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Observation-Based Lane-Vehicle Assignment Hierarchy

Microscopic Simulation on Urban Street Network

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A lane-assignment model in a vehicle-based microscopic simulation system describes a vehicle's position during its journey on an urban street network. In other words, it is used to estimate an individual vehicle's location, speed, routing plan, lane-choice plan, lane-changing plan, and car-following plan from its entrance to a street network until the end of the trip. From the authors' observations and study of lane-choice and lane-changing behavior, it is concluded that a vehicle is assigned to a lane in a logical manner depending on the relationship between its route-planned motivation and traffic conditions in the current lane and other lanes. A lane-assignment model consists of three components: lane choice, car following, and lane changing. The lane-changing component is composed of three submodels—a decision model, a lane-changing condition model, and a lane-changing maneuver model. Rules are discussed for lane-choice and lane-changing modeling based on videotaped observations over four-lane urban streets. Then a heuristic structure of a lane-vehicle-assignment model is proposed, which exposes the inherent relationship between vehicle-based travel behavior and lane-vehicle assignment on an urban street network. With the addition of a lane-assignment model derived from observed data, a simulation may be developed to correctly represent travel behavior and dynamic traffic assignment at the lane level and provide a more effective tool for design and evaluation of the performance of strategies for traffic control, traveler information, and congestion alleviation.

Vehicle-based dynamic network models, which include both simulation and optimization models, are used to analyze traffic problems by simulating individual travel behaviors and movement of vehicles. Compared with flow-based models, vehicle-based microscopic models are more effective tools for design and performance evaluation of strategies for traffic control, traveler information, and congestion alleviation. For these reasons, microscopic simulation for a large-scale network suggests itself as a plausible tool for the advanced traveler information system (ATIS) and the advanced traffic management system (ATMS) in U.S. intelligent transportation systems (ITS) (*1*).

ATIS and ATMS in an urban street network call for a vehicle-based simulation model on the lane level for operational evaluation, which requires a correct representation of dynamic microscopic traffic flow phenomena (*2*, pp. 1–37). One core element of a microscopic simulation model is the lane-vehicle-assignment model, which assigns vehicles dynamically to lanes in a multilane street segment. As the most important components of a lane-vehicle-assignment model, lane-choice, car-following, and lane-changing problems have received considerable research interest. However, no research has been undertaken that examines urban lane assignment, especially based on field observations, because of the difficulty in obtaining good, simple, and clean data. Furthermore, it is also impossible to calibrate and validate existing theoretical models without observed trajectory data.

The authors conducted lengthy videotaped observations over eight urban streets in Kansas City, Missouri, and a study of vehicle trajectory data collection using the video-capture technique and the authors' developed software Vehicle Video-Capture Data Collector (VEVID) (*3*). Presented here is the authors' understanding of the vehicle-based behavior involved in lane-based traffic assignment on the basis of careful analyses of videotaped observations. The structure and hierarchy of a lane-vehicle-based traffic assignment model are then proposed, including a brief introduction of a lane-choice model and a lane-changing model. Car-following observation is a complex topic and will be discussed in other papers. More details regarding the study of lane-changing behavior and modeling are introduced in another paper (Wei et al.) in this Record.

VEHICLE-BASED TRAVEL BEHAVIOR

It is the unique characteristic of microscopic simulation to be capable of inferring properties concerning the macroscopic behavior of the actual system from representations of vehicle-based travel behavior rather than flow-based behavior. Therefore, simulation model developers must clearly specify the relationships of vehicle-based travel behavior and the structure in the system being simulated. By doing so, they can better understand the system and how it works (*4*).

It is well known that flow-based traffic assignment is estimated from the simulation of link-based routes. Similarly, lane-vehicle-based traffic assignment is associated with estimation of lane-based routes in simulation, as illustrated by Figure 1. Field observations by the authors using videotapes indicate that there are three main categories of vehicle-based travel behavior that have a great impact on estimating lane-based routes: initial lane-choice, car-following, and lane-changing behavior, as illustrated by Figure 2. Major findings or inferred conclusions regarding observed lane-choice and lane-changing behavior are introduced as follows. An assumption for the following discussion is that all drivers have origins and destinations and route or path plans in mind before departure or en route.

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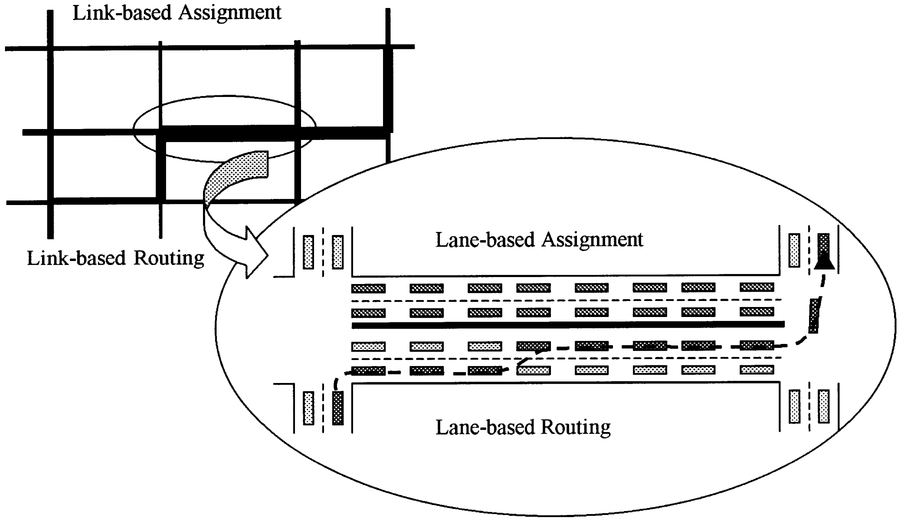


FIGURE 1 Relationship between link-based and lane-based routing and assignment.

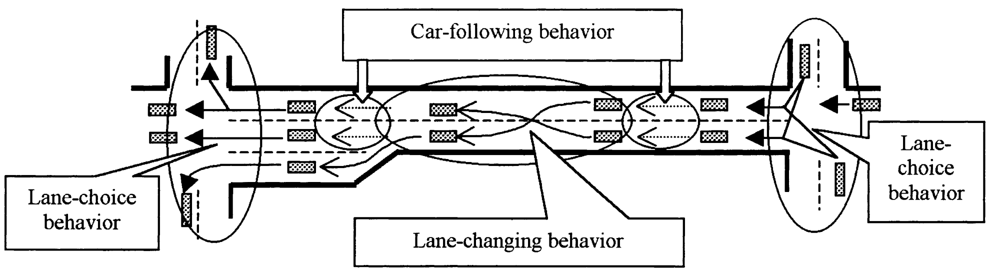


FIGURE 2 Vehicle-based travel behavior concerning lane-based assignment.

Observations of Lane-Choice Behavior

First, the authors noted that lane-choice behavior occurred frequently during field observations (*5*). For instance, referring to Figure 3, a driver gets into the rightmost lane when he or she enters the segment from the left-turn point and does not need to make a lane change before making a right turn at the next intersection. Obviously, this initial lane-choice behavior does not obey driving regulations; that is, a driver should get into the closest lane no matter whether he or she will go straight through or make a turn at the next intersection. The authors' observations indicate that a great number of drivers do not follow driving regulations in practice. They most likely choose the lane, termed the target lane, that has direct access to the exit lane at the next intersection with the maximum ease (Figure 3). If drivers intend to make a turn at a downstream intersection subsequent to the immediate one, they likely prefer getting into the lane, termed the preemptive lane, that leads them to minimize lane changes before making such a turn (Figure 3).

The authors' observed data show that generally 66.8 to 73.1 percent of drivers from turn entries initially chose the farther lane to make a turn at the next intersection, whereas 26.2 to 33.2 percent chose it for traveling through the next intersection without turns (but may

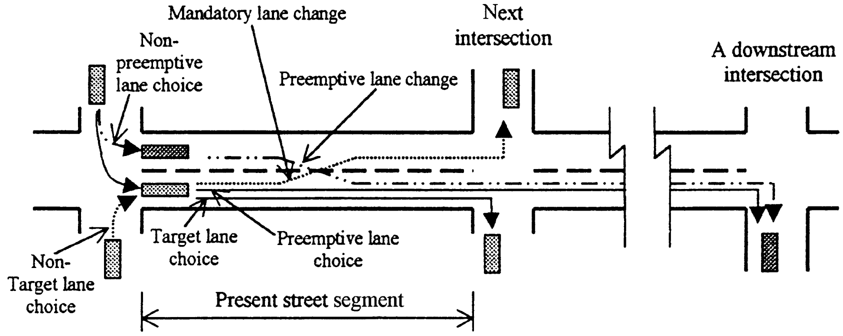


FIGURE 3 Concepts of lane-choice and lane-changing behavior.

make turns at a downstream intersection). Only 0.0 to 0.7 percent of drivers initially chose the closest lane and then changed to the farther lane to make a turn at the next or a downstream intersection. In this case, the closest lane is the nontarget lane.

Second, lane choice seems dependent on both a driver's travel route plan at downstream intersections and the driver's aggressiveness. In most cases, a driver selects a lane in the light of its potential convenience for intended maneuvers during his or her remaining journey. In short, the objective of lane choice is to execute this travel maneuver plan effectively and efficiently.

Third, control facilities like traffic lights actually provide opportunities for drivers from turn entries at an intersection to choose an appropriate lane, though driving regulations encourage drivers to select the closest lane to enter an urban street segment.

Fourth, the current lane type is classified as the target lane, nontarget lane, preemptive lane, or nonpreemptive lane depending on entry type (left or right) and particular maneuver (left or right turn or through) at the next or a downstream intersection. Lane choice can be classified as target-lane choice and non-target-lane choice as well as farther-lane choice and closest-lane choice.

Finally, if a driver tends to make a turn at the next intersection, the initial lane choice is the target lane. If the closest lane is the driver's preemptive lane, the driver chooses the closest lane. If the farther lane is the driver's preemptive lane, he or she chooses either the farther lane or the closest lane depending on his or her aggressiveness, described by an aggressiveness index.

Observations of Lane-Changing Behavior

Two types of lane-changing behavior, mandatory and discretionary, were defined traditionally (*6*). In a mandatory lane change, a driver changes lanes with the purpose of getting into the correct target lane to keep on the right route for a particular maneuver at the next intersection. Lane changes made to avoid collisions, slowdowns or blockage, and temporary lane closure ahead are referred to as discretionary lane changes or nonmandatory lane changes. However, analyses of samples through videotaped observations disclosed that traditionally defined nonmandatory lane-changing behavior actually consists of discretionary lane changing and another special type of lane-changing behavior never mentioned in previous research. This special type of nonmandatory lane changes occurs when a driver who intends to make a turn at a downstream intersection after the next one (at least one segment away) moves to the desirable lane. Obviously, this is not a traditionally defined discretionary lane change. A new term, preemptive lane change, was created to describe this type of lane change. Figure 3 illustrates the concept of preemptive lane-changing behavior.

Decisions for both mandatory and preemptive lane changes are dependent on the motivation to search for a target lane (long-term motivation). The only distinction between the two is that in a mandatory change, the driver makes a turn at the next intersection, whereas in a preemptive change, the driver makes a turn at a downstream intersection away from the next one, as illustrated by Figure 3. A decision for a discretionary lane change is based on short-term motivation, which refers to avoidance of potential delay or gaining a speed advantage (short-term motivation). If these two motivations arise simultaneously in a driver's decision making for lane changes, the long-term motivation takes priority over the short-term motivation.

Sampling indicates that 36.0 percent of lane-changing cases fall into the mandatory type, whereas discretionary cases account for 46.4 percent and the preemptive type, 17.5 percent. All lane-changing samples were observed not to occur within an intersection but midblock.

The following rules resulting from observations concerning driver behavior are set up to construct a lane-changing model:

- A driver reevaluates her or his strategy for maneuvering at the next (exit) intersection when entering a new street segment—either he or she makes a turn or goes straight through the intersection. Meanwhile, the type of the current lane corresponds with the route need: it is the target lane if the driver is already in the correct lane to turn off the segment, as illustrated by Figure 3. Otherwise, it is the nontarget lane, and the driver will have to move to the target lane for an intended turn at the next intersection. If a driver plans to go through the next intersection and turn at a downstream intersection, the current lane may be regarded as the preemptive lane if he or she can reach such an objective by staying in the current lane. If the current lane is not such an ideal lane, it is referred to as a nonpreemptive lane.
- A driver who intends to change lanes is assumed to have two objectives: getting into the correct lane and gaining speed, including maintaining desired speed or avoiding a possible delay. The former objective refers to long-term motivation with priority in decision making, whereas the latter refers to short-term motivation with second priority in decision making.
- When a vehicle is in the target lane, the driver intends to change lanes only if an incident or blockage occurs. In this case, the vehicle is generally close to the intersection at which the driver intends to turn off, so she or he has no desire to change lanes unless there is a chance to pass a blockage ahead and to change back into the target lane. In order to avoid a blockage or slowdown ahead, the driver attempts a passing maneuver (double-lane change) if an acceptable condition is available.
- When a vehicle is in the nontarget lane, the driver has to make a mandatory lane change to get into the target lane before approaching the next intersection, as illustrated by Figure 3. Thus, the driver keeps searching for an acceptable opportunity to change lanes. If no chance is available even when the vehicle is approaching the exit intersection, the driver has to slow down or even to stop to await an acceptable gap. In most cases, according to the authors' field videotaped observations, there is a vehicle in the target lane that slows down and leaves the lane changer a gap for safe merging. This condition is defined as the cooperation condition.
- When a vehicle is in a preemptive lane, the driver in fact has already reached his long-term objective. Short-term motivation is the only reason that he or she explores a lane change. If it is not possible to pass the preceding vehicle, the driver may change to an adjacent lane to maintain his or her desired speed. If no condition is available for either passing or a single-lane change, the driver is assumed to remain in his or her current lane.
- When a vehicle is in a nonpreemptive lane, the driver attempts to change into the preemptive lane on the basis of his or her long-term motivation, as illustrated by Figure 3. The driver will implement this maneuver only if an acceptable condition is available; otherwise the driver will stay in his or her current lane. He or she keeps trying until an acceptable condition for the lane-changing maneuver is available.

STRUCTURE OF HEURISTIC LANE-VEHICLE-ASSIGNMENT MODEL

A lane-assignment model describes a vehicle's position during its journey on an urban street network. From observations and study of lane-choice and lane-changing models reported by Wei et al. (*3*) and in another paper by Wei et al. in this Record, it can be seen that a vehicle is assigned to a lane in a logical manner depending on the relationship between its route-planned motivation and traffic conditions in the current lane and other lanes. Therefore, lane assignment can be presented in the form of a heuristic structure, as shown in Figure 4, which was developed on the basis of logic resulting from analyses of observations of lane-choice and lane-changing behavior over eight streets in Kansas City, Missouri.

A lane-assignment model consists of three components: lane choice, car following, and lane changing. The lane-changing component is composed of three submodels—a decision model, a lane-changing condition model, and a lane-changing maneuver model. In all, the lane-assignment model estimates an individual vehicle's location, speed, routing plan, lane-choice plan, lane-changing plan, and

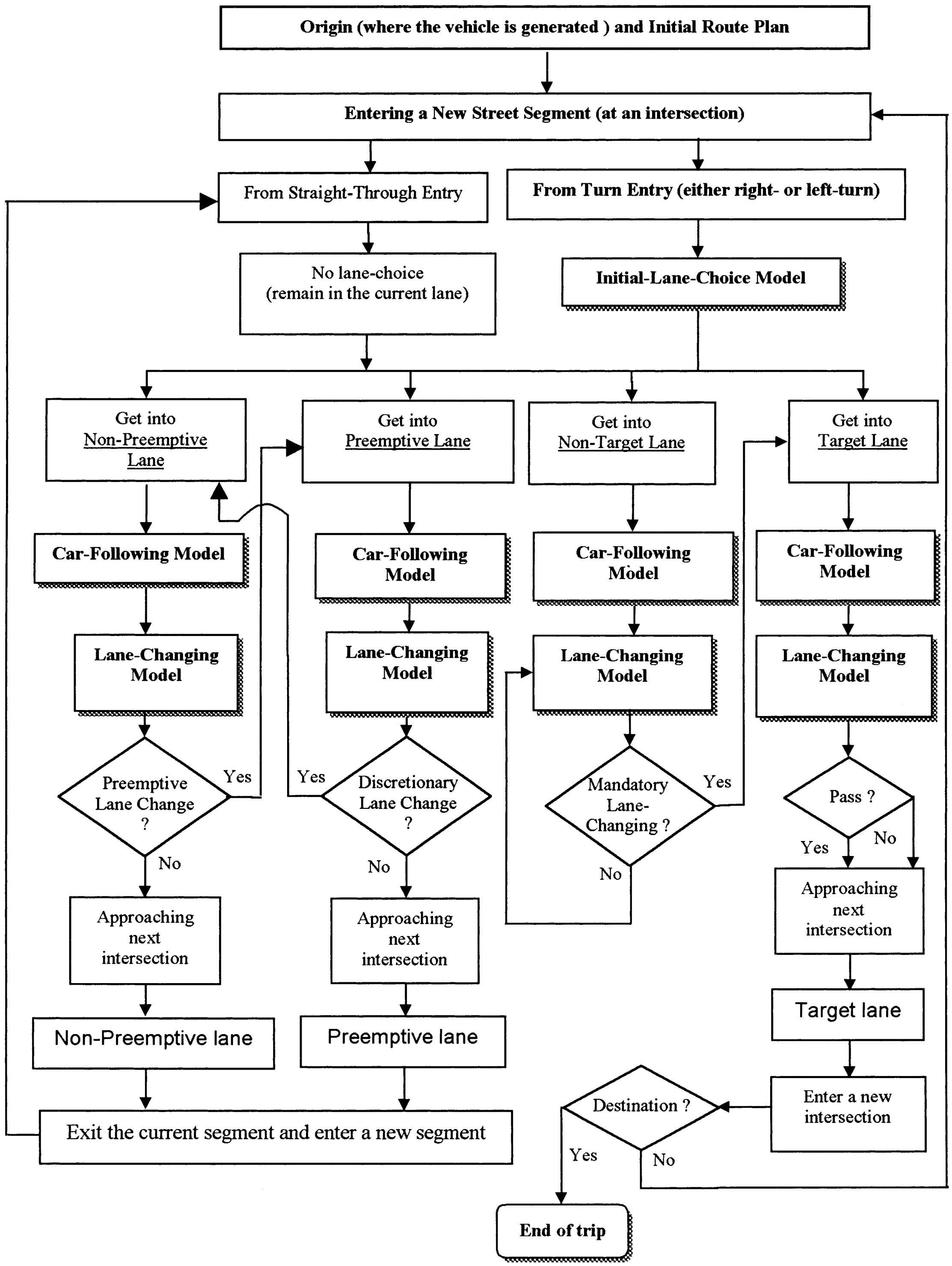


FIGURE 4 Structure of lane-vehicle-assignment model for urban street networks.

car-following plan from its entrance into the street network until the end of the trip. Figure 4 indicates that a vehicle's trip on an urban street network can be simulated by a series of states, and Figure 5 illustrates some of the states in the process of lane assignment:

- The origin state sets up the original location at which a simulated vehicle is generated in a street network plus the departure time and the destination location at which the trip ends. An intersection closest to the original location is where the vehicle enters the street network.
- The route-planning state designs a route plan based on the vehicle's origin and destination and current traffic and road conditions in the network.
- The lane-choice state chooses a lane as the vehicle enters a street segment from an intersection using the lane-choice model.
- The car-following state describes the vehicle's location, speed, spatial and temporal relation with the preceding vehicle (if it exists) at each simulated time moment, as well as its reaction to any changes in the preceding vehicle's speed. Since car-following models have been prevalent in the literature and existing information is quite useful, no new attempts in this area were pursued in the study.
- The lane-changing state recognizes the vehicle's request and decision for changing lanes, lane-change type (mandatory, preemptive, or discretionary), lane-changing conditions to determine whether acceptable gaps are available for changing lanes, and lane-changing maneuvers. Location, acceleration, speed, and duration are estimated at each simulated time moment during a lane change.
- The exiting state checks the vehicle's current lane and its driver's intention as he approaches the end (next intersection) of the current street segment to go straight, turn, or reach his destination. If the approaching intersection is the destination, the vehicle's trip is ended and is no longer traced. Its recorded locations, clock time, speeds, accelerations, and maneuvers are stored in the database when any action occurs that leads to the change of the vehicle's state.
- The new-entering state determines the driver's lane choice (if the travel continues) to enter the next street segment from the current intersection after the driver has exited an intersection on the last street segment. Then the model proceeds to a lane-choice state as described above. The lane-assignment model repeats the above process until the end of the requested period of time.

Heuristic Lane-Choice Model

A lane-choice model is used in traffic simulation to assign a vehicle to a proper lane when it is entering a street segment from an entry intersection. On the basis of analyses of observations, a driver's heuristic decision making can be described by a rule-based or heuristic model. Figure 6 is a flowchart of a heuristic lane-choice model.

A driver's aggressiveness may be represented by an index value of 0 to 10, with 10 being the most aggressive. A driver with an aggressiveness index value of over a specific value ω may be regarded as an aggressive driver. The authors conducted an auxiliary survey to obtain a small-sized sample to determine aggressiveness characteristics for the study area. The survey is beyond the focus of this paper and will not be introduced here.

Lane-Changing Model

Figure 7 describes the relationship among components of a lane-changing model. From the logic shown in Figure 7, a lane-changing process includes three actions: decision making, recognizing acceptable conditions (gaps or headway between the lead and the lag vehicles), and lane-changing maneuvers. The initial lane choice and the route-maneuvering plan at the next intersection (i.e., either to go straight through or make a turn) contribute to a driver's long-term motivation to change lanes. The driver has a short-term motivation to change lanes only if an incident or blockage occurs ahead. As a result of decision making, the driver determines his willingness or intention to change lanes and the type of lane change (i.e., mandatory, preemptive, or discretionary). Passing is a special case of discretionary lane change and usually occurs in the target lane. Passing includes two lane-changing maneuvers: moving to another lane and coming back to the previous lane. While the driver is making a decision to change lanes, he needs to check if acceptable space between the lead and the lag vehicles is available. If the lane-changing condition is acceptable, he executes a lane change. Therefore, a lane-changing model is suggested to consist of three submodels: decision model, condition model, and maneuver model. These three submodels are briefly described as follows.

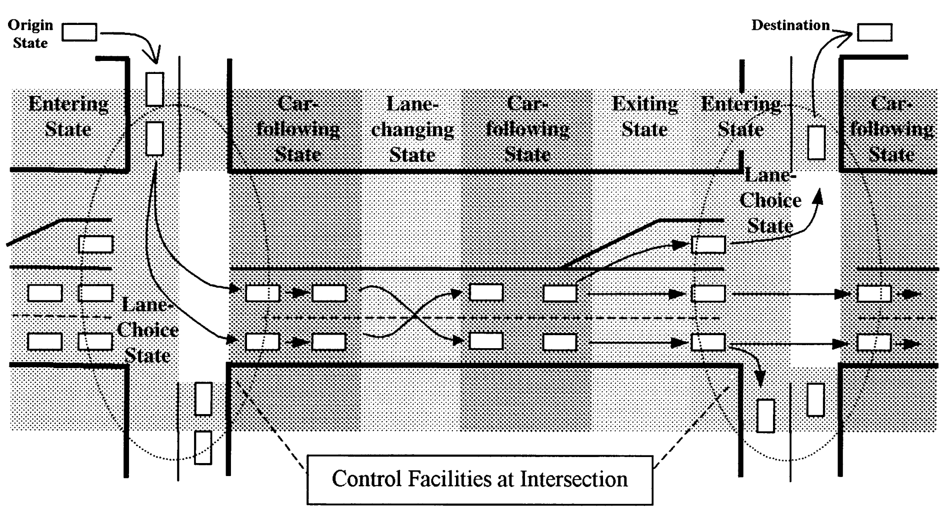


FIGURE 5 Lane vehicle assignment in terms of states.

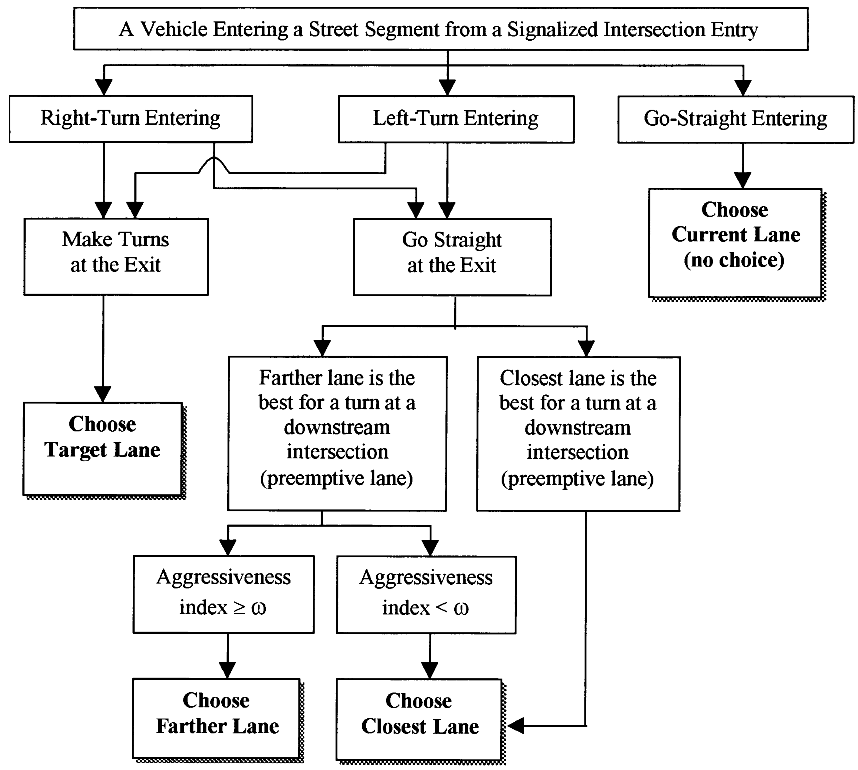


FIGURE 6 Flowchart of heuristic lane-choice model.

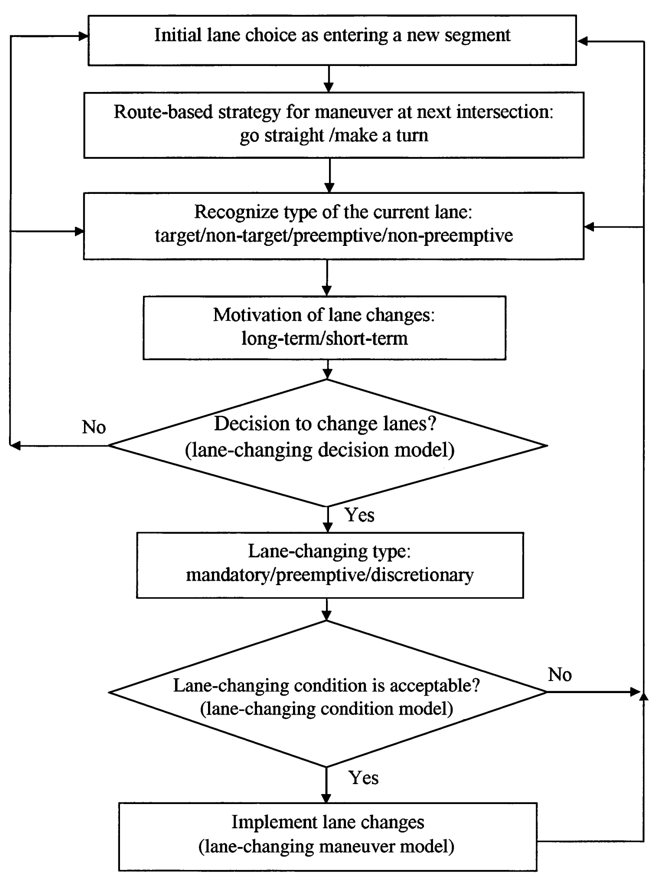


FIGURE 7 Structure of lane-changing model.

Decision Model

The heuristic-based lane-changing decision model is described as follows:

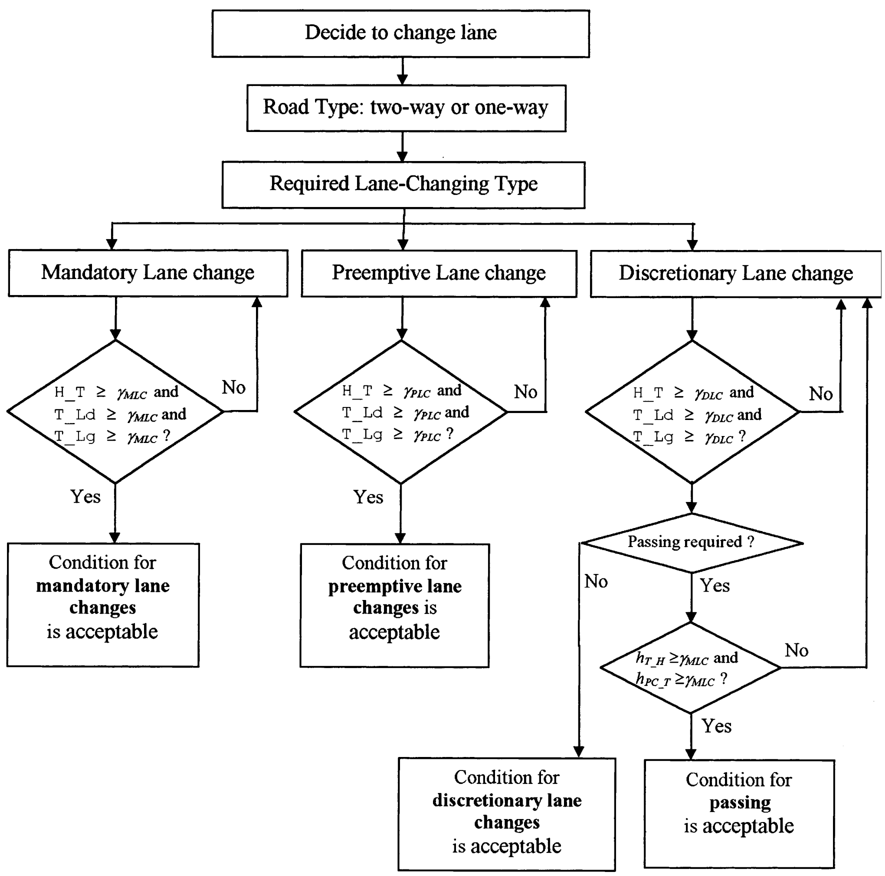
- If a driver's current lane is a nontarget lane, the driver is willing to make a mandatory lane change;
- If a driver's current lane is a nonpreemptive lane, the driver is willing to make a preemptive lane change.
- If a driver's current lane is a preemptive lane, the driver is willing to make a discretionary lane change only if the speed advantages and disadvantages are greater than the threshold, which is discussed in another paper by Wei et al. in this Record.
- If a driver's current lane is the target lane, the driver is willing to pass the head vehicle only if his speed disadvantage is greater than the threshold. If the driver thinks the required type of lane change is passing, this is a special case of discretionary lane change because of the fact that the driver will change lanes and then change back.

Condition Model

A driver has to search for acceptable conditions to implement a lane change if he decides to leave the current lane. Continuously changing speeds and gaps between the prospective lane changer and other vehicles directly affect the prospective lane changer's behavior in implementing a lane change. Headway is recommended as a vital factor in lane-changing condition models. Observed values of thresholds of relative headways corresponding to a typical probability threshold are discussed by Wei et al. (*3*). The rules involved in the lane-changing condition model are illustrated by a flowchart (Figure 8).

Maneuver Model

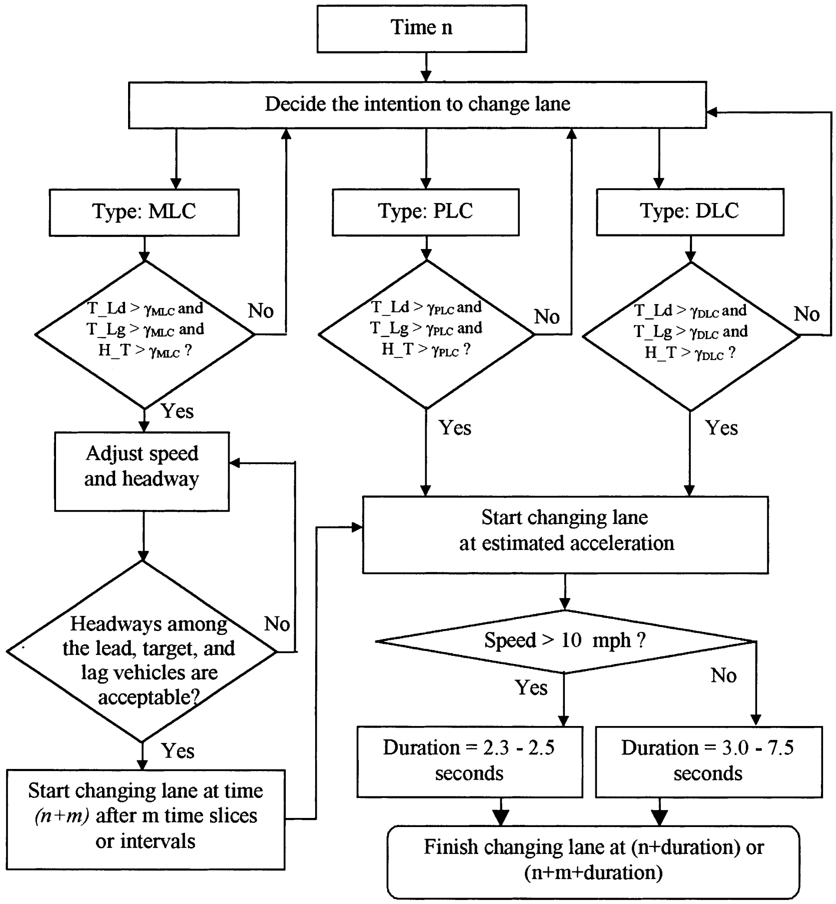
The primary concerns in a lane-changing maneuver are the vehicle's duration of changing lanes and how the vehicle's speed or acceleration at the beginning of a lane change affects this duration. Statistical results of correlation analysis between speed and acceleration at the



Notes:

T_Ld: headway between 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: headway between lane changer (target vehicle) and the back vehicle in adjacent lane that intends to follow the target vehicle after the lane change occurs;
H_T: headway between lane changer (target vehicle) and the ahead vehicle in present lane followed by the lane changer before the lane change occurs;
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 8 Lane-changing condition model.



Notes:

MLC: mandatory lane change; PLC: preemptive lane change; DLC: discretionary lane change
Others: see notes in Figure 8

FIGURE 9 Flowchart of lane-changing maneuver model (1 mi = 1.6 km).

beginning of a lane change and the duration of a lane change indicate that there is little correlation between speed and acceleration or between acceleration and duration. Therefore, there may be no need to model the influence of speed or acceleration on duration of a vehicle's lane change. As a result of observed data analyses, a heuristic structure for a lane-changing model was developed as shown in Figure 9.

SUMMARY

This research provides a start in the development of a lane-vehicle-assignment model on an urban street network. On the basis of new findings from observations conducted on four-lane urban streets (two lanes in each direction), the study developed heuristic structures for a lane-assignment model along with a lane-choice model and a lane-changing model. The methodology for the models and the heuristic models presented provide a good basis for further research on streets with six or more lanes and are expected to help simulation system developers clearly specify the relationship and structure of vehicle-based travel behavior with the system being simulated. With the addition of this information, a simulation system may be developed to correctly represent travel behavior and dynamic traffic assignment at the lane level.

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