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Evaluating variability in foot to pedal movements using functional principal components analysis

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ABSTRACT

There are reasons why the driver's foot may not be applied to the correct pedal while driving and this can lead to unintended consequences. In this study, we seek to capture common and unique patterns of variations in drivers' foot movements using functional principal components analysis (FPCA). This analysis technique was used to analyze three categories of pedal response types (direct hits, corrected trajectories, and pedal errors) based on the various foot to pedal trajectories. Data from a driving simulator study with video data of foot movements for 45 drivers was used for analyses. Most foot movements show common patterns associated with direct hits and corrected trajectories with some level of variation. However, those foot movements associated with unique patterns might be early indicators of pedal errors. The findings of this study can be used with collision mitigation systems to provide early detection of foot trajectories that are more likely to result in a pedal error.

1. Introduction

Pedal misapplications usually occur when the driver misses the pedal or presses the accelerator pedal when he or she intended to hit the brake pedal (Tran et al., 2011). During normal driving, the drivers generally use the accelerator pedal more than the brake pedal. The ability to switch between responses (i.e., accelerator or brake pedal) is an executive function that may have a close relationship to pedal misapplications. Tasks that require switching of responses might be impaired (Gilbert & Shallice, 2002; Philipp & Koch, 2005), depending on the most recent pedal use (Doshi et al., 2012).

Early studies have shown that pedal (mis)applications can be related to pedal designs (Collins et al., 2015) as well as driver characteristics such as age, gender, height, shoe/foot length, foot to pedal contact area/force (Schmidt et al., 1999; Schmidt et al., 1997, Lococo et al., 2012; Lococo et al., 2017). Lococo et al. (2012) noted that pedal error crashes were more likely associated with older and female drivers. In a more recent study, Lococo et al (2017) showed that anthropometric variables also impact drivers' foot positioning and foot movement while driving.

The pedal application is a skill-based motion conducted in an unconstrained space with no visual target and no feedback until an initial pedal depression occurs. In a study by Vernoy and Tomerlin (1989), drivers misperceived the vehicle centerline as being further right of the actual one. However, this misperception was not correlated with pedal errors (Vernoy and Tomerlin, 1989). Without the aid of visual feedback, drivers have to move the foot towards the target (i.e., gas/brake pedal) based on perception and experience. Two important cues for pedal operation are the pedal positioning and the "feel" (Pollard & Sussman, 1989). The direction and curvature of motions are critical and the feedback from touching the pedal (including pressure, texture, shape, position or contour) is important for distinguishing between pedals and for adjusting foot placement.

The foot trajectories or the desired direction and curvature of motion have a close relationship with muscle activities. More specifically, strength and duration could impact the foot trajectories (Schmidt, 1989) as pedal depression requires repeated performance of muscular contraction with accurate force and timing. This human neuromuscular control system could be viewed as a multi-staged process, which transform sensory input into motor output through neural architectures (Shinsuk & Sheridan, 2004). Researchers have shown that the human brain can take into account the dynamic properties of the peripheral musculoskeletal system in the initial stage, and plan accordingly before execution of any muscle activities in the final stage (Gomi & Kawato, 1996; Pennisi, 1996; Shadmehr & Mussa-Ivald, 1994). The time that a driver has to stop at an intersection can also impact the variability of foot movements (Sharpe et al., 2017).

Few studies have examined the entire foot trajectory process (Tran et al., 2011) and even fewer studies have been able to model the different types of pedal applications (either correct or not) based on foot

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movements. Several studies have modeled drivers' intentions to press the brake pedal during emergency situations and have revealed that drivers tend to exhibit a two-stage braking process (Prynne and Martin, 1995, Ising et al., 2012). In the first stage, the brake pedal is typically depressed to a moderate level; and in the second stage, the driver brakes harder to achieve the required deceleration. Hillenbrand et al. (2005) has developed an algorithm for a collision prevention assistant system based on drivers' normal and emergency braking reaction. Drivers' braking action (whether there is a need to brake and whether the driver planned to do so) was predicted by McCall & Trivedi (2007) with information collected from the vehicle, surrounding environment and the driver's foot positions around the pedal. Tran et al. (2011) used data from an optical flow based foot tracking to predict driver's foot gestures (e.g., "move towards brake/accelerator", "brake/accelerator engaged" or "release brake/accelerator"). Wu et al. (2017) studied factors within various driving scenarios and the relationship between foot placement and pedal application types using a naturalistic driving study. The findings revealed four pedal types (incorrect trajectory, hesitation, back pedal hook and pedal error) that could impact safety if not corrected in a timely manner. The paper indicated that foot to pedal trajectory (prior foot location or the task sequence prior to driving) could impact the likelihood of a pedal misapplication.

These previous studies did not examine the variations in foot trajectories across the entire pedal application process, instead, they focused more on the process before drivers move their foot and press a pedal. Foot movement variations are important because some of them could be direct factors that cause pedal misapplications. The purpose of this study is to identify the relationship between the foot trajectories and the pedal application type using the drivers' foot to pedal movements for braking. In this paper, we use data from a previous study (see Wu et al., 2015) to identify the more common approaches used by drivers when they move toward and finally press the pedal(s). Several dominant modes of variation will be discussed and the type of pedal applications related to these modes of variation will be then be modeled.

2. Methods

2.1. Data

The dataset used in this study came from a simulated environment using an instrumented vehicle (Toyota Camry 2012) secured in a stationary position. A detailed explanation of the experimental design can be found in Wu et al (2015). To summarize, drivers were guided to complete a series of pedal response task based on traffic signals that would be shown horizontally with the red light on the left side and the green light on the right side (see Fig. 1). In this current study, we are interested in capturing the variances in drivers' foot movements towards the brake pedal.

Lococo et al., 2012 indicated that most errors occur when the driver's foot transitions from the floor towards the pedal(s). To capture the entire procedure of pedal application, a reference line was drawn on the floor pan (Fig. 2). During the "null state" or between signals, drivers' are asked to place their feet behind this reference line.

Video cameras were used to record the entire foot movement process. A motion detection technique was used to extract foot trajectories for the brake pedal applications from the videos for the 45 drivers. There were 21 females with mean standing height of 67 in. (170.2 cm) and 24 males with mean standing height of 72 in. (182.9 cm). The participants age ranged from 18 to 83 years old (mean = 54.37, sd = 22.76). Because participants had different shoe sizes, the movement from the tip of the shoe was tracked (Fig. 2 shows the track point). Each driver performed nine brake pedal applications during the study. The foot trajectories were time-stamped and traced 30 times per second with recordings in X and Y coordinates in pixel units. The pixels were then converted into mm distance for readability. A total of 346 pedal applications were usable for the forthcoming analysis after missing data and low quality videos were removed.

2.2. Functional data analysis

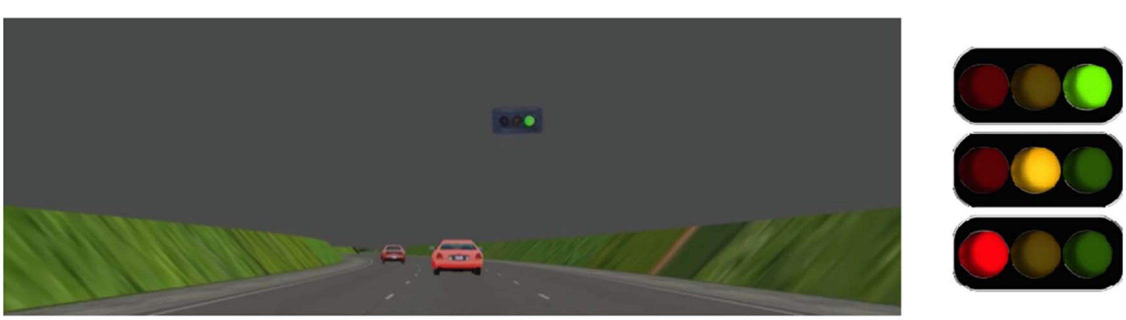
To capture a profile of different pedal behavior, a spline was initially fit as a basis function for each task completed by the drivers. Functional Principal Components Analysis (FPCA) is then applied to the splined curves to identify a reduced set of components that can provide the greatest insights into the variations in pedal movement. The components observed in the FPCA for the direct hits and corrected trajectories are then compared to the trajectories observed in the pedal errors. Those that are not similar to the direct hits and corrected trajectories are then investigated further.

The foot to pedal trajectory is a continuous function over time. We therefore, use motion detection techniques on the video to create functional representations, which are then used to reconstruct every continuous foot movement curve (Ramsay & Silverman, 2006). An appropriate function basis is then selected that can capture the shape of the sampled data and also possess convenient computational properties (Ramsay & Silverman, 2002). B-Splines, which are made of polynomials, each one spanning a limited interval and then composed together smoothly, were used in this study. The B-spline functions were fitted by minimizing the sum of squared errors (Graves et al., 2009) with order of four (i.e., cubic B-spline) and 26 numbers of knots. This places a knot at every other observation point, and corresponds closely to a spline smoothing result. The cubic B-spline function with k knots has the basis function expansion:

$$x(t) = \sum_{j=1}^{K+4} B_j^4(t)\beta_j \quad (1)$$

where $B_j^4(x)$ is the set of cubic B-splines basis functions which are combined linearly.

Different patterns of foot movements were observed among different drivers and even within the same driver. Principal components



(a) (b)

Fig. 1. Example of the simulated road environment.