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Characterizing and Modeling Observed Lane-Changing Behavior

Lane-Vehicle-Based Microscopic Simulation on Urban Street Network

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Key findings are discussed regarding characteristics of lane-changing behavior based on observations of an urban street network. An in-depth exploration of observed lane-changing behavior and its modeling were conducted using vehicle trajectory data extracted from video observations using VEVID, a software package developed by the authors, integrated with a video-capture system. As a result, rules for modeling lane-changing behavior are proposed with respect to various types of lane changes. A lane-changing model consists of three components: a decision model, a condition model, and a maneuver model. Drivers' decisions to change lanes depend on travel maneuver plans, the current lane type (i.e., the relationship between the current lane and the driver's planned route), and traffic conditions in the current and adjacent lanes. A lane-changing condition model is the description of acceptable conditions for different types of lane changes. A lane-changing maneuver model describes a vehicle's speed and duration when a certain type of lane change occurs. All of these models are established in a heuristic structure.

A lane-changing model is an important component of lane-specific vehicle-based microscopic traffic simulation models, such as those used for the evaluation of some intelligent transportation system (ITS) applications, including the advanced traveler information system (ATIS) and the advanced traffic management system (ATMS) (*1*). However, lane-changing behavior has not been studied extensively, especially on urban street networks. In addition, most available models are based on either theoretical analysis or limited spot observations, most likely because of the difficulty of getting simple, clean vehicle trajectory data appropriate for studying lane-changing behavior. In fact, most available models deal with lane-changing behavior for freeways and may not be suited to urban streets.

Because of the recent availability of the low-cost and high-quality video-capture technique along with high-speed and high-capacity personal computers, it is now feasible to digitize full-motion video at a rate of up to 30 frames per second. To help extract traffic-related data from a digitized video, computer software called Vehicle Video-Capture Data Collector (VEVID) was developed by the authors (*2*). Availability of this tool enabled the authors to conduct field observations and to study vehicle-based travel behavior and simulation modeling using empirical data. Results from the study on lane-changing behavior modeling on urban streets are presented and an example of research using a solid empirical ground is demonstrated.

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The authors conducted lengthy videotaped observations over eight urban streets in Kansas City, Missouri, and extracted trajectory data from almost 1,000 vehicles using VEVID. A discussion is provided of key findings on characteristics of lane-changing behavior derived from the observations. An in-depth exploration of observed lane-changing behavior and its modeling was conducted on the basis of vehicle trajectory data. The purpose of this study was to characterize lane-changing behavior on an urban street network to provide the basis for structuring a lane-changing model. A lane-changing model consists of three components: a decision model, a condition model, and a maneuver model. Drivers' decisions to change lanes depend on route plans, the current lane type (i.e., the relationship between the current lane and the driver's planned route), and traffic conditions in the current and adjacent lanes. A lane-changing condition model is the description of acceptable conditions for different types of lane changes. A lane-changing maneuver model describes a vehicle's speed and duration when a certain type of a lane change is executed. All of these models are established in a heuristic structure.

ANALYSIS AND INTERPRETATION OF OBSERVATIONS

Study Scope

The scope is confined to two-lane one-way and two-way streets (or four-lane streets) with signalized intersections in an urban downtown area. Since a street with a posted speed limit of less than 30 mph (48 km/h) usually bears light traffic and fewer lane-changing events occur, according to the authors' observations in Kansas City, Missouri, sites with posted speed limits of 30 mph or more were desirable. Eight one-way and two-way street sections eventually were selected. All targeted vehicles were passenger cars. A total of 994 samples of lane-changing behavior were observed and analyzed.

Classification of Lane Changes on Urban Network

There are many reasons for drivers to change lanes during their travel on urban streets. Two types of lane-changing behavior, mandatory and discretionary, have traditionally been defined (*3*). It was recognized through observations that a driver's intentions both to keep staying in the right path and lanes and to gain a speed advantage are the general reasons for changing lanes on an urban street. Gaining a speed advantage here includes cases like maintaining a driver's desired speed, avoiding potential delay caused by slowdown or blockage ahead, and expecting downstream congestion in the current lane. Some cases related to road conditions were not considered in the study, for example, a driver changing to an adjacent lane in order to drive on smoother pavement. In addition, it was observed that a number of lane changes were made to get into the correct lane for a convenient turning maneuver at a downstream intersection rather than for a speed advantage. This type of lane change is termed a preemptive lane change in this paper.

For the clarity of the following analysis, Figure 1 defines the various vehicles involved in a lane-changing maneuver. The three types of lane changes—mandatory, preemptive, and discretionary—are defined and analyzed in the following sections.

Mandatory Lane Change

A mandatory lane change refers to a lane change that a driver has to make before he gets out of the current segment or miss his route, be forced to detour, or find that the current lane is closed ahead. In this case, the lane to which a driver desires to change is termed the target lane. For instance, a driver who plans to make a turn at the next intersection must change to the lane that has access to the exit at which he wants to turn off. A mandatory lane change occurs when a driver desires to get out of a left lane to avoid a left or right exit that is not on his planned route. In another example, the driver makes a mandatory lane change when a lane closure is ahead or when he is going into a merging area. If no acceptable gaps are available, a cooperative maneuver by the lag vehicle, for example, slowing down so as to leave sufficient room for the lane changer, is required.

Preemptive Lane Change

A preemptive lane change refers to a lane change performed to position the driver in the proper lane for an eventual maneuver (e.g., to turn left or right or to get out of the exit lane of the intended closed lane), even though he does not intend to make such a maneuver at the next intersection but at some subsequent intersection. In this case the driver has neither such a strong desire to change lanes as he does in a mandatory lane change nor an urgent need to avoid potential delay to gain a speed advantage. The basic purpose for such a lane change is to get in the correct lane in advance. Of the total 994 lane-changing samples, 461 were classified as preemptive lane changes. The preemptive lane-changing samples were analyzed on the basis of different traffic conditions in which the changes occurred. Figure 2 shows several typical cases of preemptive lane changes. In these cases, the lane to which a driver desires to change is defined as the preemptive lane.

Figure 2*a* shows the case of clear conditions, which accounted for 34.1 percent of the total lane changes. No speed advantage or benefit, urgency, or intended turn movements could be observed to explain these lane changes. Drivers maintained very similar speeds after changing lanes and went straight through at the next intersection. A reasonable explanation is that they were moving to a desirable lane (i.e., the preemptive lane, as defined previously) to be ready for an intended turn movement at a downstream intersection (not the next one). A driver familiar with the area may make a preemptive lane change because, for example, he expects possible congestion in the preemptive lane of the downstream segments, where it would be difficult to execute a lane change.

Figure 2*b* shows another typical example in which a vehicle moves to a higher-density lane from a lower-density lane. Meanwhile, large enough gaps acceptable for a lane change are available in an adjacent lane. In this case no speed advantage or other temporary advantage in delay reduction accompanies such a lane change. This case accounts for 7.3 percent of the preemptive lane-changing samples.

Figure 2*c* refers to the case in which a vehicle changes to a lower-density lane from a higher-density lane although other drivers with similar conditions or even smaller headways to the preceding vehicle in their current lane did not execute a change. Moreover, the lane changers did not speed up or overtake the previous leaders after their lane changes. None of this type of maneuver, which accounts for 12.2 percent of the preemptive lane-changing samples, is likely aimed at a temporary advantage.

In Figure 2*d* a lane changer, after a lane change, is still behind a preceding vehicle in the current lane or the leader in the target lane. In this case, the speed advantage is near zero. This case accounts for 24.4 percent of the preemptive lane-changing samples.

Decisions for both mandatory and preemptive lane changes are dependent on the driver's desire to be in a target lane. The only distinction between the two changes is that a mandatory lane change refers to the maneuver that keeps a driver from missing the correct route at the next intersection, whereas a preemptive lane change refers to the maneuver motivated by a desire to turn or avoid potential trouble and get into the correct lane at some intersection subsequent to the next one.

Discretionary Lane Change

A discretionary lane change is one in which a change is executed to pass a slower-moving vehicle. A driver expects a lane change whenever he thinks the speed of the vehicle ahead in the current lane is intolerable and acceptable gaps are available in the target lane.

To describe a driver's willingness to make a discretionary lane change in a quantitative model used in a simulation, speed advantage

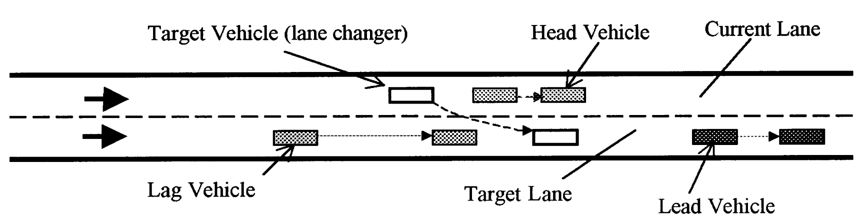

FIGURE 1 Definition of vehicles affecting lane-changing behavior.

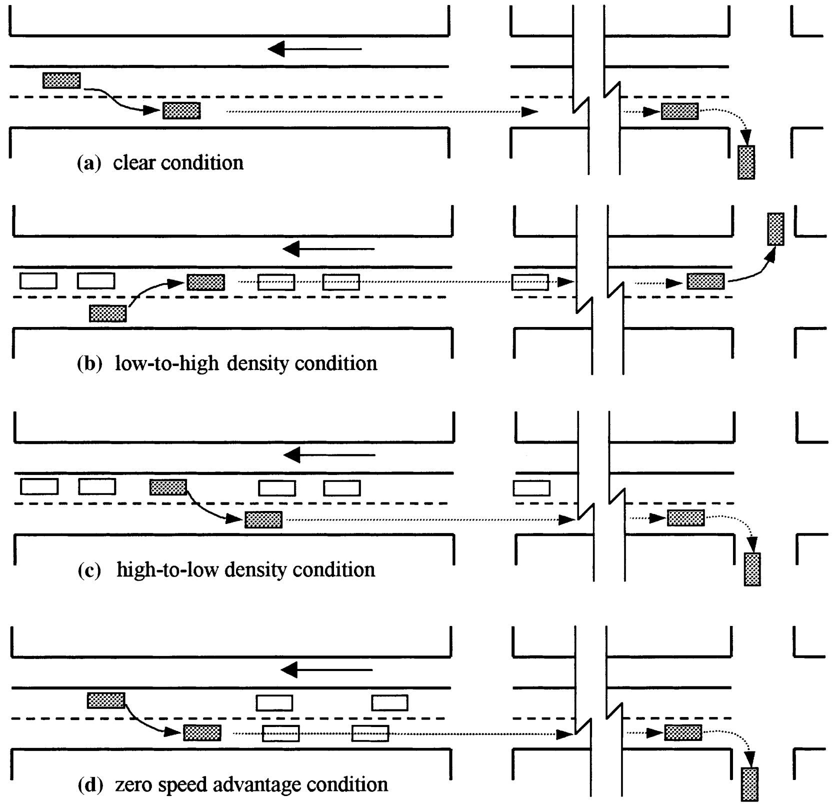

FIGURE 2 Typical cases of preemptive lane changes.

and speed disadvantage must be defined. Willingness to make a discretionary lane change is determined by both a speed disadvantage and an advantage in the times being simulated if the vehicle currently is in the target lane or the preemptive lane. Speed disadvantage is defined as a mathematical function of the relative difference between the desired speed of the target vehicle (i.e., the intended lane changer) and the current speed of the preceding vehicle. Speed advantage is described by the relative speed difference between the lead vehicle in the target lane and the head vehicle in the current lane. The suggested mathematical expressions are

$$SD = \frac{V_T - V_H}{V_T} \tag{1}$$

$$SA = \frac{V_{Ld} - V_H}{V_{Ld}} \tag{2}$$

where

SD = speed disadvantage,
V_T = target vehicle's desired speed (ft/s),
V_H = head vehicle's speed (i.e., preceding vehicle) (ft/s),
SA = speed advantage,
V_{Ld} = lead vehicle's desired speed in adjacent lane (ft/s), and
V_H = head vehicle's speed (ft/s).

It is impossible to know drivers' real desired speeds from watching videotapes only. However, it has been noted from the authors' digitized video observations that a vehicle generally reaches a stable speed 2 to 5 s after completion of a lane change. Thus, it may be assumed that this stable speed might be used to estimate a vehicle's desired speed.

Figure 3 shows an example of the distribution of *SD* and *SA* when mandatory and preemptive lane changes are started on an urban street. Obviously, as a mandatory or preemptive lane change occurs, pairs of *SD*s and *SA*s are scattered mainly over three quadrants of the coordinate system: ($SD \geq 0$, $SA \geq 0$), ($SD \leq 0$, $SA \geq 0$), and ($SD \leq 0$, $SA \leq 0$). However, Figure 3 illustrates the distribution of pairs of *SD*s and *SA*s as discretionary lane changes begin in the case of two-way streets. It is apparent that almost all *SD* and *SA* pairs are located in the first quadrant of the coordinate system.

These findings imply that from the standpoint of speed advantage, a driver tends to consider a discretionary lane change only if the following two conditions exist: (*a*) The driver perceives that the speed of the head vehicle is less than his desired speed. This condition is described as a speed disadvantage, in which the driver perceives that *SD* is positive for the time being. (*b*) The driver perceives that he could increase speed by changing to another lane. This condition is described as a speed advantage, in which the driver perceives that *SA* is greater than a certain positive value for the time being. At the moment when the head vehicle is stopped ahead, both *SD* and *SA* equal 1 because of the zero speed of the the head vehicle for the time being. For example, the vehicle ahead has broken down or is leaving an on-street parking lot. Then the driver definitely generates the willingness to make a discretionary lane change. However, decision making for mandatory or preemptive lane changes may not be affected by *SD* or *SA* because a temporary speed advantage is a very weak motivator compared with remaining in the right lane in accordance with a route plan. Samples observed over one-way streets show similar characteristics.

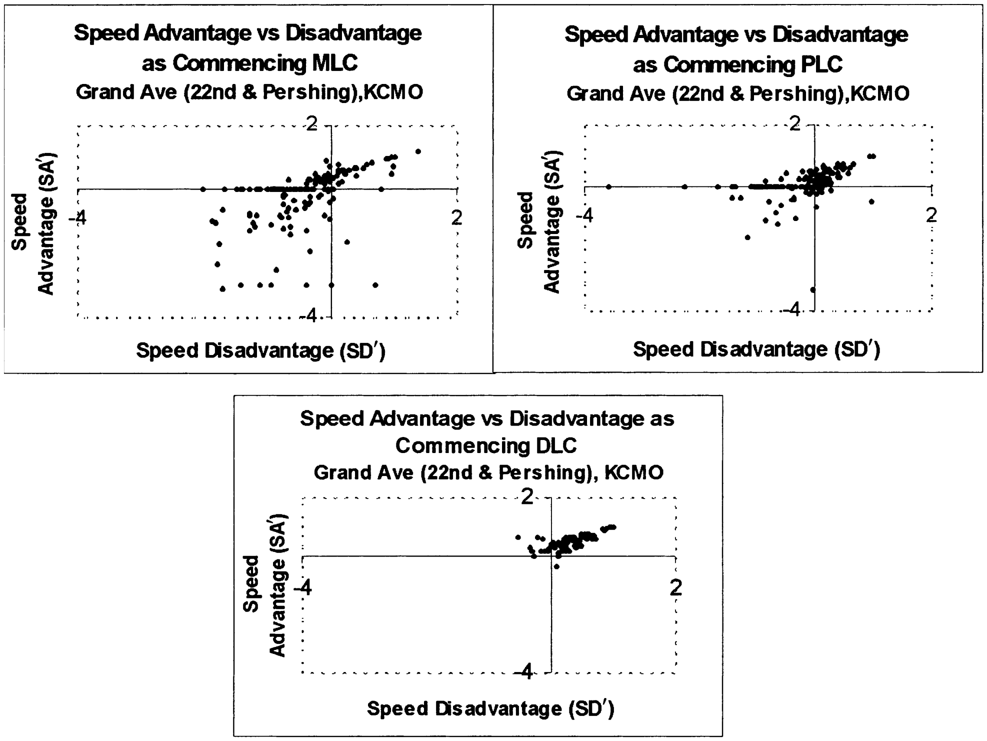

FIGURE 3 Distribution of *SD′* versus *SA′* for mandatory (MLC), preemptive (PLC), and discretionary (DLC) lane changes (two-way sample). KCMO = Kansas City, Missouri.

Accordingly, it may be assumed that *SD* and *SA* are two contributing factors in the decision to make a discretionary lane change. However, a mandatory lane change is necessary for a driver's planned route. A decision to make a preemptive lane change is also based on a driver's planned route and not on speed gains. It is normally true that if a driver needs to change lanes to get into the target lane for a planned route, he will change lanes regardless of whether the change affords any speed gain.

Objective conflict has been commonly recognized as one of the reasons that lane-changing behavior modeling is complex. For instance, a driver's desire to maintain a certain speed can conflict with his need to be in the correct lane for a particular maneuver (*4*). In this case, the decision to change lanes is governed by the intended route rather than speed. In other words, it may be assumed that route-oriented motivation generally has higher priority than speed-gain-oriented motivation in lane-change decision making. Subsequently, conflicts of lane-changing objectives in modeling could be avoided.

STRUCTURE OF HEURISTIC LANE-CHANGING MODEL

From analyses of videotaped observations, rules concerning driver behavior are set up to construct a hierarchy for a lane-changing model, as illustrated in Figure 4. From the logic shown in Figure 4, the lane-changing process includes three actions: making the decision, recognizing acceptable conditions (gaps or headway between the lead and the lag vehicles), and making the lane-changing maneuver. Therefore, a lane-changing model is suggested to consist of three submodels: a decision model, a condition model, and a maneuver model. These three submodels are described briefly as follows.

Decision Model

The lane-changing decision model is designed to describe a driver's willingness to change lanes and to determine the required type of lane change. Rules included in the lane-changing decision model are illustrated in Figure 5.

It is assumed that the current lane type is the starting point to decide on the need for a lane change and to determine the type of lane change. As in the previous explanation of mandatory lane changes, a driver must first consider a mandatory lane change before approaching the next intersection if the current lane is not a target lane. After he gets into the target lane, he may think of passing a slower-moving vehicle if he is able to change back into the target lane before approaching the next intersection.

If a driver is not in the target lane and his choice of staying in the current lane does not conflict with his planned route until he crosses the next intersection, there are two possible cases. If keeping in the current lane will still be possible for one or more downstream segments subsequent to the next intersection, willingness for a discretionary lane change, if any, may be generated while the driver is able to change back. While the driver stays in the current segment, the current lane is regarded as a preemptive lane. From Figure 5, it can be seen that this definition is for convenience in constructing the decision-making process for simulation modeling. On the other hand, if the current lane becomes the wrong lane with regard to the planned route when the driver crosses a downstream intersection, he is currently in a nonpreemptive lane. He needs to search for the correct lane (i.e., the preemptive lane here) that leads him onto his route. Figure 5 illustrates the heuristic process in determining lane-changing types.

Regression models of cumulative curves on observed *SD* and *SA* data are used to simulate the probability of a driver's decision to make

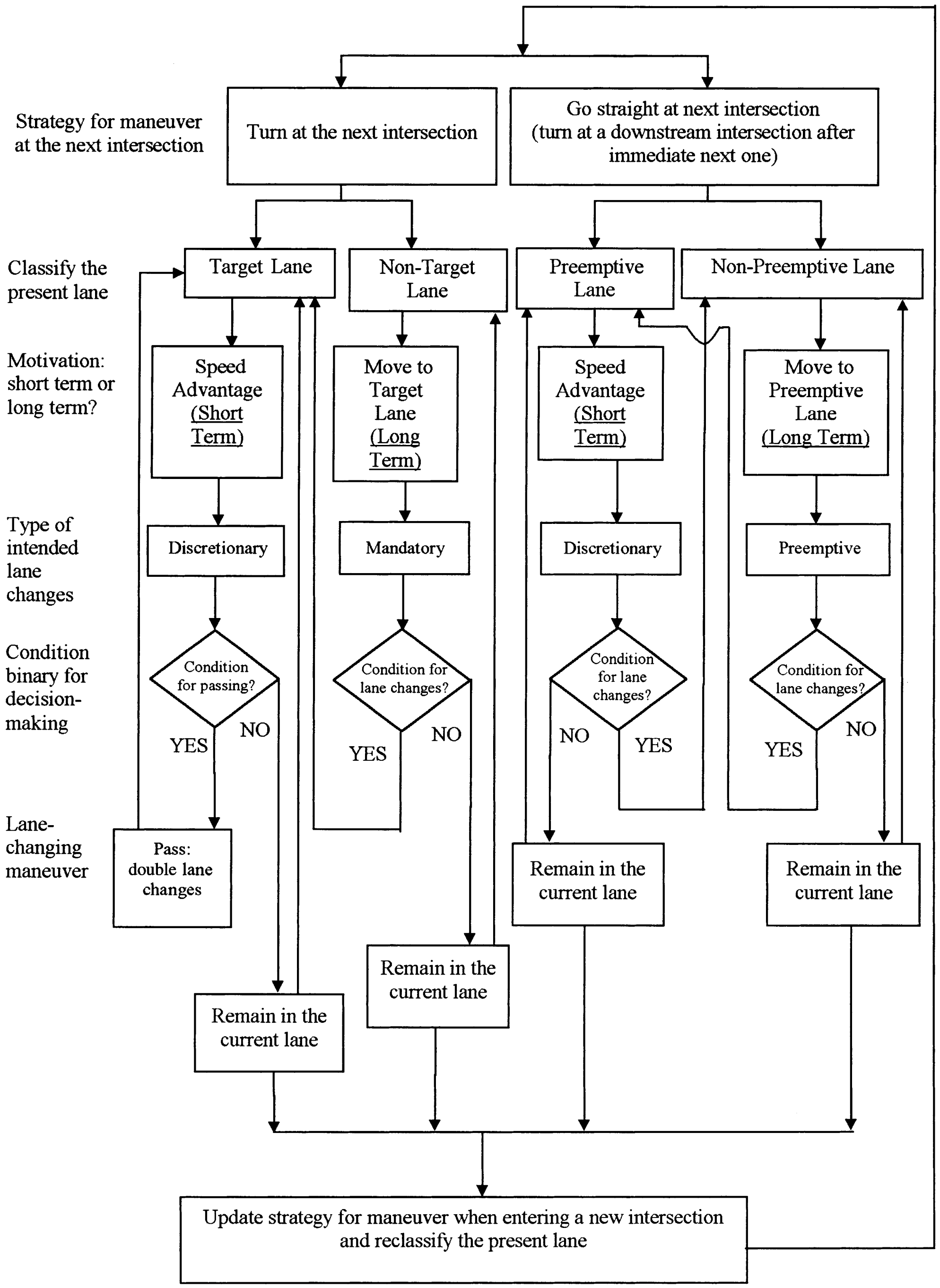

FIGURE 4 Lane-changing hierarchy.

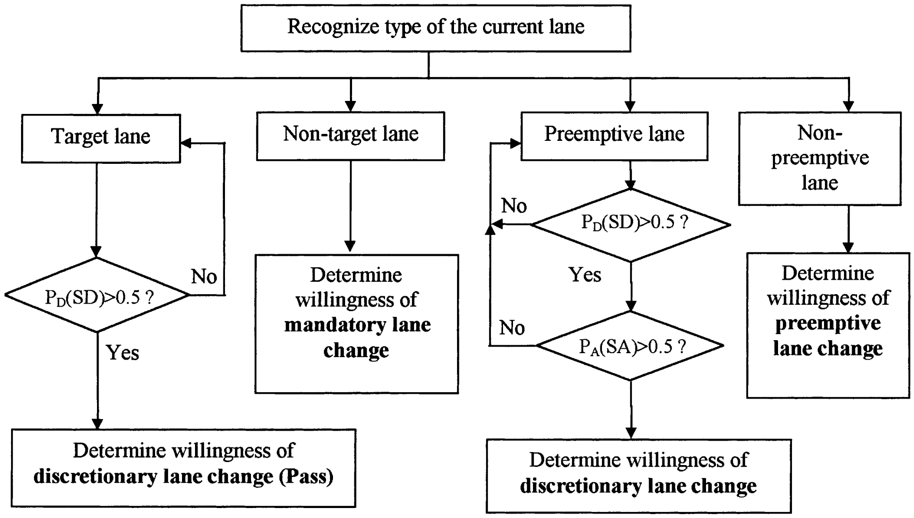

FIGURE 5 Hierarchy of lane-changing decision model.

a discretionary lane change. It is assumed that a driver decides to make a discretionary lane change if the probability calculated by a corresponding regression model is higher than a certain value (probability threshold). Since a lane-changing decision has two possible answers, yes or no, typical probability threshold values might be suggested as 50 percent. Probability models derived from cumulative curves of *SD* and *SA* data are as follows:

For two-way streets:

$$P_D(SD = x) = 0.1449 + 0.7927x + 0.8848x^2 - 0.411x^3 - 0.5119x^4 \quad (3)$$

$$P_A(SA = x) = 0.0149 + 0.2097x + 1.1081x^2 + 1.2074x^3 - 1.6351x^4 \quad (4)$$

For one-way streets:

$$P_D(SD = x) = 0.0657 + 0.3528x + 1.0552x^2 + 0.2522x^3 - 0.8627x^4 \quad (5)$$

$$P_A(SA = x) = 0.145 + 0.1592x + 0.637x^2 + 0.3837x^3 - 0.3197x^4 \quad (6)$$

where $P_D(SD = x)$ is the possibility of being intolerant of the head vehicle's speed when $SD = x$ and $P_A(SA = x)$ is the possibility of making a decision to change lanes when $SA = x$ only if $P_D(SD = x)$ is no less than the threshold value.

Condition Model

A driver has to search for acceptable conditions to execute a lane change if he decides to leave his current lane. The head vehicle in the current lane plus the lead and the lag vehicles in the lane that is being targeted by the prospective lane changer are the primary considerations. Continuously changing speeds and gaps between a prospective lane changer and other vehicles directly affect the prospective lane changer's behavior with respect to changing lanes. Headway is usually used to describe the temporal relationship between two immediately consecutive vehicles in motion. The concept of headway in fact depicts the comprehensive effect of speeds and spatial relationships between vehicles. Accordingly, headway is a vital factor in lane-changing condition models.

Vehicle trajectory data extracted by VEVID from observations of two-way and one-way streets in Kansas City, Missouri, include all targeted vehicles' locations, speeds, accelerations, and gaps, as well as headways at the specified time that a lane change occurs. From the trajectory data it is quite easy to obtain values of the headways between the lane changer and all other vehicles including head, lead, and lag vehicles. Table 1 summarizes the probability models for lane-changing conditions, and Table 2 shows values of typical headway thresholds that were derived from cumulative curves of observed headways.

If a vehicle's speed changes from V_0 to $V_{\Delta t}$ during a period of time Δt, its acceleration or deceleration is α_a or $\alpha_d(\pm\alpha)$. Within Δt, the distance the vehicle travels is $S_{\Delta t}$. Assume that the times estimated to experience a pass-out lane change and transition period are t_T and t_{trans}, respectively. The status of the lane changer (target vehicle), the head vehicle, and the pass-control vehicle at the current moment is represented in the form (location, speed, acceleration), that is, (X_T, V_T, α_T), (X_H, V_H, α_H), and (X_{PC}, V_{PC}, α_{PC}), respectively, as illustrated in Figure 6. After $\Delta t = t_T + t_{\text{trans}}$, these three vehicles are estimated to move S_T, S_H, and S_{PC} (5).

At the current moment, headways to the head vehicle and pass-control vehicle at time ($t_T + t_{\text{trans}}$) are predicted as h_{T_H} and h_{PC_T}, respectively. Then the acceptable condition for passing is

$$\begin{cases} h_{T\_H} = \dfrac{(X_H - X_T) + (S_T - S_H)}{V_H + \alpha_H \Delta t} \geq \gamma_{MLC} \\[2ex] h_{PC\_T} = \dfrac{(X_{PC} - X_T) + (S_{PC} - S_H)}{V_T + \alpha_T \Delta t} \geq \gamma_{MLC} \end{cases} \quad (7)$$

Observed average values of t_T and t_{trans} are 2.0 s and 1.4 s, respectively, and Δt is estimated as 3.4 s, given all headway thresholds,

TABLE 1 Summary of Probability Models for Lane-Changing Conditions

Road Type	Types of Relative Headway	Type of Lane Changes: Mandatory (MLC)	Preemptive (PLC)	Discretionary (DLC)
Two-way	To the head vehicle (H_T)	$P(MLC/H\_T=x) = 0.835Ln(x)-0.0679$, $R^2 = 0.9537$	$P(PLC/H\_T=x) = 0.7743Ln(x)+0.1164$, $R^2 = 0.9839$	$P(DLC/H\_T=x) = 0.856Ln(x)+0.1712$, $R^2 = 0.9682$
	To the lead vehicle (Ld_T)	$P(MLC/Ld\_T=x) = 0.9192Ln(x)-0.0693$, $R^2 = 0.9897$	$P(PLC/Ld\_T=x) = 0.758Ln(x)-0.0617$, $R^2 = 0.9759$	$P(DLC/Ld\_T=x) = 0.9979Ln(x)-0.0104$, $R^2 = 0.9340$
	To the lag vehicle (T_Lg)	$P(MLC/T\_Lg=x) = 0.9192Ln(x)-0.0693$, $R^2 = 0.9714$	$P(PLC/T\_Lg=x) = 0.8171Ln(x)-0.0248$, $R^2 = 0.9763$	$P(DLC/T\_Lg=x) = 0.8068Ln(x)+0.0023$, $R^2 = 0.9516$
One-way	To the head vehicle (H_T)	$P(MLC/H\_T=x) = 0.8345Ln(x)-0.0572$, $R^2 = 0.9623$	$P(PLC/H\_T=x) = 0.95Ln(x)-0.1769$, $R^2 = 0.9517$	$P(DLC/H\_T=x) = 0.7631Ln(x)+0.1517$, $R^2 = 0.9942$
	To the lead vehicle (Ld_T)	$P(MLC/Ld\_T=x) = 0.9288Ln(x)-0.0629$, $R^2 = 0.9776$	$P(PLC/Ld\_T=x) = 1.015Ln(x)-0.2267$, $R^2 = 0.9758$	$P(DLC/Ld\_T=x) = 1.0922Ln(x)-0.2523$, $R^2 = 0.9826$
	To the lag vehicle (T_Lg)	$P(MLC/T\_Lg=x) = 1.2197Ln(x)-0.2853$, $R^2 = 0.9819$	$P(PLC/T\_Lg=x) = 0.8931Ln(x)-0.1421$, $R^2 = 0.9828$	$P(DLC/T\_Lg=x) = 0.6964Ln(x)+0.0904$, $R^2 = 0.9608$

Note: $P(MLC/H\_T=x)$ = probability of acceptance of the target vehicle's headway of x relative to the head vehicle for a mandatory lane change.

$P(MLC/Ld\_T=x)$ = probability of acceptance of the target vehicle's headway of x relative to the lead vehicle for a mandatory lane change.

$P(MLC/T\_Lg=x)$ = probability of acceptance of the target vehicle's headway of x relative to the lag vehicle for a mandatory lane change.

$P(PLC/H\_T=x)$, $P(PLC/Ld\_T=x)$, $P(PLC/T\_Lg=x)$ have similar definitions as the above but for a preemptive lane change.

$P(DLC/H\_T=x)$, $P(DLC/Ld\_T=x)$, $P(DLC/T\_Lg=x)$ have similar definitions as the above but for a discretionary lane change.

γ_{MLC}, γ_{PLC}, and γ_{DLC}, as described in Table 2. The rules making up the lane-changing condition model are described in a flowchart (Figure 7), in which *T_Ld* refers to the headway between the lane changer (target vehicle) and a vehicle in the target lane that the lane changer intends to follow after the lane change occurs; *T_Lg* refers to the headway between the lane changer (target vehicle) and the lag vehicle in the target lane that intends to follow the target vehicle after the lane change occurs; and *H_T* refers to the headway between the lane changer (target vehicle) and the head vehicle in the current lane followed by the lane changer before the lane change occurs.

Maneuver Model

In summary, Figure 8 shows a flowchart of the lane-changing maneuver model, which provides the basis for writing the computer code.

If it is assumed that a driver decides to change lanes and that headways are acceptable in the target lane at that moment, the next issue in the simulation is to model the lane-changing maneuver. The primary concerns are duration of the maneuver and how the duration is affected by the vehicle's speed and acceleration just before the maneuver. The statistical results of correlation analysis between

TABLE 2 Observed Values of Typical Headway Thresholds

Percentile (Probability Thresholds)	Types of Relative Headway	Two-way Street γ_{MLC}	Two-way Street γ_{PLC}	Two-way Street γ_{DLC}	One-way Street γ_{MLC}	One-way Street γ_{PLC}	One-way Street γ_{DLC}
50%	To the head	2.10	1.62	1.36	2.20	2.12	1.58
	To the lead	1.53	1.88	1.82	2.01	2.15	1.93
	To the lag	1.79	1.79	1.96	1.96	2.17	1.72

Note: γ_{MLC}: threshold in the case of mandatory lane change;
γ_{PLC}: threshold in the case of preemptive lane change;
γ_{DLC}: threshold in the case of discretionary lane change.

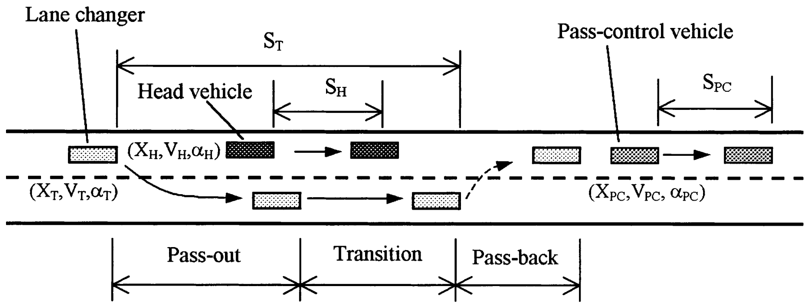

FIGURE 6 Decision making for passing (passing one vehicle only).

speed and acceleration when a lane change begins and the duration of a lane change indicate that there is little correlation between speed and acceleration or between acceleration and duration [values of correlation coefficients fall into (–0.358, +0.358)]. The observed duration values do not vary much with speed unless it is under 7 mph (11 km/h). That finding implies that duration is not significantly dependent on speed.

Table 3 shows statistical results of lane-changing durations with the confidence interval at 95 percent. The data indicate that the average duration of lane changing ranges from 2.33 to 2.52 s with standard deviations from 0.56 to 0.93 s. Mode values are concentrated on 2 to 2.5 s. Therefore, 2.30 s may be recommended as a general description of the duration of the lane-changing maneuver. However, the duration should be much longer under heavy traffic conditions when vehicles are moving bumper to bumper at less than 10 mph (16 km/h). From statistical results of observed data, the duration is seen to range from 3.0 to 7.5 s when the speed is less than 10 mph, with an average of 4.4.

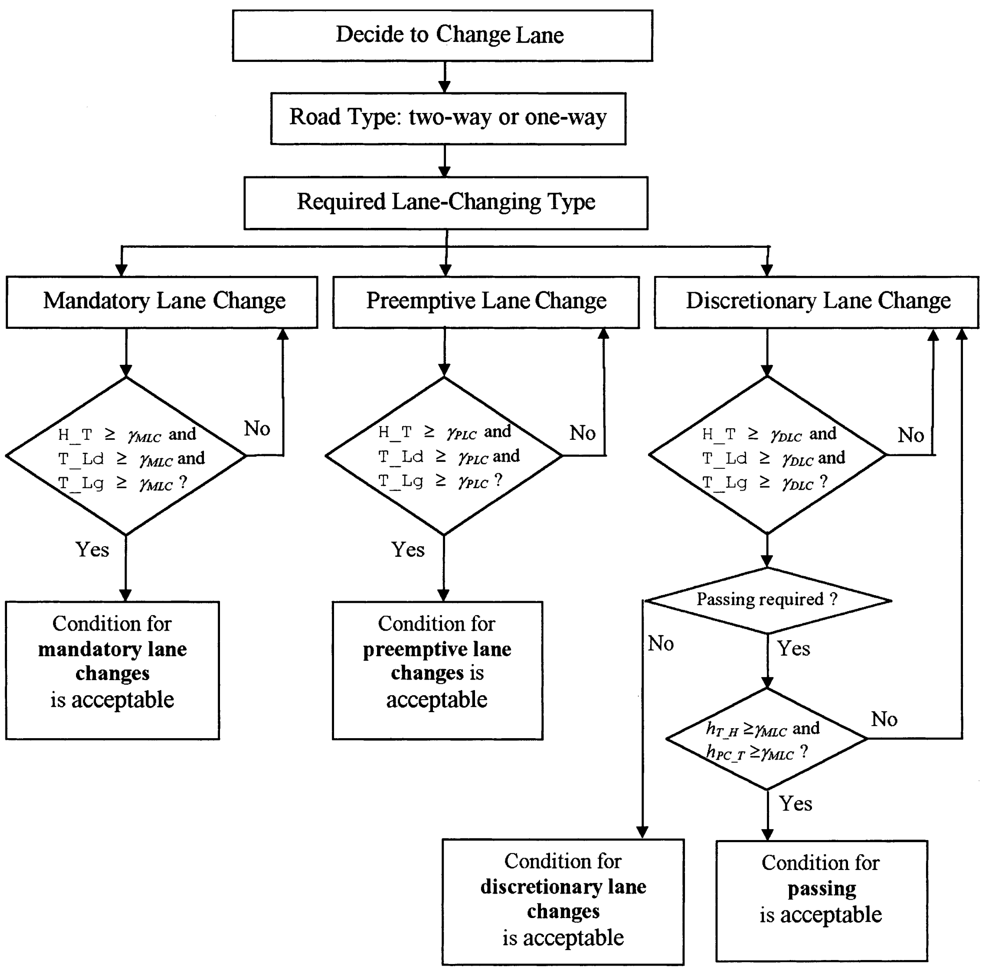

FIGURE 7 Flowchart of rules in lane-changing condition model.

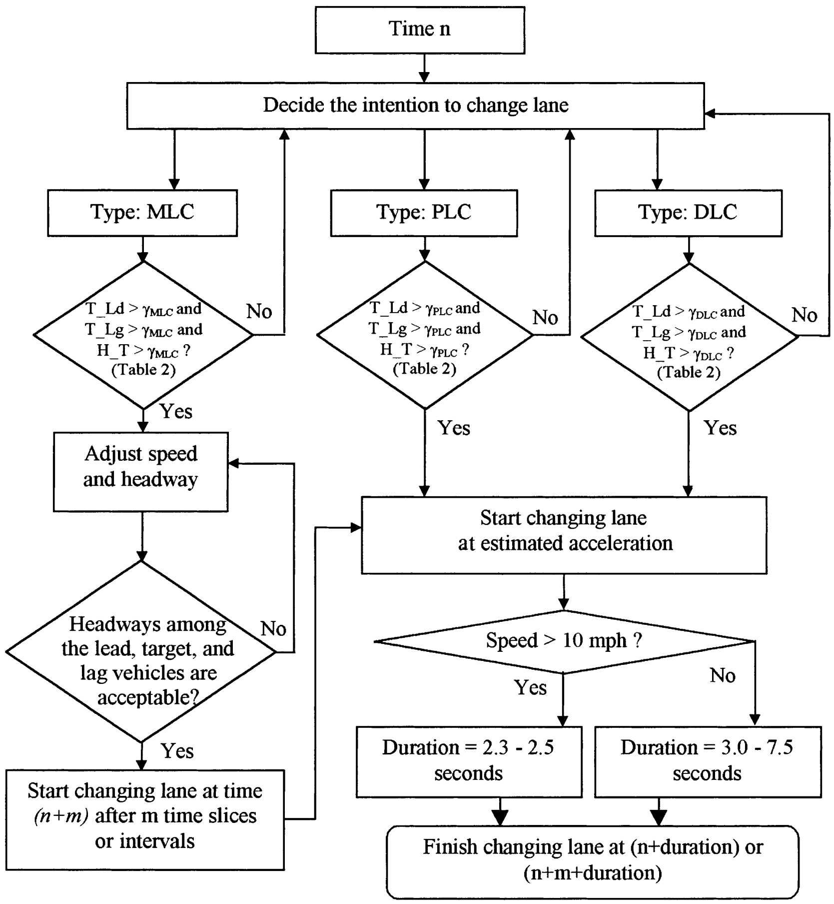

FIGURE 8 Flowchart of rules in lane-changing maneuver model (1 mi = 1.6 km).

TABLE 3 Descriptive Statistical Analysis of Lane-Changing Duration

Road Type	Descriptive Statistical Analysis	MLC	PLC	DLC
Two-way	Mean (μ)	2.48	2.46	2.46
	Median	2.5	2.5	2.5
	Mode	2.5	2	2
	Standard Deviation	0.66	0.63	0.73
	Minimum	1.5	1.5	1.5
	Maximum	7.5	6	6
	Sample Size (n)	263	343	119
	Confidence Interval (95%)	(2.40, 2.56)	(2.39, 2.52)	(2.33, 2.59)
One-way	Mean (μ)	2.34	2.33	2.52
	Median	2	2	2.5
	Mode	2	2	2
	Standard Deviation	0.63	0.56	0.93
	Minimum	1.5	1.5	1.5
	Maximum	4.5	4.5	5.5
	Sample Size (n)	115	114	64
	Confidence Interval (95%)	(2.35, 2.37)	(2.32, 2.34)	(2.49, 2.54)

TABLE 4 Observed Maximum Accelerations for 10-mph Increments

Type	Typical Maximum Acceleration Rate on Level Road α (ft/sec^2)				
Starting Speed	0 - 15 ft/s (0 - 10 mph)	15 - 29 ft/s (10 - 20 mph)	29 - 44 ft/s (20 -30 mph)	44 - 59 ft/s (30 - 40 mph)	59 - 73 ft/s (40 - 50 mph)
Two-way	+11.2 -8.8	+12.0 -15.6	+10.4 -11.0	+8.4 -10.5	+7.8
One-way	+8.9 -6.9	+10.8 -12.7	+11.0 -11.2	+6.9 -12.6	+6.3

1 mi = 1.6 km.
1 ft = 0.3 m.

The speed of a lane-changing vehicle when it begins a lane change might be different from that of the lead or lag vehicle at the same moment. Thus, a lane changer may accelerate or decelerate in executing a lane-changing maneuver so as to keep a safe headway to the lead or to the lag vehicle. Acceleration varies with the individual speeds of the lane changer and the lead vehicle as well as with the differences between them. Table 4 shows observed maximum acceleration or deceleration values for each 10-mph increment for determining thresholds of acceleration in the simulation of a lane-changing maneuver.

Assume that at time $t(n)$, the target vehicle decides to change lanes and starts searching for acceptable conditions for maneuvering. If the gap between the lead and lag vehicles is not acceptable, the target vehicle and lag vehicle have to slow down to create larger gaps for the target vehicle to safely merge. At time moment n, the target, lead, and lag vehicles are moving at $V_T(n)$, $V_{Ld}(n)$, and $V_{Lg}(n)$, respectively, and their acceleration rates are denoted by $\alpha_T(n)$, $\alpha_{Ld}(n)$, and $\alpha_{Lg}(n)$. They would move $S_T(n, n+1)$, $S_{Ld}(n+1)$, and $S_{Lg}(n+1)$ at time $t(n+1)$. At time $t(n)$, the objective of speed adjustment for the lane changer is

$$\frac{X_{Ld}(n) + S_{Ld}(n,\ n+1) - X_T(n) - S_T(n,\ n+1)}{V_T(n+1)} \geq \gamma_{Ld\_T} \tag{8}$$

$$\frac{X_T(n) + S_T(n,\ n+1) - X_{Lg}(n) - S_{Lg}(n,\ n+1)}{V_{Lg}(n+1)} \geq \gamma_{T\_Lg} \tag{9}$$

Then acceleration at $t(n)$ is adjusted by Equations 10 through 12:

$$\alpha_T(n) \leq \frac{\dfrac{[X_{Ld}(n) - X_T(n)] + [V_{Ld}(n) - V_T(n)]}{\Delta n} + \dfrac{1}{2}\alpha_{Ld}\Delta t^2 - \gamma_{Ld\_T}V_T(n)}{\dfrac{1}{2}\Delta t^2 + \gamma_{Ld\_T}\Delta t} \tag{10}$$

$$\alpha_{Lg}(n) \leq \frac{\dfrac{[X_T(n) - X_{Lg}(n)] + [V_T(n) - V_{Lg}(n)]}{\Delta n} + \dfrac{1}{2}\alpha_T\Delta t^2 - \gamma_{T\_Lg}V_{Lg}(n)}{\dfrac{1}{2}\Delta t^2 + \gamma_{T\_Lg}\Delta t} \tag{11}$$

$$\alpha^*_{Lg}(n) = \min\{|\alpha_{Lg}(n)|, +\alpha\} \qquad \text{or}$$

$$\alpha^*_{Lg} = \max\{-|\alpha_{Lg}(n)|, -\alpha\} \tag{12}$$

where $\Delta t = t(n+1) - t(n)$ and α refers to values in Table 4.

SUMMARY

Using video-capture techniques and the VEVID software, the authors conducted a lengthy observation of lane-changing behavior on urban streets and analyses of observed vehicle trajectory data. This study presents new findings from real-world observations, which inspired the authors, from a systematic standpoint, to explore the hierarchy in recognition and understanding of lane-changing behavior on urban streets. On the basis of new findings from observations conducted on four-lane urban streets (two lanes in each direction), the authors developed a heuristic structure for a lane-changing model. The models presented in this research are a significant advancement in lane-specific vehicle-based microscopic simulation modeling and provide a good basis for conducting further research on streets with six or more lanes, as well as for improving microscopic simulation models.

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