. Although this is possible, it seems unlikely to have been the case. There is nothing about the GDL process that would be expected to produce larger benefits years after initial licensing. Indeed, the greatest effect of GDL should be found in the initial months of driving. Following that period, the protective restrictions are removed and whatever benefits (as distinct from improved driving abilities) may have accrued from extensive practice driving during the learner period would be expected to erode as all drivers accumulate more practical driving experience and incorporate the learning that results from this into their driving. That is, the greatest difference between pre-GDL licensees and those licensed under a GDL system, in both the experience and protection provided by GDL, would exist during the first days of solo licensure. Accordingly, we placed more credence in the findings that did not include adjustments for 25-54-year-old novice crash rates.

Conclusions

Initial crash rates and their trajectory during the first three years of licensing are inversely proportional to age at licensing. Following introduction of GDL, the difference in crash incidence between individuals licensed at ages 16, 17, and 18 are compressed to the point that they are barely distinguishable during the initial months of licensing, but they diverge later with those licensed at 18 improving more quickly that those licensed younger. Finally, whereas the crash-reducing effects of GDL on drivers licensed at age 16 were clear and consistent, the modest to non-detectable effect on drivers licensed at 17 raises questions about what effect might be expected if GDL were expanded to cover drivers older than 17.

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Appendix A: The California GDL Program

Novice California drivers who are 16 or 17 years of age are licensed under California's GDL program. This GDL program includes a six-month minimum learner permit holding period (Stage 1) prior to being allowed to drive unsupervised, during which young teens must drive under adult supervision for at least 50 hours. Before the GDL program was implemented in July 1998, they were only required to hold a learner permit for one month. To obtain a learner permit they must be at least age 15½ years, have completed a driver education course, and be enrolled in a behind-the-wheel driver training course. Prior to January 1, 2004, the minimum learner permit age was 15 years. After holding the learner permit for at least six months and completing driver training, they may obtain a provisional license (Stage 2) with which they are allowed to drive unsupervised; however, they are restricted from driving during 11 PM to 5 AM and from transporting any passenger younger than age 20 years. Note that the passenger restriction only applied to the first six months of provisional driving and the nighttime restriction start time was 12 AM for those who received provisional licenses before January 1, 2006. The current provisional license period lasts for 12 months or until they turn age 18 years, after which they may drive under all conditions (Stage 3). Novice drivers licensed at age 18 years or older are not subject to the GDL program.

Appendix B: The North Carolina GDL Program

Novice North Carolina drivers who are 16 or 17 years of age are licensed under the North Carolina GDL program. This GDL program includes a 12-month minimum learner permit holding period (Stage 1) prior to being allowed to drive unsupervised, during which young teens must drive under adult supervision (there was no specified minimum number of hours of supervision during the period covered in this study). Before the GDL program was implemented in December 1997, they were not required to hold a learner permit for a specified period of time. To obtain a learner permit they must be at least age 15 years, and have completed a driver education course. After holding the learner permit for at least 12 months, they may obtain a limited provisional license (Stage 2) with which they are allowed to drive unsupervised; however, they are restricted from driving during 9 PM to 5 AM and from transporting more than one passenger younger than age 21 years. The provisional license period lasts for six months or until they turn age 18 years, after which they may drive under all conditions (Stage 3). Novice drivers licensed at age 18 years or older are not subject to the GDL program.