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Spatial variation in teens' crash rate reduction following the implementation of a graduated driver licensing program in Michigan

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Abstract

Motor vehicle crashes are a leading cause of injury, and teen drivers contribute disproportionately to that burden. Graduated Driver Licensing (GDL) programs are effective at reducing teen crash risk, but teen crash rates remain high. Between-state variation in the teen crash rate reduction following GDL implementation has been documented, but this is the first study to examine small-area variation in such a reduction. Fusing together crash data from the Michigan State Police, census data, and organizational data (alcohol outlet, movie theatre, and school locations), we analyzed spatial correlates of teen injury crash, and place-based features that modified the injury crash rate difference following GDL implementation. Specifically, using census-based units, we estimated changes in injury crash rates among teens using negative binomial regression controlling for spatial auto-correlation, and tested whether any measured spatial characteristics modified the crash rate change in the pre versus post GDL periods. There was a substantial reduction in teen crashes after GDL implementation (RR = 0.66, 95%CI: [0.65, 0.67]), and this effect was robust across gender and time-of-day (light/dark). We found evidence that this reduction varied across space; areas with more alcohol outlets corresponded to a larger daytime crash rate reduction post-GDL, while areas near schools corresponded to a smaller daytime crash rate reduction. Concentrations of movie theatres corresponded to larger post-GDL crash rate reductions after dark. Maximizing the substantial successes of GDL programs requires understanding why crash rate reductions were larger in some areas following GDL implementation, and harnessing that understanding to improve its effectiveness across a state, focusing on identifying priorities for improving driver training (e.g., by parents and driver educators), law enforcement, and future policy changes to current GDL laws.

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Keywords

Graduated driver licensing; Spatial; Crash risk; Teen drivers

1. Introduction

1.1. Public health burden of teen crashes

Motor vehicle crashes are a leading cause of morbidity and mortality among teen drivers (Centers for Disease Control and Prevention National Center for Injury Prevention and Control, 2015), resulting in an estimated $3.4 billion in combined medical costs and lost productivity annually (Centers for Disease Control and Prevention National Center for Injury Prevention and Control, 2010). Despite the fact that fewer than 5% of all drivers are teens (Bureau of the Census, 2011), it is estimated that 12.2% of all traffic crashes are caused by teen drivers (Safety Resource Center, 2017), including 8% of fatal traffic crashes (Rocky Mountain Insurance Information Association, 2017). Between that, and the fact that teens experience nearly triple the risk of fatal crash per mile driven (Insurance Institute for Highway Safety Highway Loss Data Institute, 2017) compared to drivers age 20 and over, teen drivers' status as a tremendously high-risk group is well-defined. Recognizing this burden, policy interventions, such as graduated driver licensing (GDL), that specifically address teen drivers have been implemented. GDL has been one of the most effective teen crash policy interventions (Shope and Molnar, 2003; Chen et al., 2006; Shope, 2007; McCartt et al., 2010; Masten et al., 2011; Conner and Smith, 2017), and has also lowered non-crash related outcomes, such as citations (DePesa et al., 2017). Those successes have led to GDL's widespread dissemination and implementation throughout all 50 states and the District of Columbia. Despite this increased implementation, crash burden among teen populations remains high. To build upon the previous success, researchers are examining mechanisms of improving existing GDL policies and requirements (Williams 2011). Harnessing that opportunity, though, requires first understanding the circumstances (e.g., spatial conditions) under which the crash rate reduction following GDL implementation is maximized. The purpose of this paper is to present the first ever analysis of spatial variation in the teen crash rate reduction following the implementation of a GDL program, and the spatial correlates of that variation.

1.2. GDL policies and variation in their effectiveness

Although there is variation by state, GDL policies typically includes three licensure phases: i) a learner license or permit, where the teen may only drive with supervision, and may be required to complete a minimum number of supervised practice driving hours over a specified period of time; ii) an intermediate phase, where the teen can drive independently, but with restrictions (e.g., nighttime driving restriction, number of passengers); and iii) a full license (Insurance Institute for Highway Safety Highway Loss Data Institute, 2011). This phase-based system is rooted in several principles: i) training over an extended period is more effective than intensive training over a short period; ii) reducing exposure to high-risk driving conditions decreases crash risk until additional experience has been accumulated;

and iii) greater maturity results in better decision-making and therefore safer driving practices.

Given the variability in the characteristics of driving exposure across locales, how well a given implementation captures those guiding principles may be context specific. In particular, driving conditions in some localities may call for more supervised driving time, different driving restrictions, or a longer waiting period. For example, a teen learning to drive in a large urban center may be presented with more challenging and complex driving situations, which may require additional training to master. In addition, driving exposures and their entailed risks are locale specific; for example, what constitutes a high-risk driving scenario in an urban center (e.g., large multi-lane intersections) may differ dramatically from those in a rural area (e.g., icy gravel roads on a foggy night). Given that GDL policies are typically specified at a state level, and many states (e.g., Michigan) have a mixture of these context specific areas (e.g., urban and rural), such considerations plausibly affect the overall effectiveness of a statewide GDL policy. While locally-specific GDL policies are not practicable, identifying features of areas where crash rate reductions following GDL implementation are lower (or higher) are important for parents and driver educators, as well as law enforcement, to consider; identifying those features is the primary goal and contribution of this work.

Substantial variation has been observed in the effectiveness of GDL policies. A review of GDL policy evaluations covering 21 studies of GDL effectiveness (Shope, 2007) found that published reductions in teen driver crashes ranged from ≥5.6% (Dee et al., 2005) to 38–40% (Baker et al., 2007), with the overall conclusion that GDL effectiveness at reducing crash rates was in the 20–40% range. Similarly, a more recent survey of GDL programs across 34 studies, spanning three countries—US, Canada, and New Zealand (Russell et al., 2011)—found that, although GDL showed positive effects in all cases, the level of effectiveness varied substantially, with crash rate reductions among 16 year olds ranging from 8% to 27%. There is evidence that some of this heterogeneity is related to variation among states in the strength of their individual GDL components (McCartt et al., 2010). One study showed that states with GDL components, such as night restrictions, that tend to lower teen driving frequency – as opposed to improving driving practices – are the most effective (Karaca-Mandic and Ridgeway, 2010). A nationwide review by the AAA Foundation for Traffic Safety (AAA News Room) showed that states with more comprehensive GDL programs had more than double the reduction in injury crashes, and more than triple the reduction in fatal crashes among 16-year-old drivers (relative to the overall reduction of crashes in states with less comprehensive GDL programs). A common thread among these studies, which was borne out in a more recent review (Williams et al., 2016), is that strengthening state-level programs would increase their effectiveness. Yet, no studies have examined how small-area characteristics correspond to differential crash-rate reductions after the implementation of GDL. Given previous calls in the literature for conceptual frameworks to improving adolescent motor vehicle safety that integrate policy analysis with socio-ecological frameworks for the study of health behavior (Runyan and Yonas, 2008), this is a notable gap in our current understanding of GDL effectiveness. Understanding this potential differential effectiveness of GDL may aid in identifying avenues through which GDL can be improved with locale-specific emphases or enhancements by parents, driver educators, and law enforcement.

1.3. Place-based determinants of crash risk

Traffic crashes do not occur randomly geographically, and researchers have found evidence that place-based features explain some of the spatial heterogeneity. While individual-level factors are clearly associated with traffic crash risk (e.g., alcohol consumption, male gender), crash risk also is modulated by the driving environment, consisting of both natural (e.g., weather) and man-made (e.g., street geometry) components (Bivand et al., 2008). From a socio-ecological perspective, these components likely interact and combine to produce crash risk rather than acting as static risk factors. Empirical evidence suggests that spatial factors including alcohol outlet location and density (Scribner et al., 1994; Giacopassi and Winn, 1995; Treno et al., 2007; Lipton et al., 2018), socio-economic factors (Aguero-Valverde and Jovanis, 2006; Lipton et al., 2018), population density (Quddus, 2008), average daily travel (Venkataraman et al., 2013), roadway types/intersections and geometry (Quddus, 2008; Rhee et al., 2016; De Silva et al., 2018; Guadamuz-Flores and Aguero-Valverde, 2017), and urbanicity (Noland and Quddus, 2004; De Silva et al., 2018) are all associated with traffic crash. Related studies have also analyzed risk of pedestrian-involved motor vehicle crashes and their spatial correlates (LaScala et al., 2000), including place-based features such as alcohol outlets and vacant lots (Nesoff et al., 2018).

The aforementioned studies have produced valuable place-based information, such as the identification of areas where enhanced pedestrian safety measures should be introduced (Blazquez and Celis, 2013), but there remain two primary limitations to the current literature on the spatial analysis of teen drivers’ traffic crash risk. First, existing literature on the spatial correlates of teen crash risk focuses on unlicensed/never-licensed drivers and not specifically on place-based risk factors for all licensed teen drivers (Hanna et al., 2012). Filling this gap has potential to elucidate priorities for improving teen driver safety programs. Second, dynamic analyses of the effectiveness of GDL have been limited to its temporal dimensions (e.g., Langley et al., 1996), and have not focused on small-area heterogeneity in the crash rate reduction following GDL and, if present, what factors explain that variation. Given the importance of place in prior studies of crash risk, it is plausible that place-based features could generate a dynamic property of crash rate reductions following GDL implementation; such information could inform the enhancement of GDL implementation for maximal efficacy.

1.4. Study overview

In this study, we further clarify the previously established effectiveness of GDL in Michigan (Shope and Molnar, 2001; Shope and Molnar, 2004) by conducting an analysis of small-area variation in the difference in teen traffic crash rates before vs. after GDL implementation. Using crash data from the Michigan State Police and census population data, we determined crash rates per unit of population in 1918 census-based areas constructed through the systematic combination of census tracts to generate a common “super tract” unit of analysis between the 1990 and 2000 censuses. Within each unit we also tabulated demographic characteristics, number of alcohol outlets, number of schools, number of malls, and number of movie theatres. We then used negative binomial spatial regression to model small-area characteristics that are associated with i) teen crashes in the pre-GDL period (1994–1995) and the post-GDL period (2000–2001); and ii) differential changes in crash rate in the pre-GDL period (1994–1995) vs. the post-GDL period (2000–2001). These analyses were also repeated after stratifying by driver sex, light condition (daylight vs. dark) at the time of the crash, and crash severity (non-fatal injury/fatal injury vs. non-injury). The study aim was to understand the role of place-based features in teen driver crashes, both in terms of its effect on rates of teen crashes, and how place contributes to differential teen crash rate reductions following GDL implementation.

2. Methods

2.1. Unit of analysis

The basic spatial unit for analysis was the census tract, but because crash data were linked to the nearest census (i.e., pre-GDL data were nearest the 1990 census; post-GDL data were nearest the 2000 census) and census tracts changed in minor ways from 1990 to 2000, we could not use raw census tracts. To generate a common areal unit system in the pre- vs. post-GDL periods, we used census relationship files (United States Census Bureau), which provide a basis for determining how census units change from one census to the next. Using those files, we iteratively combined existing raw census tracts into 1918 “supertract” units that were the same in both censuses, and thus were able to be compared pre/post GDL implementation. In a large majority of cases, these supertracts consisted of 1 census tract (82.8%); in 97.0% of cases they consisted of at most 3 census tracts. All census demographics below are computed as percentages at the supertract unit, and point-based variables (crashes, school, and organizations) are counts within each supertract. Supertracts with zero population in either the pre- or post-GDL period (8 of the 1918 units) were excluded from analysis. We chose this approach instead of using Traffic Area Zones (TAZs) as the unit of analysis, because there were no corresponding census relationship files for TAZs, and therefore no practicable way to generate a common system of areal units between the pre- (1994–1995) and post-GDL (2000–2001) time periods that could be directly linked with data from the 1990 and 2000 censuses.

2.2. Data sources

We used data from four sources: the Michigan State Police, the 1990 and 2000 decennial US censuses, the Center for Educational Performance and Information, and Infogroup. All data used were deidentified and publicly available, and thus the study was classified as exempt by the University of Michigan Institutional Review Board (IRB).

2.2.1. Crash data—Crash data were based on Michigan State Police reports and were obtained from the Center for Management of Information for Safe and Sustainable Transportation (CMISST) at the University of Michigan Transportation Research Institute. These data consisted of all police reported crashes and each crash had a latitude and longitude coordinate. Crashes involving passenger cars, vans, and light trucks were included in the analyses; crashes involving all-terrain, farm, or construction vehicles, go carts, off-road vehicles, and delivery vans/vehicles over 10,000 pounds weight were excluded to reduce crash severity variation due to vehicle size. GDL was implemented in Michigan April 1, 1997; the years 1994–1995 were used as the "pre-GDL" time period, and 2000–2001 were used as the "post-GDL" time period. Crash data from 1996 were excluded from the analysis because teen drivers were becoming aware of the GDL policy launch, and crash data from 1997 were excluded because of the mid-year GDL implementation. Data from 1998 and 1999 were also excluded because during these two years the teen driver population still included a mix of drivers who were licensed before and after GDL was implemented.

Attributes connected to the crash reports were used to create subsets of crashes. In particular, teen crashes were identified using driver age (ages 15–19), and an adult comparison group was identified using crashes in which the driver's age was 45–64. Other attributes included were driver sex, crash severity as measured by the KABCO scale (National Safety Council, 1996), and whether the crash occurred during daylight or dark. For this study, we restricted our focus to crashes that resulted in confirmed injury (including fatal injury), i.e., crashes with KABCO scores of K (fatal injury), A (incapacitating injury), and B (non-incapacitating injury).

2.2.2. Census data—The socio-demographic data for years 1990 and 2000 were obtained from U.S. Decennial Census based on census tracts (U.S. Census Bureau, 1991). Seven variables were calculated to characterize the socio-demographics of the driving environment: % below poverty line, % African American, % without college degree (of those age ≥25), % unemployed (of those age ≥16). These factors were chosen based on Sampson's measure of community collective efficacy (Sampson et al., 1997), which refers to the capability of community members to regulate the behavior of themselves and others in the community. For parsimony, these factors were combined into a concentrated disadvantage index, where higher numbers indicated greater neighborhood disadvantage, using the factor weights described in Sampson et al. (1997).

2.2.3. School data—Michigan primary and secondary school locations were obtained from The Center for Educational Performance and Information. The data were received in table format with postal addresses each school's location. ArcGIS Desktop 10.5 Business Analyst (ESRI, Inc., 2016, Redlands, CA) was used to geocode the addresses to a point location. All public and private pre-kindergarten through grade 12 schools that were open on or before 2002 and were still active in 2002 were included. Virtual Schools, Special Education Center Programs, Juvenile Detention Facilities, Delinquent Institutions, Locked-down Schools, Residential Child Care Institutions, and Non-School Nutrition Sponsors were excluded. The school data were only summarized at a single time point (post-GDL) because school locations are relatively static and there was little variation from the pre-to post-GDL periods.

2.2.4. Establishment data—The latitude and longitude coordinates of business establishments in Michigan were obtained from Infogroup (Infogroup Inc., 2012). The primary Standard Identification Classification (SIC) codes were used to identify business establishments where alcohol can be consumed or purchased (on- and off-premise alcohol outlets), and locations that attract teens (malls and movie theaters). See Appendix Table 1 for a description of the SIC codes used. On-premise alcohol outlets included bars, night clubs, and restaurants, and off-premise alcohol outlets included grocery stores, supermarkets, and gas stations. All alcohol outlets were combined into a single category. The establishment data were only available after 2000, and thus a single time point was used for analysis.

2.3. Analytic approach

We began with descriptive analyses and graphical displays of teen injury crash rates at the supertract level in Michigan, both before and after GDL was implemented, as well as estimates of the pre-post difference in those crash rates among teens (and among adults 45–64 for comparison) across each subset (male/female, daylight/dark). The denominator of the crash rate for teens in the pre-GDL period (1994–1995) was the number of youth aged 10–14 in that supertract in 1990 (i.e., those who would be age 15–19 in the years of analysis); in the post-GDL period (2000–2001), the number of youth age 15–19 in the 2000 census for that supertract was used. Among adults, the number age 40–59 in 1990 and the number age 45–64 in 2000 were used for the denominators in the pre- and post-GDL periods, respectively. We augmented this descriptive analysis with a basic, unadjusted, geographically weighted regression (GWR) analysis, designed to most clearly display spatial heterogeneity in the post-GDL crash rate reduction; for that analysis we used the R package spgwr (Bivand et al., 2017). The GWR models were log-linked for consistency with the primary analysis described below. Based on that analysis, we conducted a Moran's I test of spatial non-randomness in the post-GDL crash rate reduction, using inverse distance weighting, to verify that there is spatial variation to be parsed in the subsequent analysis.

For the initial analysis of Y_i, the number of teen crashes in supertract i in a given time period (pre- and post-GDL implementation), we use a negative-binomial regression model:

$$\log(E(Y_i)) = \log(N_i) + X_i\beta + \phi(s_i) \tag{1}$$

where X_i is a vector of place-based features for supertract i, s_i are the coordinates of the centroid of supertract i, and N_i is the number of youth age 10–14 in supertract i in the 1990 census. The offset $\log(N_i)$ is used so that what is effectively being modeled is the injury crash rate per person rather than the raw crash total, making our analysis exposure-normalized in a sense, by effectively modeling the estimated per-person crash rate. The $\phi(s_i)$ is a non-parametrically estimated thin-plate spline in the spatial coordinates used to model any residual spatial trend. Due to the duality between regularized smooth function estimation (which is how the $\phi(s_i)$ is estimated), and a particular class of Gaussian random effects models (Wood, 2011), this is equivalent, in a sense, to a generalized linear model with spatial random effects. Most importantly, this approach produces residuals that are free from spatial auto-correlation, which is required for correct p-values. This approach has been used previously for generalized linear modeling with spatial dependence (e.g., Bivand et al., 2008; Goldstick et al., 2015). We used negative binomial rather than Poisson regression to automatically model overdispersion in the outcome, which is also required for correct p-values, and has been used in prior crash research (Quddus, 2008). The regression coefficients, β, are the primary inferential target and were used to model the effects of micro-level factors on teen injury crash rates.

For the second analysis, we conducted pre-post analysis using a model analogous to that described above, with indexing by time *(t=0* indicating pre-GDL, and *t=1* indicating post-GDL):

$$\log(E(Y_i)) = \log(N_{it}) + \alpha t + X_{it}\beta + \theta X_{it} \times t + \phi(s_i) \tag{2}$$

The term α captures the overall pre/post difference when all spatial covariates equal their means (the covariates were pre-centered). The coefficients θ estimate how the pre-post difference changes based on the spatial covariates; for example, if there was an overall pre/post reduction, then negative and positive coefficients indicate features associated with areas where the post-GDL crash rate reduction was larger, or smaller, respectively. We will test the significance of the coefficients θ to determine spatial features that modify the pre/post GDL change in crash risk.

3. Results

3.1. Descriptive analyses

In the pre-GDL period (1994–1995) there were 9686 teen injury crashes; the average supertract had 5.08 teen crashes (SD = 6.27) and the number of crashes in a supertract ranged from 0 to 90. The overall teen crash rate across the state was 2.97 crashes per 100 population in the pre-GDL period. In the post-GDL period (2000–2001), there were 6913 teen crashes and the average supertract had 3.63 crashes (SD = 4.75); across supertracts the number of crashes ranged from 0 to 61. In the post-GDL period, the overall teen crash rate was 1.97 per 100 population.

The overall rate of teen injury crashes (including fatal crashes) in Michigan, was 34% lower in the post-GDL period than in the pre-GDL period (RR = 0.66, 95% CI: [0.65, 0.67]), a significantly greater reduction than that seen in the adult comparison group (RR = 0.72, 95% CI: [0.71, 0.73]). Teen injury crash rate ratios were similar among male teen drivers (RR = 0.66, 95% CI: [0.64, 0.68]) and female teen drivers (RR = 0.66, 95% CI: [0.64, 0.68]), and during daylight (RR = 0.66, 95% CI: [0.64, 0.68]) and dark (RR = 0.65, 95% CI: [0.63, 0.67]). The reduction in crash rates was significantly less among all subsets of the adult comparison group, including male adult drivers (RR = 0.73, 95% CI: [0.71, 0.75]), female adult drivers (RR = 0.71, 95% CI: [0.69, 0.73]), daylight (RR = 0.70, 95% CI: [0.69, 0.72]), and dark (RR = 0.75, 95% CI: [0.73, 0.78]). The average supertract had 11.1 (SD = 12.8) alcohol outlets, 0.1 (SD = 0.4) movie theatres, 3.2 (SD = 3.8) schools, and 0.1 (SD = 0.3) malls. The average of the concentrated disadvantage index was 0.8 (SD = 0.5) with a range of (0.22, 2.75).

Maps of overall teen injury crash rates before and after GDL in each supertract are shown in Fig. 1, and the geographically varying regression coefficient for the pre/post GDL change in injury crash rates is shown in Appendix Fig. A1. The GWR showed spatial variation in the pre/post GDL change in injury crash rates, with the largest reductions in the southeast area of the state, which coincides with the location of Detroit, the largest urban center in the state (Appendix Fig. A1); a Moran's I test with inverse distance weighting showed significant spatial non-randomness in that effect ($p < 0.001$). In contrast, the teen injury crash rates pre-and post-GDL shown in Fig. 1 show notable small-area variation in injury crash rates, suggesting that small-area characteristics may relate to the post-GDL changes in teen injury crash rates, and that larger area smoothing like that done with the GWR may be an oversimplification.

3.2. Spatial modeling of teen injury crashes during the pre- and post-GDL periods

Table 1 shows the spatial regression results of teen injury crashes in both the pre- and post-GDL time periods. In the pre-GDL period, alcohol outlet concentration was associated with higher crash rates, and this effect was robust across all crash subsets (male/female, daylight/dark); in the post-GDL period, those same effects appeared qualitatively, but the rate increase associated with a fixed unit increase in alcohol outlets was between 37% and 54% smaller in the post-GDL period (e.g., in crashes overall, the rate increase associated with 10 more alcohol outlets decreased from 18% to 10%, or a 44.5% reduction). Schools were associated with lower crash rates in the pre-GDL period, and this effect appeared for all crash subsets; this effect was attenuated in the post-GDL period for all injury crash subsets. In both the pre- and post-GDL periods, areas with higher values for the concentrated disadvantage index had lower teen injury crash rates, and those rate ratios did not differ appreciably across crash subsets or in the pre- vs. post-GDL period. Across all models, the spatial model produced a lower Akaike Information Criteria (AIC) than the model excluding the residual spatial term, indicating that the improved model fit justified the added complexity of modeling the spatial trend.

3.3. Pre/post analysis of GDL effectiveness with combined spatial model

Table 2 shows the combined model of teen injury crashes in both the pre- and post-GDL periods, with main effects and interactions with the GDL indicator. The baseline crash rate reduction in the post-GDL period was 37% overall, and all other main effects (of alcohol outlets, movie theatres, schools, malls, and the concentrated disadvantage index) were qualitatively similar to the pre-GDL results from Section 3.2. above. Among all injury crashes, increased alcohol outlet concentration corresponded to a larger reduction in the crash rate after GDL was implemented, with an approximate 7% increase in the crash rate reduction for every 10 alcohol outlets in the supertract. Also, among all injury crashes, more schools indicated a smaller reduction in the crash rate after GDL began; for each school in a supertract, there was a 3% decrease in the crash rate reduction. So, for example, the model estimated that in a supertract with five schools, the crash rate after GDL began was $0.63 \times 1.03^5 = 0.73$ of what the pre-GDL rate was, or 27%, rather than the 37% reduction seen overall. Across all models presented, the spatial model again produced a smaller AIC than the model excluding the residual spatial term.

3.3.1. GDL effects on injury crashes by driver sex—

Examining only crashes where driver sex was recorded, the baseline injury crash rate in a given supertract reduced by 33% among male teen drivers and by 36% among female teen drivers after GDL was implemented (Table 2). Among male teens, similar results to the overall effects were found for the spatial factors: increased alcohol outlet concentration corresponded to a greater post-GDL crash rate reduction, while more schools corresponded to a smaller post-GDL crash rate reduction. Similar trends were observed among female teens, but alcohol outlets (p =

0.08) and schools ($p = 0.07$) did not significantly modify the GDL pre/post difference. Among female teens, there was a trend indicating that malls may decrease their post-GDL crash rate reduction, but this effect was not statistically significant ($p = 0.16$).

3.3.2. GDL effects on injury crashes by daylight/dark—Including only crashes where light conditions were recorded, the baseline injury crash rate in a given supertract reduced by 37% in daylight, and reduced by 34% after dark (Table 2). Results among daylight crashes closely mirrored the overall results, with alcohol outlet and school concentration corresponding to increased, and decreased, effectiveness of GDL, respectively. Results among crashes occurring after dark showed schools remained a significant modifier, lowering the post-GDL crash rate reduction, but alcohol outlets were not significant. Higher numbers of movie theatres increased the post-GDL crash rate reduction by 17% for each additional movie theatre; e.g., a supertract with one movie theatre is estimated to have a post-GDL crash rate that is $0.66 \times 0.83 = 0.55$ that of the pre-GDL crash rate, or a 45% reduction– a larger reduction than the baseline level of 34%.

4. Discussion

We used public data sources to quantify the crash reduction after the implementation of GDL in Michigan, and how it varies as a function of place-based characteristics, as well as across different injury crash subsets (driver sex, light conditions at time of crash). This is the first study to examine place-based characteristics that modify the crash rate reduction following GDL implementation. Consistent with a consensus of the prior literature (Shope et al., 2001, Shope and Molnar, 2004), we found that the 1997 implementation of GDL in Michigan was associated with a clear reduction in teen drivers' injury (including fatal) crash rates—larger than the correspondent reduction among adult drivers. Our results extend the broad literature on the effectiveness of GDL programs by showing that, in Michigan, the injury crash rate reductions associated with the new GDL program differed across locations, and some of those differences can be explained by micro-area characteristics. Alcohol outlet concentration was associated with substantially higher risk of teen injury crash; yet, those same areas also corresponded to larger crash rate reductions after the implementation of GDL. Conversely, while schools were associated with lower teen injury crash risk, those same areas saw smaller overall crash reductions after GDL was implemented. These findings are not purely explained through ceiling effects, because the place-based characteristic with the largest (protective) effect – the concentrated disadvantage index – did not modify the pre/post-rate ratio associated with GDL in the combined model. In addition, although areas with movie theatres showed no overall difference in teen injury crash rates after dark, they did display a significantly larger reduction in that crash rate after GDL was implemented. Our findings suggest that place-based enhancement of GDL programs, such as strengthening driver training, encouraging more parental supervision, and increasing practice driving in areas where teens are likely to drive most, e.g., around schools, could contribute to increasing the already substantial progress made through GDL programs.

The finding that crash rate reductions were greater in areas with more alcohol outlets suggests that the Michigan GDL program succeeded either in lowering teens' exposure to high-risk driving scenarios, or in improving teen drivers' ability to handle them. Higher alcohol outlet concentration is often associated with measures of social disorganization (Nielsen et al., 2010), and is hypothesized to coincide with areas where those more inclined to engage in criminal activity reside (Snowden and Pridemore, 2013), which may correspond to a more challenging driving environment. More generally, larger numbers of alcohol outlets may indicate a generally more populated, and urban, area, which may also be intimidating for a young driver. Reductions of crash rates in such areas indicate either that young drivers were avoiding driving in these areas or were doing so more safely, which may indicate a positive outcome of the GDL program. Alternatively, alcohol outlet concentration here may be acting as a proxy for urban vs. rural supertracts, in which case this finding could indicate greater effectiveness of GDL in urban/suburban, rather than rural, communities.

Further evidence of an urban/rural component in the effectiveness of GDL lies in the finding that areas with more movie theatres saw larger crash reductions in the dark post-GDL than other areas. Movie theatres are more likely to exist in more populated supertracts, and are more likely to be frequented in the evening by teenagers. In the post-GDL period, areas with movie theatres saw a larger reduction in the injury crash rate among teens after dark, indicating that teens may more confidently navigate driving in populated areas at night. Alternatively, it may be that GDL implementation has corresponded to lower frequency of teen driving at night near movie theatres, relative to pre-GDL. In any case, identification of, and expansion of, the GDL components that generated this improved ability to avoid serious crashes in more populated areas, and at night, is a possible avenue for building upon the achievements of GDL programs.

While the overall post-GDL injury crash risk for teens was lower near schools, the crash rate reduction post-GDL was smaller in areas with more schools than the overall reduction. Teen crashes (both all and fatal) are known to peak in the hours just before and after school, which are also high-mileage hours (high exposure) for teen drivers (Williams, 2003). Areas proximal to schools – particularly high schools – may represent locales with larger concentrations of teen drivers, indicating that GDL may be less effective in scenarios where more drivers are inexperienced. This finding suggests that GDL's effectiveness may partially rely on the defensiveness of more experienced drivers to avoid crashes with teen drivers. Reinforcing defensive driving concepts in GDL programs, particularly in situations where novice drivers are overrepresented, may help to improve the effectiveness of GDL in such cases.

We found that alcohol outlets and concentrated disadvantage were both associated with teen crash risk. Paradoxically, we found that the strongest protective factor for teen driving crashes was the concentrated disadvantage index. This is in contrast to prior literature showing that areas of socioeconomic disadvantage were at high risk for crash (Aguero-Valverde and Jovanis, 2006), although we note that work was not specific to teen drivers' crash risk. One possible explanation is that teens in more disadvantaged communities are less likely to have the means to drive and therefore have less opportunity to experience crashes (Shults et al., 2015). Alternatively, disadvantaged areas and people with less social capital tend to have greater distrust of the police (MacDonald and Stokes, 2006), and thus there could be underreporting of crashes in such areas. In any case, it is unlikely that concentrated disadvantage protects teens from crash risk, but a closer examination of the place-based features of such communities may provide further insights to avenues for crash risk mitigation. On the other hand, our finding that crash risk was elevated near alcohol outlets was consistent with the preponderance of literature on spatial correlates of crash risk (Lipton et al., 2018; Scribner et al., 1994; Giacopassi and Winn, 1995; Treno et al., 2007).

We note several limitations of this work. First, using population size (in the corresponding age range) as the denominator for crash rates may be a limitation. Construction of an ideal denominator would only count licensed drivers and would also take into account where, how far, and how often they are driving; however such comprehensive public, geolocated, statewide data are not available. Most crashes, however, do occur near an individual's residence (Abdalla et al., 1997; Haynes et al., 2005), and the number of licensed drivers in a given age group is likely to be closely related to the size of that age group in a geographic locale. Thus, the resulting rate is likely to be highly correlated with the true one. Relatedly, differences in the pre- vs. post-GDL periods in teen driving frequency could confound the pre/post comparison. Measurements of those frequencies are not available, but national data indicates that the reduction in teen driving frequency—measured as average daily person trips, dropped by 10.9% (from 4.6 to 4.1) from 1995 to 2001 among those age 16–20 (Hu and Reuscher, 2004), which is notably smaller than the teen crash rate reductions seen post-GDL in Michigan, suggesting that crash rate reductions were not primarily attributable to differences in driving frequency/exposure. Second, our analysis is restricted to a single state. Given the variability in GDL's components, how it is implemented, and other state-specific factors (such as demographic characteristics), it is plausible that analyses of data from other states could generate different results. Future studies incorpating spatial factors in other states could further elucidate how GDL is effective and what further improvements could be made. Third, the time periods of the data used in these analyses do not allow consideration of modern crash risk factors, such as distraction through smart phone use. Studies using more recently instituted GDL programs would be invaluable in checking the sensitivity of these conclusions to that limitation. Fourth, ideally our analysis would be restricted to crashes caused by teens; however causal attribution was not encoded in the data used here, presumably because in many crashes, true fault is difficult to determine, making such attributions unreliable. Our analysis, like prior analyses of Michigan crash data (e.g. Shope and Molnar, 2004) instead used number of crash involvements as the outcome. Finally, there is an implicit assumption of the lack of spatial confounding, so that the identified interactions are not a product of an unmeasured variable that correlates both with crash risk and the spatial features identified; most plausibly this is a concern with regard to traffic exposure. Confounding is a concern with any observational study but, nonetheless, future analogous studies with better measures of traffic exposure would add to the literature.

This work sought to understand whether there was spatial variation in the crash rate reduction following implementation of a GDL program in Michigan, and whether small-area characteristics explained any of that variation. While GDL implementation corresponded to a reduced injury crash risk among teens in the state of Michigan overall, the magnitude of that reduction varied and was more pronounced in more populated areas, and less pronounced in areas near schools. This work builds upon prior studies examining how the characteristics of a GDL program modulate its effectiveness by quantifying how the same program can have differential effectiveness across a spatial landscape. To maximize the already substantial gains produced by GDL programs requires understanding why GDL is more effective in certain areas and harnessing that understanding to improve its effectiveness across an entire state. Harnessing that understanding has potential to improve driver training (e.g., by parents and driver educators), as well as future policy changes to current GDL policies, to further reduce the teen driver crash burden.

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Appendix A

Table A1

Standard Identification Classification (SIC) codes used to classify organizations.

Organization	SIC Code
Alcohol Outlets	581,301 (Bars)
	541,103 (Convenience Stores)
	541,105 (Grocers - Retail)
	592,102 (Liquors - Retail)
	581,304 (Night Clubs)
	594,716 (Party Supplies)
	581,208 (Restaurants)
	554,101 (Service Stations - Gasoline & Oil)
Malls	651,201 (Shopping Centers & Malls)
Movie Theaters	783,201 (Theaters - Movie)

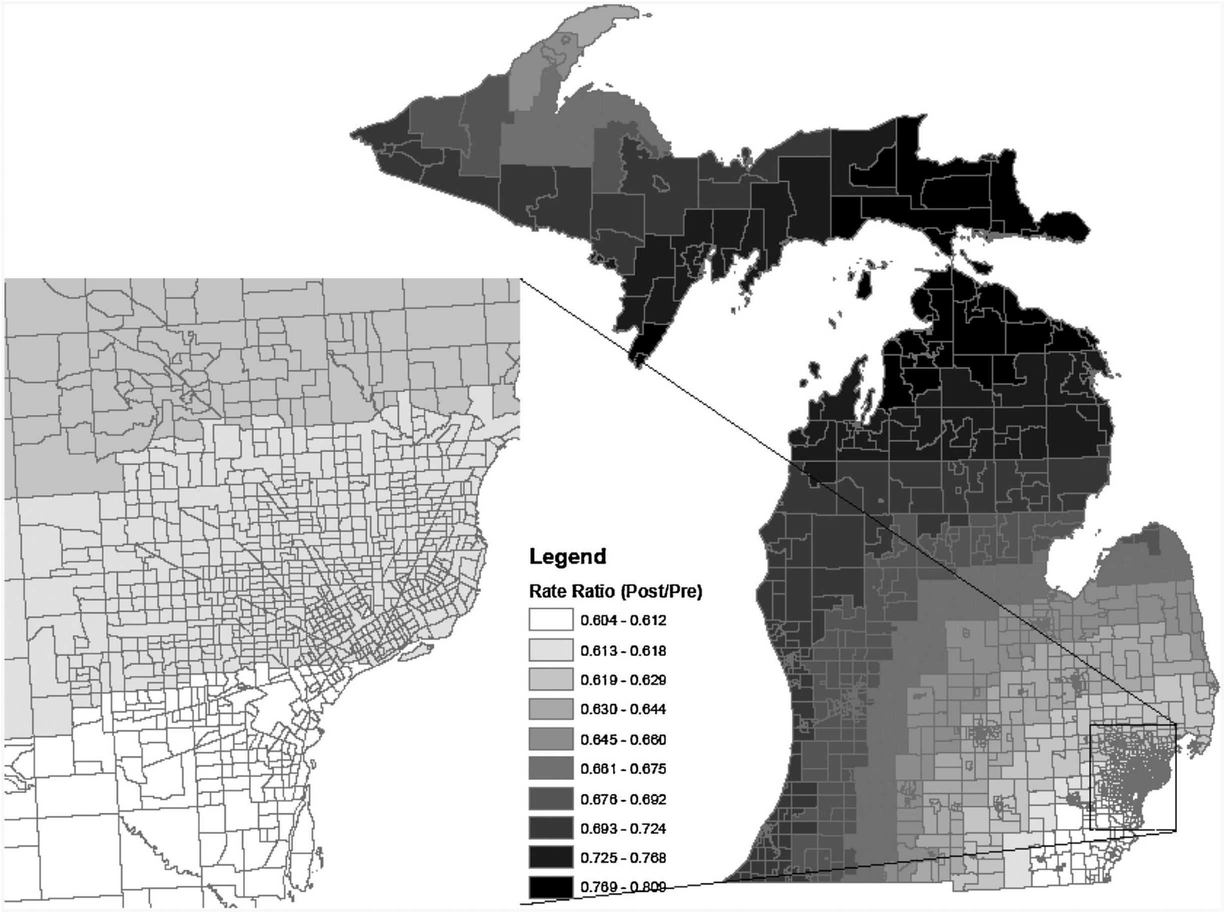

Fig. A1.
Smoothed teen crash rate reduction in Michigan following implementation of a GDL program.
Note: Crash rate reductions were smoothed using unadjusted geographically weighted negative binomial regression models. Pre-GDL crash rates are from 1994 to 1995 and post-GDL crash rates are from 2000–2001.

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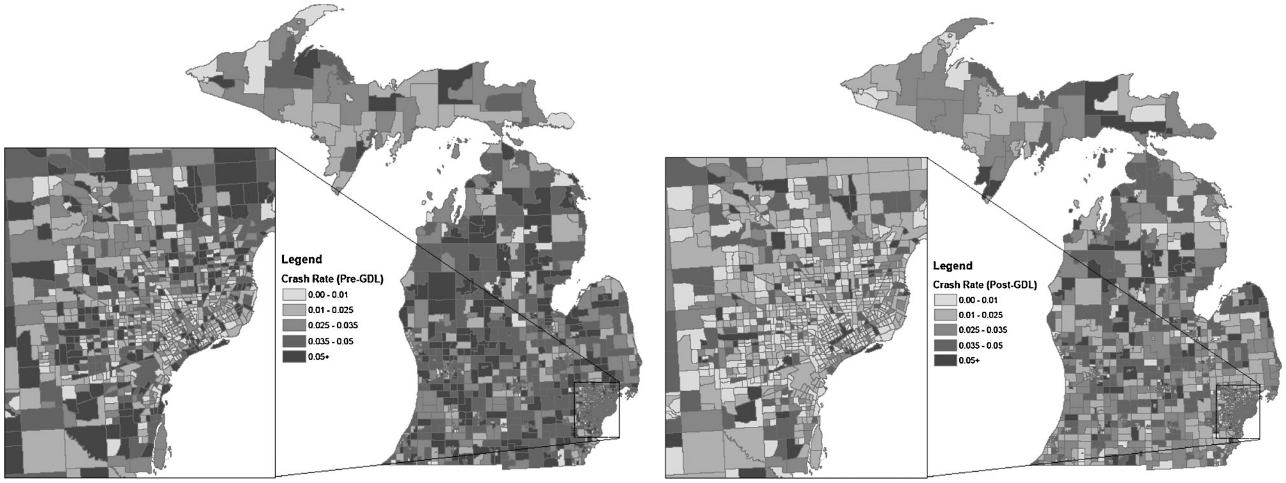

Fig. 1.

Pre-GDL (1994–1995; left) and Post-GDL (2000–2001; right) crash rates among teen drivers by census unit.

Table 1

Negative binomial spatial regression results on teen injury crash rates pre- and post-GDL.

	Overall	Male Teens	Female Teens	Daylight	Dark
Pre-GDL (1994–1995)					
Base rate (per 1000)	34.4 (33.3, 35.6)	35.8 (34.6, 37.2)	29.3 (28.2, 30.4)	21.1 (20.3, 21.9)	12.5 (11.9, 13.0)
Alcohol Outlets (per 10)	**1.18 (1.14, 1.23)**	**1.15 (1.11, 1.20)**	**1.16 (1.12, 1.21)**	**1.17 (1.12, 1.22)**	**1.17 (1.12, 1.23)**
Movie Theatres	1.08 (0.98, 1.19)	1.05 (0.95, 1.16)	**1.13 (1.01, 1.24)**	1.07 (0.97, 1.18)	1.10 (0.97, 1.24)
Schools	**0.97 (0.95, 0.98)**	**0.97 (0.96, 0.99)**	**0.97 (0.95, 0.98)**	**0.97 (0.96, 0.98)**	**0.96 (0.95, 0.98)**
Malls	0.95 (0.85, 1.07)	1.00 (0.89, 1.12)	0.89 (0.78, 1.01)	0.95 (0.84, 1.08)	0.95 (0.82, 1.11)
Concentrated Disadvantage	**0.63 (0.58, 0.67)**	**0.66 (0.61, 0.72)**	**0.58 (0.53, 0.63)**	**0.58 (0.53, 0.63)**	**0.71 (0.64, 0.78)**
ΔAIC	−17.30	−15.81	−16.29	−17.37	−1.86
Post-GDL (2000–2001)					
Base rate (per 1000)	21.4 (20.7, 22.2)	22.1 (21.3, 23.0)	19.1 (18.3, 19.9)	13.2 (12.7, 13.7)	7.8 (7.4, 8.2)
Alcohol Outlets (per 10)	**1.10 (1.06, 1.14)**	**1.07 (1.03, 1.11)**	**1.10 (1.06, 1.15)**	**1.08 (1.03, 1.12)**	**1.11 (1.05, 1.16)**
Movie Theatres	0.98 (0.89, 1.07)	0.98 (0.89, 1.08)	0.98 (0.88, 1.09)	1.04 (0.94, 1.15)	0.89 (0.79, 1.01)
Schools	**0.98 (0.97, 1.00)**	0.99 (0.98, 1.00)	**0.98 (0.96, 0.99)**	0.99 (0.98, 1.00)	0.98 (0.97, 1.00)
Malls	1.01 (0.90, 1.13)	1.00 (0.89, 1.13)	1.03 (0.90, 1.17)	0.96 (0.85, 1.09)	1.07 (0.92, 1.25)
Concentrated Disadvantage	**0.66 (0.61, 0.72)**	**0.64 (0.58, 0.71)**	**0.65 (0.58, 0.72)**	**0.63 (0.57, 0.69)**	**0.69 (0.61, 0.77)**
ΔAIC	−77.97	−72.79	−63.51	−80.06	−21.33

Note: Approximately 3% of crashes were missing driver sex; 1% were missing light condition; those cases were excluded from the corresponding stratified model, but were included in the overall model.

Note 2: Entries are crash rate ratios associated with a one-unit increase in the predictor (unless otherwise specified).

Note 3: Bolded entries indicate $p < 0.05$.

Note 4: The “Base rate” row reflects the crash rate when all covariates are set to the mean values.

Note 5: The ΔAIC row shows the AIC of the spatial model minus the AIC of the model without a spatial trend component.

Table 2

Combined negative binomial spatial regression model results on teen injury crash rates.

	Overall	Male Teens	Female Teens	Daylight	Dark
Main Effects					
GDL (0: No, 1: Yes)	**0.63 (0.57, 0.70)**	**0.67 (0.60, 0.75)**	**0.64 (0.57, 0.72)**	**0.63 (0.56, 0.71)**	**0.66 (0.57, 0.76)**
Alcohol Outlets (per 10)	**1.18 (1.01, 1.02)**	**1.15 (1.11, 1.20)**	**1.17 (1.12, 1.21)**	**1.17 (1.12, 1.22)**	**1.18 (1.12, 1.23)**
Movie Theatres	1.06 (0.97, 1.17)	1.04 (0.94, 1.14)	1.10 (0.99, 1.22)	1.05 (0.95, 1.16)	1.09 (0.96, 1.23)
Schools	**0.96 (0.95, 0.97)**	**0.97 (0.96, 0.98)**	**0.96 (0.95, 0.98)**	**0.97 (0.96, 0.98)**	**0.96 (0.95, 0.97)**
Malls	0.96 (0.86, 1.07)	1.00 (0.89, 1.13)	0.89 (0.79, 1.01)	0.95 (0.84, 1.08)	0.96 (0.83, 1.11)
Concentrated Disadvantage	**0.64 (0.60, 0.69)**	**0.68 (0.63, 0.74)**	**0.60 (0.55, 0.65)**	**0.59 (0.55, 0.64)**	**0.72 (0.65, 0.79)**
Interactions					
GDL × Alc Outlets (per 10)	**0.93 (0.88, 0.98)**	**0.93 (0.88, 0.98)**	0.95 (0.90, 1.01)	**0.92 (0.87, 0.98)**	0.94 (0.88, 1.01)
GDL × Movie Theatres	0.94 (0.82, 1.07)	0.96 (0.83, 1.10)	0.91 (0.78, 1.05)	1.01 (0.88, 1.04)	**0.83 (0.70, 0.99)**
GDL × Schools	**1.03 (1.01, 1.04)**	**1.02 (1.01, 1.04)**	1.02 (1.00, 1.04)	**1.02 (1.01, 1.04)**	**1.02 (1.00, 1.05)**
GDL × Malls	1.04 (0.89, 1.22)	0.99 (0.84, 1.18)	1.14 (0.95, 1.36)	1.01 (0.85, 1.20)	1.11 (0.90, 1.37)
GDL × Disadvantage	0.99 (0.89, 1.10)	0.92 (0.81, 1.03)	1.04 (0.91, 1.18)	1.01 (0.89, 1.14)	0.94 (0.81, 1.09)
ΔAIC	−85.98	−88.67	−65.36	−86.10	−27.87

Note: Approximately 3% of crashes were missing driver sex; 1% were missing light condition; those cases were excluded from the corresponding stratified model, but were included in the overall model.

Note 2: In the main effects, entries are crash rate ratios associated with a one-unit increase in the predictor (unless otherwise specified); in the interactions, entries are the multiplicative effect on the corresponding crash rate ratio.

Note 3: Bolded entries indicate $p < 0.05$.

Note 4: The ΔAIC row shows the AIC of the spatial model minus the AIC of the model without a spatial trend component.