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Driver decision-making in the dilemma zone – Examining the influences of clearance intervals, enforcement cameras and the provision of advance warning through a panel data random parameters probit model

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ABSTRACT

In recent years, there have been a series of innovations in the field of vehicle detection at intersection approaches. Modern radar-based smart sensors make it possible to track individual vehicles in close proximity to an intersection. These advancements in technology potentially enable the provision of vehicle- and site-specific decision dilemma zone protection at the onset of the yellow indication at signalized intersections. To exploit this opportunity, it is critical to develop an in-depth understanding of those factors influencing a driver's decision to stop or go at the onset of yellow. This study investigates how signal timing strategies such as yellow interval durations, all-red clearance intervals, advance warning flashers, and automated camera enforcement affect driver decision-making. Data from 87 intersection approaches across five regions of the United States are used to develop a series of decision (i.e., probability of stopping) curves using vehicle trajectory and signal phasing data. A panel data random parameters probit model is used to account for heterogeneity across locations, as well as correlation in driver decision-making, due to unobserved factors that are unique to each signalized intersection. The results demonstrate drivers are more likely to stop at locations where enforcement cameras or flashers are present. Stopping was also more prevalent at intersections with lower speed limits, longer crossing distances, and where pedestrian crosswalks were present.

1. Introduction

Signalized intersections require high levels of driver attention and cognition, particularly at the onset of the yellow signal phase when drivers must make a quick decision as to whether to stop or proceed through an intersection. Of particular concern is the area referred to as the "dilemma zone". The original definition, referred to as a Type I dilemma zone, is the area of an approach to a signalized intersection where a driver can neither stop comfortably nor safely clear the intersection at the onset of yellow (Gazis et al., 1960; May, 1968). This approach uses deterministic design values such as perception-reaction time, comfortable deceleration rate, and duration of the yellow interval to determine the stopping and clearing distances. Stopping distance (X_s) is the distance from the stop bar prior to which any vehicle can stop using a comfortable deceleration. Clearing distance (X_c) is a distance from stop bar after which any vehicle can cross the stop bar without accelerating. When $X_s > X_c$, these distances form the boundaries of the dilemma zone, between which drivers could neither stop nor clear comfortably. Determining X_s and X_c provides the basis for calculating the yellow interval and, hypothetically, when signals are designed such that $X_c \geq X_s$, the dilemma zone can be eliminated.

The main limitation of defining the dilemma zone in this manner is that it assumes approaching drivers have perfect knowledge of all variables, and the decision to stop or go is therefore clear. In reality, drivers have a perception of certain variables such as their distance from the stop bar and the impending yellow duration, but lack perfect knowledge, leading to indecision when faced with the yellow display. To address this uncertainty, subsequent research introduced the term decision dilemma zone, also referred to as the decision zone or as a Type II dilemma zone (ITE Technical Committee 18, 1974). The decision dilemma zone is defined as the approach area within which the probability of deciding to stop at the onset of yellow is within the range of 10–90 percent (Zegeer and

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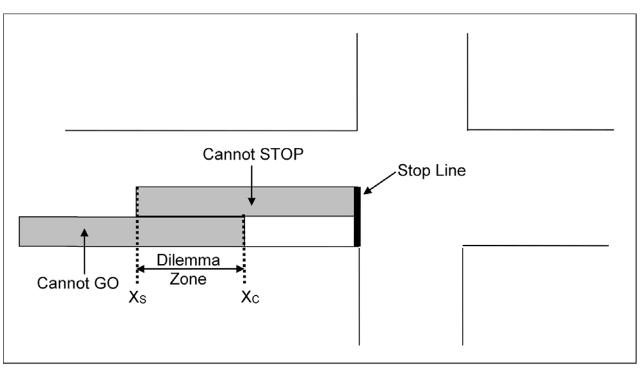
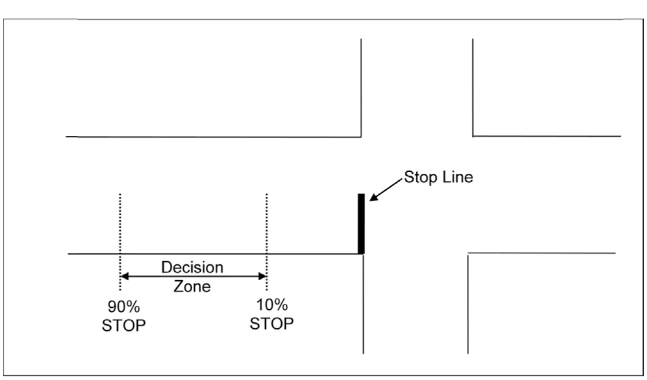
Deen, 1978). This definition accounts for the inherent variability in human perception (Sheffi and Mahmassani, 1981), which persists at any signalized intersection where vehicles arrive during the yellow interval. The two dilemma zone definitions are illustrated in Fig. 1.

Driver uncertainty in the decision dilemma zone may increase both the risk of rear-end collisions due to drivers stopping abruptly, as well as angle and left-turn head-on collisions due to red light running. Consequently, these concerns have motivated substantive research in this area. Various methods have been used to ascertain the decision dilemma zone boundaries (Herman et al., 1963; Olson and Rothery, 1962; Webster and Ellson, 1965; ITE Technical Committee, 1974; Sheffi and Mahmassani, 1981; Chang et al., 1985; Bonneson et al., 1994; Gates et al., 2007, 2012; Sharma et al., 2007). Initial attempts to model the decision dilemma zone involved a frequency-based approach to examine the probability of stopping. The percentage of drivers stopping at a given approach speed and distance from the stop bar were used to develop cumulative distribution functions. Significant variations were observed in the dilemma zone boundaries obtained from such frequency-based methods.

In order to obtain a better understanding of driver decisions in the dilemma zone, researchers have also utilized discrete choice models (e.g., binary logit and probit) to examine the likelihood of stopping at various approach speeds and distances from the stop bar (Sheffi and Mahmassani, 1981; Chang et al., 1985; Gates et al., 2007; Papaioannou, 2007; Burnett and Sharma, 2011). Such research has also sought to better understanding the underlying human decision models and explain the variation in the observed dilemma zone boundaries. This has included assessing how various site (e.g., signal timing, geometry), vehicle (e.g., vehicle type), and driver (e.g., age, gender) characteristics are associated with the decision to stop or proceed through the intersection at the onset of yellow (Köll et al., 2004; Gates et al., 2007; Papaioannou, 2007; Sharma et al., 2007; Elmitiny et al, 2009; Yan et al., 2009; Sharma et al., 2010; Burnett and Sharma, 2011; Zhixia and Heng, 2013; Abbas et al., 2014).



a Traditional (Type I) Dilemma Zone



b Decision (Type II) Dilemma Zone

Fig. 1. Traditional definition of dilemma zone vs. decision dilemma zone.

This study builds upon the extant research literature in order to gain a better understanding of how various traffic signal strategies, as well as the provision of advance information to drivers, affects decision-making at the onset of yellow. A random parameters probit model is estimated to analyze the impacts of factors, such as yellow interval duration and the presence of camera enforcement, while controlling for potential confounding factors (e.g., volumes, crossing distance, etc.). The random parameters framework is able to account for correlation among drivers on the same intersection approaches, in addition to accommodating heterogeneity due to unobserved driver- and site-specific factors.

2. Theoretical framework of driver decision-making

At the onset of yellow, drivers must decide whether to stop or proceed through a signalized intersection based upon available information, as well as their historical driving experiences at that specific intersection and other similar locations. This decision process can modeled as a relationship between each driver's perceived time to the stop bar at the onset of yellow, as well as that person's decision threshold as to whether they should stop or continue through the intersection (Sheffi and Mahmassani, 1981).

Let T_p be a driver's perception of the time to the stop bar along an approach to a signalized intersection. Since T_p may vary for a driver based on several factors, such as the distance from the stop bar, instantaneous approach speed, and knowledge of the yellow interval based on past experience, T_p can be considered a random variable:

$$T_p = t_p + \xi, \tag{1}$$

where t_p is the expected time to the stop bar based on the vehicle's instantaneous speed and distance from the intersection at the onset of yellow. To account for the variability in perception of the time to stop bar among the driving population, a random error term (ξ) is added to the model. This error term is assumed to follow a normal distribution with mean of zero and variance of σ_ξ^2.

A driver will stop if T_p is greater than their personal time threshold, T_t, which constitutes their perception of the maximum time required to safely clear the intersection under given conditions. If the driver perceives their time to the stop bar is less than this threshold (i.e., they can proceed safely), the driver will continue through the intersection. This time threshold varies across the driving population based upon each driver's experience, behavior, and other driver- or site-specific factors. Consequently, Tt is a random variable with mean value t_t and an error term that is normally distributed with mean of zero and variance of ε_ξ^2. Denoting the covariance of T_p and T_t as $\sigma_{\xi,\varepsilon}$, the probability of stopping can then be expressed as:

$$P_{STOP}(T_p) + Pr\{T_t < T_p\} = \Phi\left(\frac{t_p - t_t}{\sigma}\right) \tag{2}$$

where, $\Phi(\cdot)$ denotes the standard normal cumulative distribution function and $\sigma = \sqrt{\sigma_\xi^2 + \sigma_\varepsilon^2 + 2\sigma_{\xi,\varepsilon}}$.

Fig. 2 illustrates factors that influence a driver's decision of whether to stop or continue through a signalized intersection at the onset of yellow. The top portion of Fig. 2 shows how the required acceleration to clear the intersection and the required deceleration to stop change as a function of the time to stop bar. For given conditions (i.e., speed, distance to stop bar, yellow duration, etc.), smaller values of time to the stop bar require vehicles to decelerate more rapidly in order to stop prior to the onset of the red signal indication. In concept, a heavy deceleration threshold could be identified,