Freeway Lane-Changing Process: A Microscopic Approach

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A model analyzing the driver's process of changing from one lane to the adjacent lane is described based on research presented by Levin (1). The model uses gap acceptance concepts to evaluate the probability of accomplishing a lane change within a certain distance under various traffic conditions. Such a model can be used in determining the effectiveness of the location of freeway directional and information signs.

MODEL DESCRIPTION

Lane-Changing Process

A vehicle is traveling in lane i at time mean speed U_i adjacent to a traffic substream traveling in lane i + 1 at speed U_{i+1} (in this case, $U_{i+1} > U_i$). The probability density function of headways in the ith lane may be denoted by $\theta_i(t)$.

At a certain time t a need for a lane change (in this case, to the left adjacent lane) is established by the drivers, and the lane-changing process begins. The driver attempting the lane change looks at the adjacent lane, lane i + 1, and considers some or all of the following:

1. The speed of the approaching (lagging) vehicle in lane i + 1,
2. The relative position of the leading vehicle in lane i + 1,
3. His or her own speed and operational characteristics, and
4. His or her gap acceptance characteristics.

At time t + T, where T is the driver's decision time, the driver either accepts the gap and changes lanes or rejects it and waits for an acceptable gap. If he or she decides to accept the gap, the lane-changing maneuver begins at the earliest possible moment when a safe maneuver can be accomplished. If the gap is rejected, the driver reduces his or her speed, evaluates the next gap, and reaches an appropriate decision concerning that gap.

The lane-changing process may be full or partial. The full process occurs either

1. When the gap encountered immediately after the need for a lane change has been established is rejected because it is smaller than the driver's critical gap, or
2. When the gap encountered is greater than the critical gap but the vehicle is in such a position relative to the lagging vehicle that the lane-changing maneuver is considered hazardous and the gap is rejected.

The full process consists of the following three phases:

1. Waiting for an acceptable gap or lag,
2. Bringing the vehicle to a position relative to the accepted gap so that the lane changing maneuver can be initiated, and
3. The lane changing maneuver.

The partial process occurs when the first encountered gap, after a need for a lane change has been established, is accepted. It takes place under either one of the following forms:

Form A, the position of the attempting vehicle must be adjusted relative to the accepted gap before a safe maneuver can be initiated, and

Form B, the relative position of the attempting vehicle allows the immediate initiation of the lane changing maneuver.

Both of these forms consist of phases 2 and 3 above. Each phase in the various forms of the lane-changing process has its own distribution function with respect to the distance involved. These functions are themselves functions of traffic conditions on the facility. The expression $f_i(x_i, \overline{V}, \overline{U})$ denotes the distribution functions of the distance required to complete phase i under volume condition $\overline{V}$ and speed condition $\overline{U}$. $\overline{V}$ and $\overline{U}$ are vectors representing traffic flow rates and time mean speeds respectively on the lanes of the one-way freeway section

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during the time of the process.

Any function representing any phase of the process is independent of those characterizing other phases for a given set of speed and volume conditions. The distribution functions of the distance required for completing the various lane-changing processes were considered as the convolutions of the individual distribution functions describing each phase in the appropriate form of the process and can be presented as follows:

1. Full process

$$f_F(x,\bar{V},\bar{U}) = f_{1F}(x_1,\bar{V},\bar{U}) * f_{2F}(x_2,\bar{V},\bar{U}) * f_3(x_3,\bar{V},\bar{U}) \quad (1)$$

2. Partial process, form A

$$f_A(x,\bar{V},\bar{U}) = f_{2_A}(x_2,\bar{V},\bar{U}) * f_3(x_3,\bar{V},\bar{U}) \quad (2)$$

3. Partial process, form B

$$f_B(x,\bar{V},\bar{U}) = f_{2B}(x_2,\bar{V},\bar{U}) * f_3(x_3,\bar{V},\bar{U}) \quad (3)$$

The composite distribution representing the combination of the various lane-changing processes for a given set of volume and speed conditions is

$$f(x,\bar{V},\bar{U}) = a_F f_F(x,\bar{V},\bar{U}) + a_A f_A(x,\bar{V},\bar{U}) + a_B f_B(x,\bar{V},\bar{U}) \quad (4)$$

where a_F, a_A, and a_B are the probabilities of occurrence of the three types of the process.

Structure of the Accepted Gap

The section on the origin lane that parallels the accepted gap may be divided into three zones. One zone is that in which the driver cannot initiate a lane change because such a maneuver might end in a conflict with a leading vehicle on the destination lane. The size of this zone is the safe space lead. If a need for a lane change is established at time t while the attempting vehicle is within the above zone, the driver might find himself at time t + T either within or outside this zone. This, of course, depends on

1. The driver decision time T,
2. The relative speed $U_{i+1} - U_i$, and
3. Where within the zone the need for a lane change has been established.

If at time t + T the driver is outside the above zone, he or she is subject to form B of the partial process since he or she may start the lane-changing maneuver at time t + T. If the driver is still within this zone, he or she is subject to form A of the partial process, but the driver must be outside this zone before initiating the maneuver.

Generally, if the driver's traversed distance relative to the leading vehicle during decision time T is greater than the size of the above zone, the lane change process will be either full or form B of the partial. Conversely, if the size of the zone is greater than the decision relative distance, the driver may be subject to either one of the three types of the process.

The second zone is that in which the driver decides to reject the acceptable gap because a conflict with the lagging vehicle might result if the maneuver is executed. The driver is subject, in this case, to the full process. This zone is a combination of two subzones: the decision relative distance and the safe space lag.

The size of the third zone is, of course, a function of the size of the two previous zones and is the zone in which form B of the process takes place.

Process Phases

Phase 1 occurs when the driver attempting a lane change rejects the first gap he or she encounters in the adjacent lane after establishing a need for a lane change. The driver rejects the lane change because either

1. The gap encountered is smaller than the driver's current critical gap T_1, which is established according to an angular velocity model (2), or
2. The gap is greater than the driver's critical gap but the position of his or her vehicle relative to this gap is such that a lane change would be hazardous.

After rejecting the initial gap, the driver is assumed to change his or her speed and establish, according to the angular velocity model, a new critical gap, T_2. A distance distribution function may be derived from probability considerations of rejecting any sequence of gaps, size of average rejected gap, and speeds in the origin and destination lanes.

Phase 2 involves the movement of the attempting vehicle within the accepted gap before the lane-changing maneuver is initiated. In the case that the safe space lead is equal to or greater than the decision relative distance, the distance function in the full process is a single point function related to U_i, U_{i+1}, and the size of the safe space lead. In form A, the distance function is of a uniform nature related to U_i, U_{i+1}, T, and the safe space lead. In form B, the distance function is a single point function related to U_i and T. In the case in which the decision relative distance is greater than the safe space lead, the distance function in the full process can be described as a single point related to U_i, U_{i+1}, T, safe space lead, and the probability of the time spent in this phase. In form B, the distance function is a single point related to U_i and T.

Phase 3 is the lane-changing maneuver defined as the distance required for a vehicle to move from a straight-ahead path in the origin lane to a straight-ahead path in the destination lane.

Analysis of data collected by Worrall and Bullen (3) revealed that, for various volume and speed groupings, the distribution of the above distances was of an Erlang nature.

The probability of occurrence of each type of the process was determined for various traffic volume and speed groupings, based on the critical gap characteristics and the structure of the accepted gap.

DATA COLLECTION AND ANALYSIS

Data Collection

A northbound three-lane section (under automatic surveillance) of the Gulf Freeway in Houston was selected for this study. Data on traffic stream speeds and lane flow rates were collected by the control center, and an instrumented vehicle was driven by a test driver to obtain the following lane-changing data:

1. Delay in making a lane change once an instruction for a lane change has been given and
2. The distance traversed during the lane-changing process.

The critical gap characteristics of the test driver were determined through field measurements of his threshold angular velocity.

The characteristics of the headway distribution functions $\theta_i(t)$ on the freeway lanes were assumed to be of an Erlang nature, and the value of the parameters varied according to flow rates, as shown by Drew, Buhr, and Whitson (4).

Data Analysis

The goodness of fit of the collected data to the model developed was determined by using the Kolmogorov-Smirnov test (5) and was found to exist at the 1 percent level of significance. Traffic data used in the analysis represented freeway levels of service B, C, and D.

APPLICATIONS

Application of the developed model can be found in reference (6) where the effectiveness of the location of directional signs, spaced as recommended by the Manual on Uniform Traffic Control Devices on a four-lane freeway, was analyzed. For the purpose of this analysis effectiveness was defined as the probability of completing a lane change within a distance determined by the location and size of a sign with respect to an exit ramp, for levels of service B and C. Based on this analysis it was found that for both levels of service the effectiveness of the sign at the gore area was between 0.35 and 0.45, while for the 1.6 and 3.2-km (1 and 2-mile) signs the effectiveness was very close to 1.0.

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