Modeling of Driver Anxiety During Signal Change Intervals

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The anxiety that a driver experiences at the onset of the yellow signal during the driver's approach to a signalized intersection is analyzed. The driver's decision is modeled as a reasoning process that consists of a set of fuzzy inference rules for stopping or continuing through the intersection. The input to the rules is the information on the current condition that the driver perceives. Because neither the rules nor the perceived information is clear, the driver's decision is associated with uncertainty. This uncertainty is quantified by possibility and necessity measures. Yager's anxiety measure is used to quantify the driver's anxiety associated with making decisions under uncertainty as a function of possibility and necessity measures for the conflicting actions. Anxiety is computed for both aggressive and conservative drivers. The measures for these two extreme types of driving behavior form the range; most drivers' behavior is believed to fall between the two. The model is used to estimate the degree of anxiety and its location on an actual intersection approach on the basis of the field data. The proposed method should be useful to evaluate the accuracy and the type of information to be provided to drivers and also to analyze the decision process of elderly drivers and drivers under the influence of alcohol and drugs.

Safety and efficiency of traffic flow depends largely on the perception and reaction of individual drivers. Most of the time, each driver determines the appropriate action by exercising a set of vague driving rules. One example of this is the case of driver's action when the signal changes to yellow as he is approaching the intersection. He experiences a state of indecision and anxiety because he must evaluate many parameters and decide either to continue through the intersection or to stop in a short time period.

This study proposes a decision model that evaluates the degree of anxiety that a driver experiences when he has to choose one of the conflicting actions at the onset of the yellow signal. The method also identifies the zone in the approach where the driver experiences anxiety. Later a study of anxiety based on field data is presented. The study is part of an effort to understand driver decision processes when the perceived information and decision rules are not clear and also to understand how improved information helps the driver's decision and reduces anxiety.

The present practice of determining the signal change interval is based on the premise that each driver has complete knowledge of the information needed for the decision. In reality, the driver has neither the complete information nor the rigid rules needed to make the correct decision. As a result, regardless of how correct the setting of the interval of signal change is (the basis of the existing standards), most drivers face a period of indecision and anxiety at the onset of the yellow signal.

Indecision and anxiety are caused by the lack of clear information and well-defined criteria to make the decision. Unclear information allows different interpretations of the decision parameters by the decision maker; at the two extremes are optimistic and pessimistic interpretations. The decision mechanism under uncertainty is usually based on fuzzy inference rules, which are developed through the individual's attitude and experience. Thus, drivers make different decisions, some aggressive and some conservative.

Recently developed uncertainty theory allows the measurement of anxiety as a function of optimistic and pessimistic interpretations of the perceived information and inference rules. In this paper, the anxiety measure developed by Yager (*1*) is used to compute the degree of anxiety that a driver experiences at different locations along the approach to an intersection at the onset of the yellow signal. Further, the model is intended to help evaluate the features of a driver decision support system by examining how improved information and decision rules affect drivers' behavior and anxiety. This is a relevant issue for implementation of intelligent vehicle-highway systems (IVHS).

The existing approaches to model the driver's decision process during the signal change interval are discussed first. Then the basic measures of uncertainty—the possibility measure and the necessity measure—are explained. By a combination of these two measures, the degree of anxiety associated with choosing one of the decision options is computed. Finally, the measurement of the anxiety that aggressive and conservative drivers experience is presented using a set of data obtained at an intersection.

DRIVER ANXIETY AND THE PROBLEM

The study of driver anxiety requires understanding of the decision process, which is based on a collection of imprecise rules and vaguely perceived information. Anxiety during a decision process is discussed and the need to develop a model that expresses anxiety in the mind of a driver is defined.

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Driver Anxiety

A driver has two alternatives when the signal turns yellow while he is approaching an intersection. One is to continue through before the signal turns red; the other is to stop at the intersection. In order to make the decision, the driver requires a set of decision rules and information on the current condition.

Vagueness is embedded in the two factors in this decision process. One type of vagueness lies in the information available to the driver, who does not know, for example, how long the yellow will last nor his exact current location. Thus, the driver interprets the available information in the form of perception, which may take the form of linguistic rather than numerical expressions.

Another type of vagueness is embedded in the decision rules. The rules are not based on rigid mathematical functions; rather, they constitute a fuzzy inference system consisting of a set of "If . . . Then" rules; for example, if the vehicle is traveling at high speed and is very close to the intersection when the light turns yellow, then clear the intersection or if the vehicle is far from the intersection and traveling at a low speed when the light turns yellow, then stop. Given the input, the match between the input and the premise of a rule ("If . . .") determines the degree of truth of the application of the rule. The input is the perceived information discussed above.

Anxiety occurs when the perceived information and the decision rules are fuzzy and yet one must take one of the crisp actions, in this case either stop or continue driving. The differences among drivers' behaviors emerge from the perception of information and application of the rules. Precise numerical information about distance, for example, may not be helpful to the driver unless he has the decision rules that use it. How one interprets and perceives the given state is critical in this process. If the range of possible interpretation increases, one's anxiety should increase. If, on the other hand, rules are rigid and the information is precise, an external command can substitute for the driver's decision and no anxiety will be present.

The Problem

The problem of this study is to develop a model that represents the anxiety that a driver feels at the onset of the yellow signal. The model should be capable of measuring the degree of anxiety along the approach to the intersection. It should also be capable of evaluating the effect of improving the quality of information and rules in the driver decision support system. Further, it should be capable of explaining the differences among the driver behaviors (for example, conservative versus aggressive driving) on the basis of the difference in the interpretation and application of the rules.

The model will be helpful in addressing several important issues related to driver decision and its implication for traffic engineering: (*a*) the driving attitude of the elderly; (*b*) the perception and decision patterns of impaired drivers, such as drivers under the influence of alcohol or drugs; and (*c*) the effect of in-vehicle information systems. In IVHS, it is conceivable that the yellow signal may be transmitted to the vehicle and with the information on the vehicle's speed and location, the on-board computer may advise the driver about the appropriate action.

EXISTING APPROACHES DEALING WITH DRIVER'S DILEMMA

Driver decision and behavior during the signal change interval is a classic topic in the traffic engineering literature. Various approaches and models have been proposed to analyze the appropriate signal change intervals and the driver's decision process. They are grouped into two approaches here: the deterministic and the statistical.

Deterministic Approach

The signal change interval is provided to warn drivers of the impending red signal. When a driver approaches an intersection, there exists a point (Point A) on the approach roadway before which it is impossible for him to clear the intersection during the signal change interval. Similarly there exists a point (Point B) beyond which it is not possible for the driver to stop. If Point B is farther from the intersection than Point A, and if he is in the region between these two points, he can neither clear nor stop during the signal change interval. This zone is called the dilemma zone. Conversely, if Point A is farther from the intersection than Point B, an area called the option zone in which both the clearing and stopping maneuvers are possible exists between Points B and A. The sizes of the dilemma zone and the option zone can be controlled by the signal change interval.

Gazis et al. (*2*) developed equations for calculating the clearing distance (D_g), the stopping distance (D_s), and the signal change interval that prevents the creation of the dilemma zone. D_g is the distance measured from the intersection within which one can safely clear the intersection, and D_s is the distance measured from the intersection beyond which one can safely stop before the intersection:

$$D_g = Vd - (w + l) + a(t - d)^2/2 + V(t - d) \tag{1}$$

$$D_s = V^2/2b + Vd \tag{2}$$

where

V = speed of the vehicle (ft/sec),
d = driver perception-reaction time (sec),
t = signal change interval (sec),
b = deceleration rate (ft/sec^2),
l = vehicle length (ft),
a = acceleration rate (ft/sec^2), and
w = intersection width (ft).

When $D_g \geq D_s$, the dilemma zone is eliminated; thus the value of t should be

$$t \geq d + \frac{w + l}{V} + \frac{V}{2b} \tag{3}$$

where acceleration during clearing is assumed to be zero.

In this approach, it is assumed that all drivers have accurate information to make the decision and that all the drivers behave in the same manner by evaluating the current location with respect to D_g and D_s. Normally, this is not the case. The information available to the drivers is neither precise nor complete, and not all drivers travel at the same values of V, w, l, b, and a. As a result, regardless of how correct the signal change interval is for the design vehicle and driver, drivers experience anxiety and their decisions are different.

Statistical Approach

Many researchers have examined driver anxiety on the basis of field observations of the frequency with which drivers stop at different distances on the approach upon seeing the yellow light. The zone in the road where the "stopping probability" is between 10 and 90 percent has been assumed as the dilemma zone by many researchers. The percentage of drivers who stopped was interpreted as the probability that an individual driver would stop. Plots of the cumulative probability function were developed by many, among them Zegeer and Deen (*3*), Olson and Rothery (*4*), May (*5*), Williams (*6*), and Chang et al. (*7*).

The above approach has been expanded to model the relationship between the actions of stopping (or continuing) and the distance. The dependent variable is a binary probability value (1 if the vehicle stops and 0 if the vehicle goes) and the independent variable is the distance from the intersection. There are two types of assumption as to the assumed cumulative probability functions: a linear function and a cumulative normal function.

Linear Probability Model

The linear probability model assumes the probability of stopping as a linear function of the distance from the intersection. The probability is 1 for all the distances greater than a certain large distance and 0 for all the distances less than a certain small distance. However, the linear model may estimate a probability value greater than 1 and less than 0 for the region where the probability values are near 0 or near 1.

In order to rectify this shortcoming, a nonlinear expression has been proposed. Two of the most popular ones are the logistic function and the cumulative normal function. The estimation model that uses the logistic function is called the logit model and the one that uses the cumulative normal function is called the probit model. The probit model application is reviewed and its merits and limitations are discussed using the presentation of Sheffi and Mahmassani (*8*).

Probit Model

The probit model expresses the probability of stopping as a function of drivers' perceived time to reach the stop line (T). Considering variation among the drivers in perception and reaction time, T is assumed to be a random variable of the following form:

$$T = t + \psi \qquad (4)$$

where t is the time taken for a car to reach the stop line at a constant speed, and ψ is a random variable reflecting the differences in perception and reaction among the drivers. It is assumed that ψ is normally distributed, ψ: $N(0,\sigma_\psi^2)$.

It is hypothesized that if T is less than a critical value T_{cr}, the driver would choose to proceed through the intersection. The value of T_{cr} is also assumed to vary with the driver because of many factors, such as driving experience. Thus, the value of T_{cr} can also be assumed to follow the normal distribution:

$$T_{cr} = t_{cr} + \varepsilon \qquad (5)$$

where t_{cr} is the mean critical time and ε is the disturbance term, which is normally distributed ε: $N(0,\sigma_\varepsilon^2)$. The probability that a driver would stop is then given by

$$\Pr(\text{Stop}) = \Pr[T_{cr} < T] \qquad (6)$$

The fundamental assumption in this model is that values of both T_{cr} and T follow a normal distribution. The probability of stopping is expressed by the probability that the driver perceives the value of T to be greater than the value of T_{cr}. This is perhaps a valid assumption if the model is to represent the variation in the behavior of the population. In other words, it is valid under the following conditions: although each individual knows the values of T_{cr} and T clearly and decides either to continue or to stop with no hesitation, different persons assume different values of T_{cr} and T, and their values are distributed normally among the population. Thus, the model is useful to explain the variation of decisions for the population as a whole.

If this model is used to infer the state of mind of an individual, however, it implies that each driver's decision process is random, and on encountering the same situation he may react differently in a random manner.

Discussion of Existing Approaches

Both approaches discussed above attempt to capture the process in which the driver compares the current status (in terms of either the distance from the intersection or the time before the signal turns red) with his threshold values of decision. The deterministic approach considers that the driver knows both the current condition and the threshold values clearly and that the knowledge of all drivers is the same. The statistical approach, on the other hand, considers that each driver has a different understanding of the current values and the threshold values. In this respect, the latter approach is more realistic and attempts to account for the variation in driver behavior.

When an individual interprets a value that is vague, his perception can be represented as possibility instead of probability. The possibility distribution, in short, represents the distribution of values based on the notion of "can be," whereas the probability distribution represents the value based on the frequency of random outcomes.

Many have proposed that possibility, instead of probability, is a more appropriate form to represent the individual's choice under uncertainty. Among them are Shackle (*9*), Cohen (*10*), and Klir (*11*). If the possibility distribution is used to represent the uncertainty in the assumed values of T_{cr} and T, the choice of continuing should be based on the *possibility* that T is greater than T_{cr}, and the outcome is expressed by *possibility*.

The possibilistic approach is suited for analyzing the process of subjective inference and reasoning. It is also suited to express the degree of anxiety during the decision. Anxiety is caused by the vagueness of information provided to the decision maker. Thus, the possibilistic approach allows the assessment of the effectiveness of specific engineering measures in mitigating driver anxiety.

BASIC MEASURES OF UNCERTAINTY

Possibility and Necessity Measures

Traditionally, probability has been the approach used to deal with uncertainty. Probability represents the degree of truth in terms of the frequency of occurrences based on the evidence presented. Recently, new measures that represent uncertainty have been proposed. Among them, possibility is perhaps the most often used in dealing with uncertainty involving perception and subjective judgment.

Given imprecise and uncertain information, one's perception can vary depending on the attitude in interpretation. The extreme cases are possibility-based and necessity-based interpretations. Possibility-based interpretation accounts for all nonnegative evidence and draws a conclusion, whereas necessity-based interpretation accounts for only positive evidence that supports the truth. It can be said that these two represent optimistic and pessimistic interpretations, respectively.

Given evidence E, which is fuzzy and is represented by a membership function $h_E(x)$, the possibility that a particular event A is supported is given by the following:

$$\text{Poss}(A) = \max_{x \in A} h_E(x) \tag{7}$$

Equation 7 indicates that the largest membership grade of the elements included in A represents the possibility that "the unknown is A."

Necessity measure, on the other hand, considers only the positive evidence that supports the conclusion. It is related to possibility by the following:

$$\begin{aligned} \text{Nec}(A) &= 1 - \text{Poss}(\text{not } A) \\ \text{Poss}(A) &= 1 - \text{Nec}(\text{not } A) \end{aligned} \tag{8}$$

In other words, the necessity of A is equal to the impossibility of "not A."

In this problem, given the current condition (which is characterized by vague information), the driver's judgment that the current condition indicates stopping or clearing action can be represented by these two measures. Each parameter that determines the stopping or clearing distance in Equations 1 and 2 is perceived as fuzzy by the driver; in other words, the values of both D_s and D_g are perceived as fuzzy numbers and are represented by membership functions. The driver compares the current location with the fuzzy values of D_s and D_g. The comparison can be performed in either a possibilistic or a necessity-based manner; the former represents the optimistic and the latter the pessimistic manner.

The difference between these two measures for an action signifies the degree of uncertainty of the driver for executing the action successfully. These two measures are related to the attitude of the driver (aggressive or conservative). For most persons, however, the degree of uncertainty of taking an action A is a value between Nec(A) and Poss(A). Explanation and discussion of the "Poss" and "Nec" measures are found in many books on fuzzy sets. They include Dubois and Prade (*12*), Klir and Folger (*11*), Kosko (*13*), and Zimmermann (*14*).

Uncertainties associated with the decision process that are relevant to this analysis are caused by nonspecificity, fuzziness, and confusion.

1. Nonspecificity is related to and caused by imprecise perception. The nonspecificity measure represents the level of uncertainty by a range of values for a perceived parameter.
2. Fuzziness is a type of uncertainty that is caused by vagueness in the definition of the sets, such as "high speed," "small distance," etc. This uncertainty is referred to as the fuzziness. Fuzziness of a fuzzy set is due to the presence of the elements with partial membership, which will be members of the complement of the set as well. The fuzziness is a measure of the overlap of the set with its complement.
3. Confusion is a type of uncertainty that is caused by the evidence that supports conflicting actions. It is represented by the measure of confusion proposed by Hohle (*11*).

These three types of uncertainty are characteristics of information. They cause different interpretations of the same evidence, which, in turn, result in possibility- and necessity-based conclusions by the decision maker.

Measure of Anxiety

The uncertainties explained above cause anxiety in the mind of the decision maker. Yager (*1*) has proposed an equation that expresses the degree of anxiety when a choice is made from a set of conflicting actions:

$$Ax = 1 - \int_0^1 \frac{1}{|A_\alpha|}\, d\alpha \tag{9}$$

where

Ax = degree of anxiety given information x,
A = set of alternative decisions,
$|A_\alpha|$ = number of alternatives whose possibility or necessity measures are greater than α, and

$$\int_0^1 \frac{1}{|A_\alpha|}\, d\alpha$$

is called the tranquility measure. (Ax is 1 minus the tranquility measure.)

Ax is used to represent the degree of anxiety that a driver experiences. In the case of a two-choice situation, to stop or to continue, Yager's model reduces to

$$Ax = 1 - \max(m_G, m_s) + {}^1\!/\!_2[\min(m_G, m_s)] \qquad (10)$$

where m_G and m_S correspond to the possibility and (or) necessity measures of "continue" and "stop," as will be explained later.

The anxiety measure is the highest when both measures, m_G and m_S, are equal to 0; it is equal to 0 when one of the two measures equals 1 and the other 0. This shows that anxiety is the highest when the possibility (or necessity) measures of the two conflicting actions are both 0, indicating that neither action is possible (yet one has to be chosen). It is the lowest when only one action is supported fully.

MODELING DRIVER CHARACTERISTICS AND BEHAVIOR

The decision patterns of aggressive and conservative drivers are defined and the possibility and necessity measures for stopping and continuing actions of these drivers are computed. These two types of drivers are assumed to define the range of behaviors of most drivers. These values are used to compute anxiety in the next section.

Definition of Aggressive and Conservative Drivers

An aggressive driver's primary desire is to reduce the travel time. Thus, his first choice is to go. He examines the possibility of going first at the onset of the yellow signal. He stops only if it is impossible to clear. The decision rule of the aggressive driver is

Go if possible; stop if necessary.

A conservative driver is safety conscious and resorts to a safe action. He goes only if it is impossible to stop. In other words, his first choice is to stop and he will go only if it is necessary. The decision rule of the conservative driver is

Stop if possible; go if necessary.

Between these two extreme types of drivers are some drivers who may act on the basis of "go if possible and stop if possible."

Measures of Going and Stopping

Normally a driver perceives information of the current speed, current location, and the current driving conditions as fuzzy quantities as he approaches an intersection. These values are compared with the general values of stopping and going, and if the perceived current states match the premise of the rules completely, the corresponding action is undertaken. If the perceived states match the premise of the rules of both actions partially, anxiety is assumed to occur. How the perceived states match the rules (for stopping and going) is evaluated by the possibility and the necessity measures.

The following notation is used to represent the possibility distribution of the perceptions of the current states: speed, $\pi(s)$; distance, $\pi(d)$; driving conditions, $\pi(z)$, where s is speed, d is distance, and z is an index of goodness of road or traffic conditions.

Possibility of Going

The decision to go is based on the combination of the following criteria:

Criterion 1: The current speed is high,
Criterion 2: The current location is near the intersection,
Criterion 3: The current road or traffic condition index is high.

Given $\pi(s)$, $\pi(d)$, and $\pi(z)$, the validity of each statement is evaluated by possibility measures.

For Criterion 1, the possibility that the current speed is high is computed by

$$\text{Poss}(V_h) = \text{Max Min}[\pi(s), \mu V_h(s)] \qquad (11)$$

where V_h denotes the notion "high speed" and $\mu V_h(s)$ denotes the membership grade of s in the fuzzy set of "high speed."

For Criterion 2, the possibility that the current distance is short is computed by

$$\text{Poss}(D_s) = \text{Max Min}[\pi(d), \mu D_s(d)] \qquad (12)$$

where D_s denotes the notion "short distance" and $\mu D_s(d)$ denotes the membership grade of d in the fuzzy set of "short distance."

For Criterion 3, the possibility that the road or traffic condition index is high is computed by

$$\text{Poss}(I_h) = \text{Max Min}[\pi(z), \mu I_h(z)] \qquad (13)$$

where I_h denotes the notion "high index" and $\mu I_h(z)$ denotes the membership grade of z in the fuzzy set of "high index." A road or traffic condition index is introduced to account for all other environmental effects on driver decisions, such as road surface condition, traffic condition after the intersection, geometric design.

Going is possible only when all three criteria are satisfied, in other words, the possibilities that the current speed is high, the current distance is small, and the current road or traffic condition index is high. Hence, the possibility of going under the current condition x can be computed as the minimum of the possibility measures of the three criteria:

$$\text{Poss}_x(\text{Go}) = \text{Min}[\text{Poss}(V_h), \text{Poss}(D_s), \text{Poss}(I_h)] \qquad (14)$$

Possibility of Stopping

The decision to stop is based on the following criteria:

Criterion 1: The current speed is low,
Criterion 2: The current distance is long,
Criterion 3: The current road or traffic condition index is low.

Given $\pi(s)$, $\pi(d)$, and $\pi(z)$, the validity of each statement is evaluated by possibility measures, as with the case explained above.

The possibility that the current speed is low is given by

$$\mathrm{Poss}(V_1) = \mathrm{Max\ Min}[\pi(s), \mu V_1(s)] \tag{15}$$

where V_1 denotes the notion "low speed" and $\mu V_1(s)$ denotes the membership grade of s in the fuzzy set of "low speed."

The possibility that the current distance is long is given by

$$\mathrm{Poss}(D_1) = \mathrm{Max\ Min}[\pi(d), \mu D_1(d)] \tag{16}$$

where D_1 denotes the notion "long distance" and $\mu D_1(d)$ denotes the membership grade of d in the fuzzy set of "long distance."

The possibility that the current road or traffic condition index is low is given by

$$\mathrm{Poss}(I_1) = \mathrm{Max\ Min}[\pi(z), \mu I_1(z)] \tag{17}$$

where I_1 denotes the notion "low index" and $\mu I_1(z)$ denotes the membership grade of z in the fuzzy set of "low index."

Stopping is possible only when all three criteria are satisfied, in other words, the possibilities that the current speed is low, the current distance is long, and the road or traffic condition index is low (not suitable for going). Hence the possibility of stopping under the current condition x can be computed as a minimum of the possibility measure of the three criteria:

$$\mathrm{Poss}_x(\mathrm{Stop}) = \mathrm{Min}[\mathrm{Poss}(V_1), \mathrm{Poss}(D_1), \mathrm{Poss}(I_1)] \tag{18}$$

Necessity of Going

The necessity of going is derived from the basic relationship between the possibility and necessity measures, according to Equation 8.

$$\mathrm{Nec}(\mathrm{Go}) = 1 - \mathrm{Poss}(\mathrm{Stop}) \tag{19}$$

Using Equation 18, it can be shown that this is equivalent to

$$\mathrm{Nec}_x(\mathrm{Go}) = \mathrm{Max}[\mathrm{Nec}(V_h), \mathrm{Nec}(D_s), \mathrm{Nec}(I_h)] \tag{20}$$

This expression means that going is necessary under the current condition x if the current speed is high, the current distance is short, or the road or traffic condition index is high. The necessity to go is the maximum of all these necessity measures. In other words, if any one of these conditions is necessarily satisfied, the driver will decide to go.

Necessity of Stopping

Similarly, the necessity of stopping is derived from the basic relationship between possibility and necessity measures:

$$\mathrm{Nec}(\mathrm{Stop}) = 1 - \mathrm{Poss}(\mathrm{Go}) \tag{21}$$

It can be shown that this is equivalent to

$$\mathrm{Nec}_x(\mathrm{Stop}) = \mathrm{Max}[\mathrm{Nec}(V_1), \mathrm{Nec}(D_1), \mathrm{Nec}(I_1)] \tag{22}$$

This shows that going is necessary under the current condition x only if any one of the three criteria is necessarily satisfied.

ANXIETY AND INFLUENCING FACTORS

In this section, anxiety for aggressive and conservative drivers on the basis of Yager's measure and the factors that influence anxiety are discussed.

Anxiety for Aggressive and Conservative Drivers

The degree of anxiety is computed by introducing the possibility and necessity measures developed in the previous section into Equation 10, which can be derived separately for aggressive and conservative drivers.

Because aggressive drivers utilize the rule "go if possible; stop if necessary," m_G and m_S in Equation 10 correspond to $\mathrm{Poss}_x(\mathrm{Go})$ and $\mathrm{Nec}_x(\mathrm{Stop})$, respectively. Thus, the anxiety under the current condition x is calculated as

$$Ax = 1 - \mathrm{Max}[\mathrm{Poss}_x(\mathrm{Go}), \mathrm{Nec}_x(\mathrm{Stop})] + {}^{1}\!/_{2}\mathrm{Min}[\mathrm{Poss}_x(\mathrm{Go}), \mathrm{Nec}_x(\mathrm{Stop})] \tag{23}$$

Because conservative drivers utilize the rule "stop if possible; go if necessary," m_G and m_S in Equation 10 correspond to $\mathrm{Poss}_x(\mathrm{Stop})$ and $\mathrm{Nec}_x(\mathrm{Go})$, respectively. Thus, anxiety under the current condition x is calculated as

$$Ax = 1 - \mathrm{Max}[\mathrm{Poss}_x(\mathrm{Stop}), \mathrm{Nec}_x(\mathrm{Go})] + {}^{1}\!/_{2}\mathrm{Min}[\mathrm{Poss}_x(\mathrm{Stop}), \mathrm{Nec}_x(\mathrm{Go})] \tag{24}$$

These two types of drivers constitute the range in the driving population. For most drivers, anxiety should be computed for values of $\mathrm{Nec}_x(\mathrm{Go}) \leq m_G \leq \mathrm{Poss}_x(\mathrm{Go})$ and $\mathrm{Nec}_x(\mathrm{Stop}) \leq m_S \leq \mathrm{Poss}_x(\mathrm{Stop})$ in Equation 10.

Effect of Perception on Anxiety

Vagueness in the perception of the parameters of the current condition x is represented by the shapes of the possibility distributions of the parameters $\pi(s)$, $\pi(d)$, and $\pi(z)$. Their shapes influence the values of $\mathrm{Poss}_x(\mathrm{Go})$, $\mathrm{Poss}_x(\mathrm{Stop})$, $\mathrm{Nec}_x(\mathrm{Go})$, and $\mathrm{Nec}_x(\mathrm{Stop})$.

The weakening of perception would result in possibility distributions with a larger spread and the sharpening of perception, in possibility distributions with a smaller spread. For an aggressive driver, an increase in $\mathrm{Poss}_x(\mathrm{Go})$ and at the same time a decrease in $\mathrm{Nec}_x(\mathrm{Stop})$ in Equation 23 results in a lower degree of anxiety. Similarly, for a conservative driver, an increase in $\mathrm{Poss}_x(\mathrm{Stop})$ and at the same time a decrease in $\mathrm{Nec}_x(\mathrm{Go})$ results in a lower degree of anxiety. Consequently, under the weak perception an aggressive driver may attempt to go at a distance too far from the intersection or a conservative driver may attempt to stop at a point too close to the intersection, both with little feeling of anxiety. This may help to explain the effects of impaired recognition on driving behavior, for example, driving under the influence of alcohol and drugs.

Effect of Driving Experience on Anxiety

When a driver travels on the same road and through the same intersection regularly, he tends to get an increasingly clear picture of which location is "too far" and which location is "too close" or what speed is "too high" and what speed is "too low" for the intersection. Hence, experience sharpens his perception. This explains why drivers with high familiarity of the road and the intersection experience less anxiety than unfamiliar drivers. Reduction in anxiety brings about more uniformity among the behavior of drivers. The Highway Capacity Manual (*15*), for example, makes an observation to this effect and introduces an adjustment factor to account for driver experience (commuter versus noncommuter).

ANALYSIS BASED ON FIELD DATA

In order to understand how much anxiety a driver experiences at the onset of the yellow signal, a series of field surveys was conducted at an intersection in New Castle County, Delaware. The purpose of this survey was to measure the driver's anxiety only through the observation of the final action (stopping or going). On the basis of the data, necessity measures of stopping and going were derived and the corresponding possibility measures were calculated. These observed values were used to identify anxiety and the zone of anxiety along the approach.

Survey Procedure

The selected intersection is on level terrain and has good visibility and sufficient shoulder width. The speed limit on the approach roadway is 50 mph (80 km/hr). The duration of the yellow signal is 4 sec. A video camera was placed on a pedestrian overpass at the intersection to record the following data at each instant of the yellow signal: (*a*) the location of the last vehicle that cleared the intersection and (*b*) the location of the first vehicle that stopped at the intersection.

The survey was conducted for 22 hr, and 1,120 valid data points were collected. Most vehicles approached near the 50-mph limit before the signal changed. Each data point represents evidence to be used as the basis for developing necessity measures.

Analysis

The data were used to derive necessity measures and possibility measures for stopping and going, to compute the degree of anxiety, and to identify the zone of anxiety.

It was assumed that the sampled drivers behaved rationally and consistently. In other words, if a driver decided to stop at the point where he saw the signal change, he would stop at any point farther away than that point. Similarly, if he decided to go at the point where he saw the yellow signal, he would go at any point nearer than that point. Thus, the possibility and necessity measures increase or decrease monotonically along the approach.

Computation of Necessity Measures of Stopping and Going

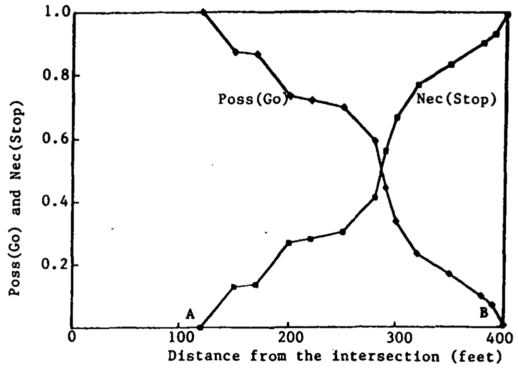
Necessity measures of stopping and going for the population were obtained from the proportion of data that supported the action necessarily. Thus, the necessity measure of stopping under a given condition x is an increasing function with respect to the distance from the intersection. $\text{Nec}_{300'}(\text{Stop})$, for example, is the proportion of drivers that stopped at 300 ft (91 m) or closer. Similarly, the necessity to go at 300 ft, $\text{Nec}_{300'}(\text{Go})$, is given by the proportion of drivers that went at 300 ft or farther. The necessity measures for stopping and going are plotted along the approach in Figures 1 and 2. Nec(Stop) is 1 at a location far away from the intersection, and it gradually decreases as the location becomes closer to the intersection. Conversely, the Nec(Go) is 1 near the intersection and decreases with increasing distance from the intersection.

Derivation of Possibility Measures of Stopping and Going

Given the necessity measures, the possibility measures for going and stopping were computed on the basis of the relationship between possibility and necessity measures (Equation 8): $\text{Poss}_x(\text{Go}) = 1 - \text{Nec}_x(\text{Stop})$; $\text{Poss}_x(\text{Stop}) = 1 - \text{Nec}_x(\text{Go})$; for example, the possibilities of going and stopping from 300 ft are $\text{Poss}_{300'}(\text{Go}) = 1 - \text{Nec}_{300'}(\text{Stop})$ and $\text{Poss}_{300'}(\text{Stop}) = 1 - \text{Nec}_{300'}(\text{Go})$. The possibility measures computed on the basis of these relationships are also shown in Figure 1.

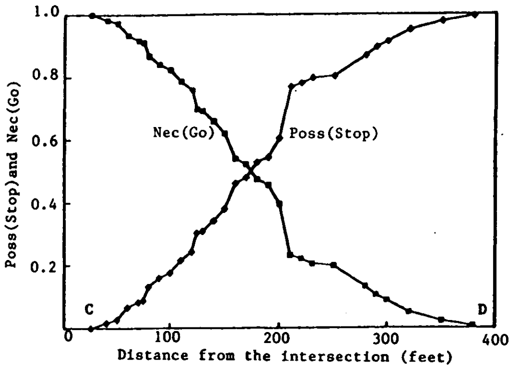
Degree of Anxiety

With the possibility and necessity measures obtained above, the degree of anxiety that aggressive and conservative drivers would experience according to Equations 23 and 24, respectively, is computed. The degree of anxiety for these two types of drivers is shown in Figures 3 and 4. It is seen that in both cases the highest degree of anxiety occurs at the location where the measures of the two conflicting choices are equal; in other words, the intersection of Poss(Go) and Nec(Stop)



Note: 1 foot = 0.3048 meter

FIGURE 1 Distribution of Nec(Stop) and Poss(Go): aggressive driver's decision measures.



Note: 1 foot = 0.3048 meter

FIGURE 2 Distribution of Nec(Go) and Poss(Stop): conservative driver's decision measures.

for aggressive drivers and the intersection of Poss(Stop) and Nec(Go) for conservative drivers. This confirms the notion that when two conflicting choices are equally supported by the perception, the maximum anxiety is felt.

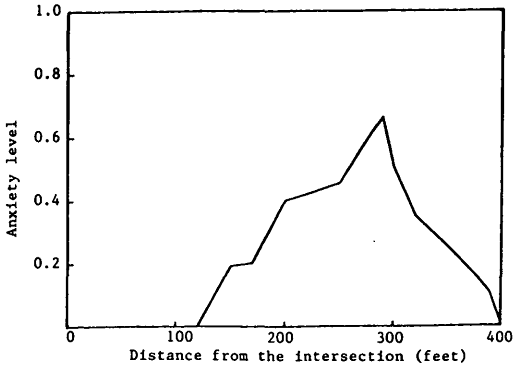
Aggressive and conservative drivers are two extreme types. Most drivers' behavior falls between these types, and their values of m_G and m_S in Equation 10 are perhaps between the possibility and necessity measures, that is, $\text{Nec(Go)} < m_G < \text{Poss(Go)}$, and $\text{Nec(Stop)} < m_S < \text{Poss(Stop)}$. To test the anxiety measures of this type of a driver, the values of m_G and m_S are taken as the middle values of their respective ranges; in other words, the assumed values are

$$m(\text{Go}) = 0.5 \times [\text{Nec(Go)} + \text{Poss(Go)}]$$

$$m(\text{Stop}) = 0.5 \times [\text{Nec(Stop)} + \text{Poss(Stop)}]$$

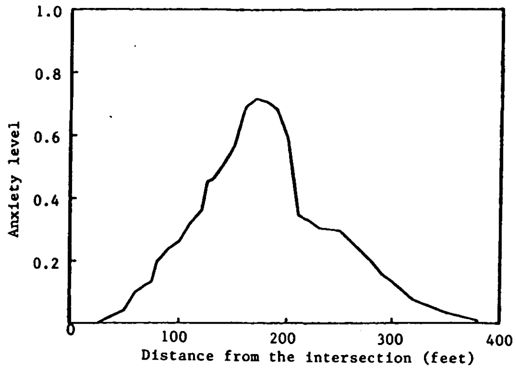
The distributions of m(Go) and m(Stop) for this driver are derived using the values obtained in Figures 1 and 2, and they are shown in Figure 5. The corresponding anxiety measure is calculated by the following equation and shown in Figure 6:

$$Ax = 1 - \text{Max}[m(\text{Go}),m(\text{Stop})] + \tfrac{1}{2}\text{Min}[m(\text{Go}),m(\text{Stop})] \qquad (25)$$



Note: 1 foot = 0.3048

FIGURE 3 Anxiety level of aggressive drivers along approach to intersection.



Note: 1 foot = 0.3048

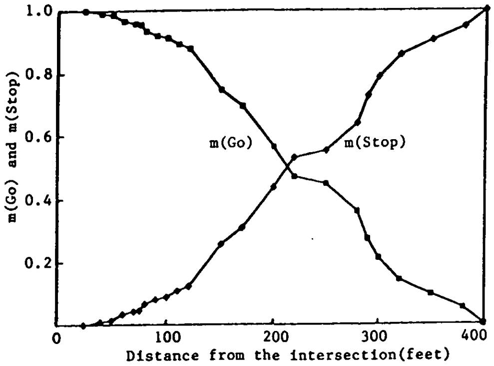
FIGURE 4 Anxiety level of conservative drivers along approach to intersection.

When this anxiety measure is compared with those in Figures 3 and 4, the anxiety measure of Figure 6 is located between those of the aggressive and the conservative drivers. This indicates that the two extreme types of drivers help define the range of drivers' decision patterns.

Zone of Anxiety

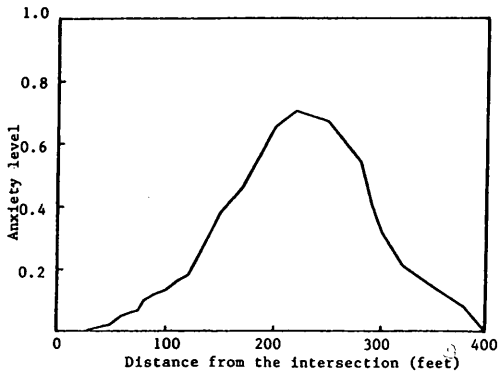
The zones of anxiety for aggressive and conservative drivers can now be identified in Figures 3 and 4. It is seen that the width of the anxiety zone for the two types of drivers is approximately same. Yet the location of the anxiety zone for conservative drivers is closer to the intersection than is that for aggressive drivers.

It is also seen that the locations of the maximum anxiety are different for the two types of drivers; that of the conservative driver is closer to the intersection than is that of the aggressive driver. This can be explained by the following. The conservative driver's first choice is to stop. Therefore, he decides to stop at a location farther from the intersection with no hesitation, and he decides to go only when he is very close



Note: 1 foot = 0.3048 meter
m(Go) = 0.5 (Nec(Go) + Poss(Go));
m(Stop) = 0.5 (Nec(Stop) + Poss(Stop))

FIGURE 5 Distributions *m*(Go) and *m*(Stop) along approach to intersection.



Note: 1 foot = 0.3048 meter
m(Go) = 0.5 (Nec(Go) + Poss(Go));
m(Stop) = 0.5 (Nec(Stop) + Poss(Stop))

FIGURE 6 Anxiety level of drivers with *m*(Go) and *m*(Stop).

to the intersection. Thus, his anxiety intensifies closer to the intersection than that of the aggressive driver.

The previous research has identified the zone of driver indecision or dilemma only on the basis of the observed data on the frequency of stopping, for example, the area where the probability of stopping is between 0.1 and 0.9. This study suggests that not only the frequency of stopping but also the frequency of going must be counted to determine the area of dilemma.

The zone between *A* and *B* of Figure 1 corresponds to the area of indecision or dilemma according to the dilemma zone by the previous studies. On the basis of this analysis, however, this area corresponds to the anxiety zone of aggressive drivers. The anxiety of conservative drivers occurs in the area where both the Poss(Stop) and Nec(Go) are greater than 0 (the area between *C* and *D* of Figure 1). Hence, the zone of anxiety is actually *C* to *B*, which is greater than that previously considered because the anxiety of the drivers who decided to go was not counted in defining the dilemma in previous studies.

CONCLUSIONS

In this paper the driver's decision process during the signal change interval is modeled. The study treats the driver's decision mechanism as a fuzzy inference process, an interaction of imprecise information and vague inference rules. Uncertainty associated with the interpretation of information and feasibility of alternative actions are measured by possibility and necessity. The decision process is analyzed for two extreme types of drivers, conservative and aggressive. Yager's measure of anxiety is proposed to measure driver anxiety.

A series of field surveys was conducted to collect data on driver decision patterns for the two types of drivers. The data were applied to the model to identify the degrees of anxiety and the zones of anxiety for the two types of drivers. Conservative drivers were found to experience anxiety closer to the intersection than aggressive drivers. The zone of anxiety was found to be greater than that previously considered when the anxiety experienced by drivers who went as well as those who stopped was taken into account.

This study is essentially theoretical in nature. The models developed, however, can be useful in understanding the effect of information on the decision process and behavior, and also in evaluating the effectiveness of improving information and communication in reducing driver (or traveler) anxiety. The study underscores the notion that regardless of how correct the timing of the yellow phase from the established standard, drivers still experience anxiety during signal change intervals. The only way to alleviate the anxiety is by providing commands to the driver externally; furthermore, the commands could be adjusted to the individual driver's decision tendency. Implementation of such a scheme is plausible under IVHS.

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