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Assessing risk-taking in a driving simulator study: Modeling longitudinal semi-continuous driving data using a two-part regression model with correlated random effects

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ABSTRACT

Signalized intersection management is a common measure of risky driving in simulator studies. In a recent randomized trial, investigators were interested in whether teenage males exposed to a risk-accepting passenger took more intersection risks in a driving simulator compared with those exposed to a risk-averse peer passenger. Analyses in this trial are complicated by the longitudinal or repeated measures that are semi-continuous with clumping at zero. Specifically, the dependent variable in a randomized trial looking at the effect of risk-accepting versus risk-averse peer passengers on teenage simulator driving is comprised of two components. The discrete component measures whether the teen driver stops for a yellow light, and the continuous component measures the time the teen driver, who does not stop, spends in the intersection during a red light. To convey both components of this measure, we apply a two-part regression with correlated random effects model (CREM), consisting of a logistic regression to model whether the driver stops for a yellow light and a linear regression to model the time spent in the intersection during a red light. These two components are related through the correlation of their random effects. Using this novel analysis, we found that those exposed to a risk-averse passenger have a higher proportion of stopping at yellow lights and a longer mean time in the intersection during a red light when they did not stop at the light compared to those exposed to a risk-accepting passenger, consistent with the study hypotheses and previous analyses. Examining the statistical properties of the CREM approach through simulations, we found that in most situations, the CREM achieves greater power than competing approaches. We also examined whether the treatment effect changes across the length of the drive and provided a sample size recommendation for detecting such phenomenon in subsequent trials. Our findings suggest that CREM provides an efficient method for analyzing the complex longitudinal data encountered in driving simulation studies.

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1. Introduction

Driving simulations provide a safe and useful method for studying driving behavior that is highly associated with the on-road driving behavior (Fisher et al., 2007). Signalized intersection management is among the most complex and dangerous driving situations (Sifrit et al., 2010). A yellow light occurs as the vehicle approaches an intersection, requiring the driver to make an immediate decision to stop or continue on. Intersection management may be particularly difficult for novice drivers (Braitman et al., 2008), particularly in the presence of peer passengers. In a recent driving simulator study, interest focused on assessing the effects of peer passenger influence on teen driving behavior, where the outcomes were the number of stops for yellow lights and the time spent, by the drivers who did not stop, in the intersections when the light had turned red (Simons-Morton et al., 2014). These two measures describe different aspects of risky driving. A more cautious driver tends to stop at the yellow light; but if a driver decides to proceed through the light, the time spent in the intersection while the light is red is a direct measure of the risk of crashing, since cars from the other direction may have entered the intersection. Indeed, red light running is a major cause of side-impact crashes, which can cause serious injury and fatalities. Managing driving within the dilemma zone caused by the light turning yellow as the vehicle approaches the intersection is also a good measure of risk acceptance, which could be expected to vary according to driving conditions and driver characteristics. In this study we evaluated the effect of teenage passengers on male novice teenage drivers' intersection management and the extent of risk they accepted as measured by time in the intersection during the red light.

This dual outcome is referred to as "semi-continuous": it is right skewed, with a preponderance of zeroes indicating that many drivers stop when they approach a yellow light and greater than zero values for those who are in the intersection after the light turns red. There are two complexities of the analysis: first, the study used a longitudinal design, in which every driver is measured multiple times over the course of the simulated drive, so the outcomes measured on the same subject at different intersections are correlated. Second, the binary part and continuous part of the outcome may also be correlated, e.g., drivers who tend to stop also tend to spend less time in the intersections while the light is red when they do enter the intersection on yellow. To model the influence of experimental conditions on longitudinal, semi-continuous data, we may consider analyzing the outcome by modeling the discrete zero component separately from the nonzero continuous component. For example, a generalized linear mixed model (GLMM) can be used for the discrete outcome and a linear mixed model (LMM) for the continuous outcome. Such an approach ignores the potential dependency between the components, and hence can lead to biased effect estimates in the LMM (Albert and Shen, 2005; Su et al., 2009; Tom et al., 2014). In this case, it may be useful to jointly model these two outcomes for valid and efficient inference.

Different fields of research have developed methods to accommodate semi-continuous outcomes (Lachenbruch, 2002). Examples include health care demand in econometrics (Duan et al., 1983) and antibody assays (Moulton and Halsey, 1996) in cancer research. For longitudinal or repeated measures designs, Olsen and Schafer (2001) examined alcohol use, Albert and Shen (2005) studied emesis episodes from chemotherapy, and Tooze et al. (2002) analyzed medical expenditures. Although repeated semi-continuous outcomes have been addressed in other areas of research, this model has not been applied within driving simulator-based research. Our aim in this paper is to show how a two-part regression with correlated random effects can be used to make efficient and valid statistical inference in a driving simulator study with complex longitudinal semi-continuous outcomes. In addition, we perform numerical simulations to compare the performance of different methods in hypothesis testing problems, and make recommendations for sample size calculation in driving simulator studies.

In Section 2, we explain the design of the teen driving simulator study. Section 3 introduces the two-part regression with correlated random effects model, which we refer to as CREM, and discusses other analysis methods that ignore the correlation feature, including the GLMM, LMM and Wilcoxon rank sum test for estimating treatment effect. In Section 4, we apply CREM to the teen driving data and present the power and type I error numerical simulation study comparing CREM to other approaches. The software R (V 3.0.1), SAS (V 9.2), and SAS macro MIXCORR (Tooze et al., 2002) were used in the estimation and simulations. We summarize our findings and discuss implications of our work for future driving simulator studies in Section 5.

2. Teen driving simulator study

The teen driving simulator study was a randomized control trial designed to study how peer passengers affect teen driving performance (Simons-Morton et al., 2014). The study investigated how the presence and the type of teen passenger, either risk-averse or risk-accepting, influenced risky-driving behavior. The participants were all male, aged 16 and 17 years old, who had previous driving experience and a Michigan driver license. A randomized two-by-two crossover design was used in which participants were randomly assigned to either a risk-averse or risk-accepting male confederate passenger. The confederate passenger interacted with the driver before the simulated drive according to a protocol designed to prime the driver with respect to the passenger's risk preference. Then each study participant completed two drives, one alone and one with the assigned passenger, with the order of the two drives randomized and counterbalanced. The two study arms differed by passenger type and drives, one with and one without a passenger (solo and passenger drives, respectively). It should be noted that the predrive priming activity could affect behavior during the solo drive, as well as the passenger drive. Ultimately, it was expected that the study participants would have elevated risky behavior while driving with a peer passenger regardless of risk orientation relative to driving solo (Ouimet et al., 2013; Simons-Morton et al., 2014). The aim of this study was to determine if the effect of peer passenger was modified by the passenger type, which would be indicated by

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