Integrated Lane Changing Models

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Abstract

This paper summarizes a series of advances in lane changing models aiming at providing a more complete and integrated representation of drivers' behaviors. These advances include the integration of mandatory and discretionary lane changes in a single framework, the inclusion of an explicit target lane choice in the decision process and the incorporation of various types of lane-changing mechanisms, such as cooperative lane changing and forced merging. In the specifications of these models, heterogeneity in the driver population and correlations among the various decisions a single driver makes across choice dimensions and time are addressed. These model enhancements were implemented in the open source microscopic traffic simulator of MITSIMLab, and their impact was demonstrated in validation case studies where their performance was compared to that of existing models. In all cases, a substantial improvement in simulation capability was observed.

Introduction

Lane changing has a significant impact on traffic flow. Lane-changing models are therefore an important component in microscopic traffic simulators, which are becoming the tool of choice for a wide range of traffic-related applications at the operational level. A number of lane-changing models have been proposed and implemented in various simulators in recent years (see Toledo, 2006 for a review). While their details vary, the general structure of these models displayed in Figure 1 is similar. Most models classify lane changes as either mandatory or discretionary (e.g., Ahmed, 1999; Ahmed et al., 1996; Gipps, 1986; Halati et al., 1997; Hidas, 2002; Hidas and Behbahanizadeh, 1999; Yang and Koutsopoulos, 1996; Zhang et al., 1998). A mandatory lane change (MLC) occurs when a driver must change lanes to follow a path, and when an MLC is required, it overrides any other considerations. A discretionary lane change (DLC), on the other hand, takes place when a driver changes to a lane perceived to offer better traffic conditions. Gap acceptance models are used to model the execution of lane changes. The available gaps are compared to the smallest acceptable gap (critical gap) and a lane-change is executed if the available gaps are greater. Gaps may be defined either in terms of time or free space. Most models also make a distinction between the lead gap (i.e., the gap between the subject vehicle and the vehicle ahead of it in the lane it is changing to) and the lag gap (i.e., the gap between the subject vehicle and the vehicle behind it in the lane it is changing to) and require both to be acceptable.

The present paper summarizes several enhancements that have been made to this generic lane-changing model in order to improve its realism and address several limitations. The organization of the paper is as follows: first, the general methodology that was used to develop each one of the models presented in this paper is given. The next three sections present enhancements that have been made to the lane-changing model: integration of mandatory and discretionary lane changes in a single frame- work, explicit modeling of the choice of the target lane and a model that incorporates courtesy behavior and forced merging in the lane-changing process. For each of these models, the modified structure of the lane-changing decision process is presented and the limitations of the basic model that it addresses are discussed and demonstrated with a real-world case study. The specification of all these models account for the heterogeneity in the behavior population and for correlations among the decisions a single driver makes over choice dimensions and time. The mathematical formulation that permits the capturing of these effects is presented in the next section. The final section concludes our findings and discusses directions for further enhancements.

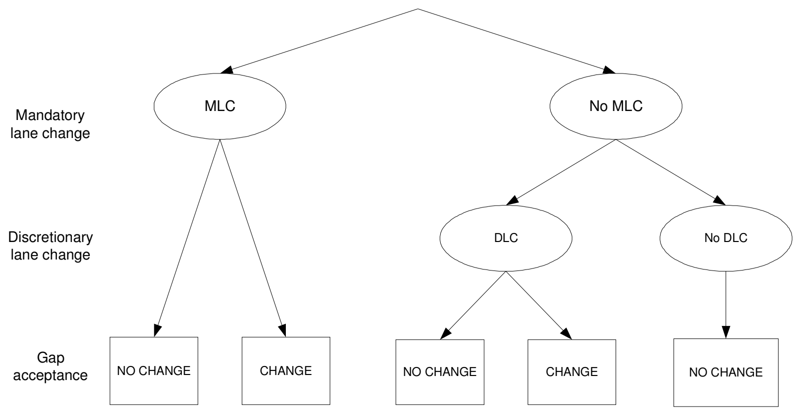


Fig. 1. Generic structure of lane changing models

Methodology

All the models that are presented here were developed using the process shown in Figure 2, which involves both disaggregate and aggregate data. Disaggregate data, consisting of detailed vehicle trajectories at a high time resolution, are used in the model estimation phase, in which the model is specified and explanatory variables, such as speeds and relations between the subject vehicle and other vehicles, are generated from the vehicle coordinates extracted from the trajectory data. The model parameters are estimated with a maximum likelihood technique in order to match observed lane changes having occurred in the trajectory data. This estimation approach does not involve the use of a traffic simulator, and so the estimated models are independent of simulators.

In order to demonstrate the benefits that may be derived from using the modified models, they must be validated and demonstrated within a microscopic traffic simulator incorporating not only the lane-changing models under investigation, but also other driving behavior models, such as acceleration models. As a result, the estimated model needs to be implemented within a microscopic traffic simulator, and MITSIMLab (Yang and Koutsopoulos, 1996) was employed in all the cases described herein. In the validation case studies, aggregate data, which is significantly cheaper to collect and in many cases readily available, could be used. Part of the aggregate dataset was first utilized to adjust key parameters in the lane-changing model as well as parameters of other behavior models, and to estimate the travel demand on the case study network. This aggregate calibration problem was formulated as an optimization problem, seeking to minimize a function of the deviation of the simulated traffic measurements from the observed measurements and of the deviation of calibrated values from their a-priori estimates, when available (Toledo et al., 2003). The rest of the data was used for the validation itself, which was based on a comparison of measures of performances that could be calculated from the available data with corresponding values from the simulator, e.g., sensor speeds and flows, the distribution of vehicles among the lanes, the amount and locations of lane changes. The calibration and validation methodology is outlined in Figure 2 (detailed in Toledo and Koutsopoulos, 2004).

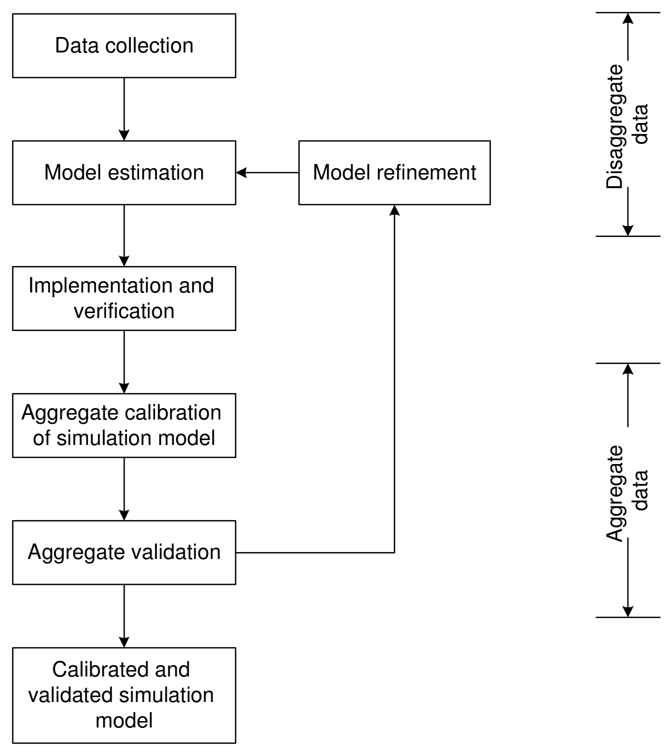


Fig. 2. Estimation, calibration and validation process

Integration of MLC and DLC

As noted above, most models classify lane changes as either mandatory or discretionary, with the former overriding the latter. This separation implies that there are no trade-offs between mandatory and discretionary considerations. For example, a vehicle on a freeway which intends to take an off-ramp will not overtake a slower vehicle if the distance to the off-ramp is below a certain threshold value, regardless of the speed of that vehicle. Furthermore, in order to implement the MLC and DLC models separately, rules that dictate when drivers begin to respond to MLC conditions need to be defined. However, this point is unobservable, and so only judgment-based heuristic rules, which are often defined by the distance from the point where the MLC must be completed, are employed.

The model shown in Figure 3 integrates MLC and DLC into a single utility model. Variables that capture the need to be in the correct lane and to avoid obstacles as well as variables that capture the relative speed advantages and ease of driving in the current lane as well as in the lanes to the right and to the left, are all incorporated in a single utility model that takes into account the trade-offs among these variables. An important goal that affects drivers' lane-changing behavior in this model is following the travel path. This goal is accounted for by a group of variables that capture the distance to the point where drivers have to be in specific lanes and the number of lane changes that are needed in order to be in these lanes. Figure 4 demonstrates the impact of these variables on the probability that a driver intending to exit a freeway through an off-ramp would target a change to the right. This probability increases when the distance to the off-ramp is smaller (approaching 1 when the distance approaches zero) and when the number of lane changes required increases. Note that with separate MLC and DLC models, the corresponding graph would be a step function, with probability 0 when the distance to the ramp is larger than a certain threshold value, and 1 when the distance is smaller.

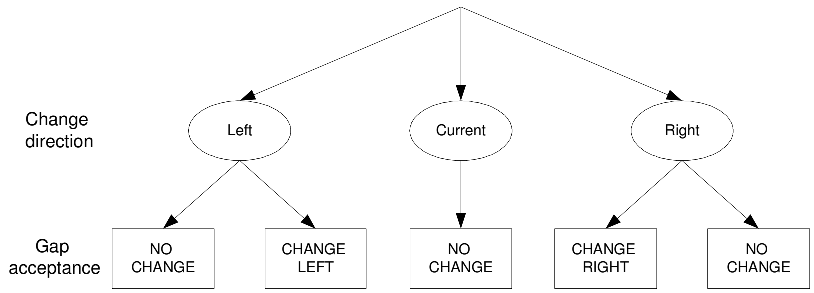


Fig. 3. Structure of the integrated MLC and DLC model.

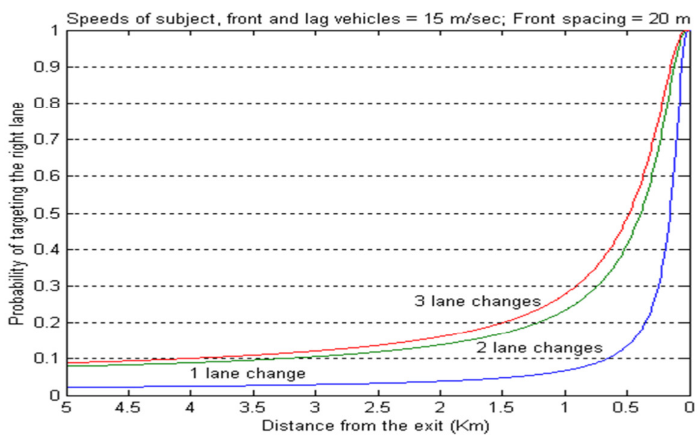


Fig. 4. Impact of the path-plan on the probability of targeting the right lane.

Explicit target lane choice

The decision to seek a lane change and the direction of change in the models introduced so far have been based on an evaluation of the current lane and the adjacent lanes to the right and to the left. Therefore, in these models, the set of lanes that the driver chooses from depends on the lane that the vehicle is currently in. In multi-lane road facilities, only a subset of the available lanes is evaluated. This approach may result in unrealistic behavior in cases where drivers change lanes not because the lane they are changing to is preferable, but as a step on their way to another lane further away in the lane change direction. This type of situation may arise, for example, in multi-lane freeways with dedicated lanes (e.g.

HOV lanes). Drivers may change lanes in the direction of the dedicated lane, even to lanes with undesirable characteristics (e.g. slower speeds) in order to eventually enter the dedicated lane, which may pro- vide higher levels of service.

In order to tackle this problem, the model shown in Figure 5 (for a driver currently in the second lane from the right, lane 2, of a four-lane freeway) has been tested. This model introduces an explicit target lane selection. Rather than choosing a direction change, drivers choose a target lane among all the available lanes. The target lane is the lane that is perceived as the best lane to be in when multiple factors and goals are taken into account. The direction of a desired lane change, if any, is dictated by the direction of the target lane from the lane that the vehicle is currently in. As with previous models, the completion of the lane change depends on its feasibility, which is captured by gap acceptance models. An estimation of this model with trajectory data demonstrated that important factors affecting the utilities of the various lanes include the microscopic and macroscopic traffic flow characteristics in the lane (e.g., the presence of heavy vehicles, the average speed and density), the impact of the path-plan (e.g., whether it would be a correct lane in order to follow the path), an inertia factor (e.g., whether it is the current lane and if not, the number of lane changes that would be required to reach it) and characteristics of the driver (e.g., aggressiveness).

To demonstrate its usefulness, the model was tested on a section of I-80 in Emeryville, California. This section, shown schematically in Figure 6, is six lanes wide, and the left-most lane is an HOV lane that can be accessed at any point in the section. Traffic speeds are significantly higher on this lane as compared to on the other lanes that experience significant queuing and delays during the peak period.

Figure 7 shows a comparison of the distribution of vehicles among lanes observed in this section to the ones predicted by two versions of MITSIMLab: one that implements the model with an explicit target lane choice, and another that implements the model described in the previous section, and which is based on a myopic choice of direction change. Overall, the model with an explicit target lane choice matched the observations better, particularly with respect to the usage of the HOV lane. The change direction model underestimated the usage of the HOV lane, mainly because it was not in the set of lane choices of the drivers entering the section from the on-ramp. Consequently, these drivers did not reach this lane. With the explicit target lane model, drivers also evaluated the HOV lane and some chose to change to this lane. As a result, the utilization of the HOV lane was higher and closer to the real- world observations. Additional validation results have been presented in Choudhury et al. (2007a).

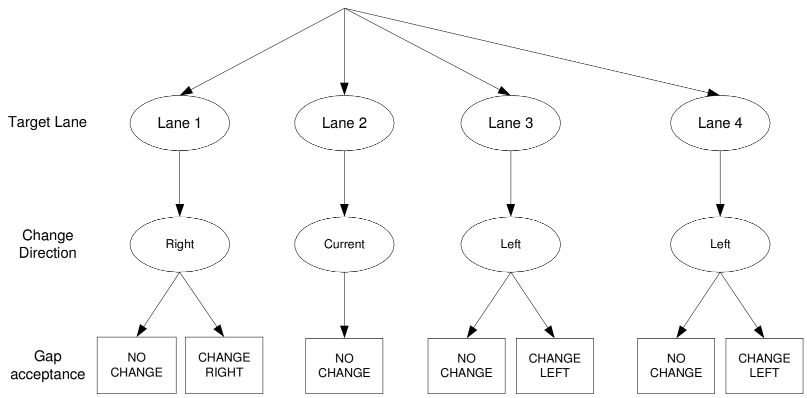


Fig. 5. Structure of model with explicit target lane choice (current lane is lane 2)

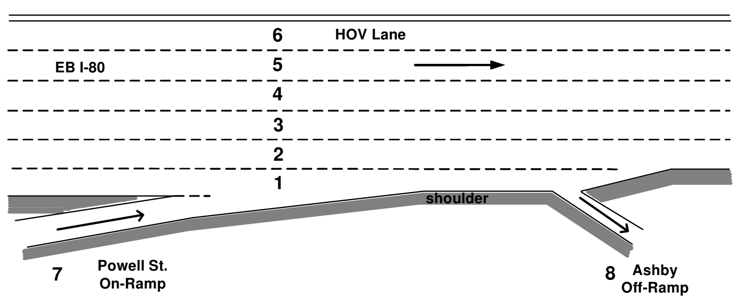


Fig. 6. The I-80 site, Emeryville California

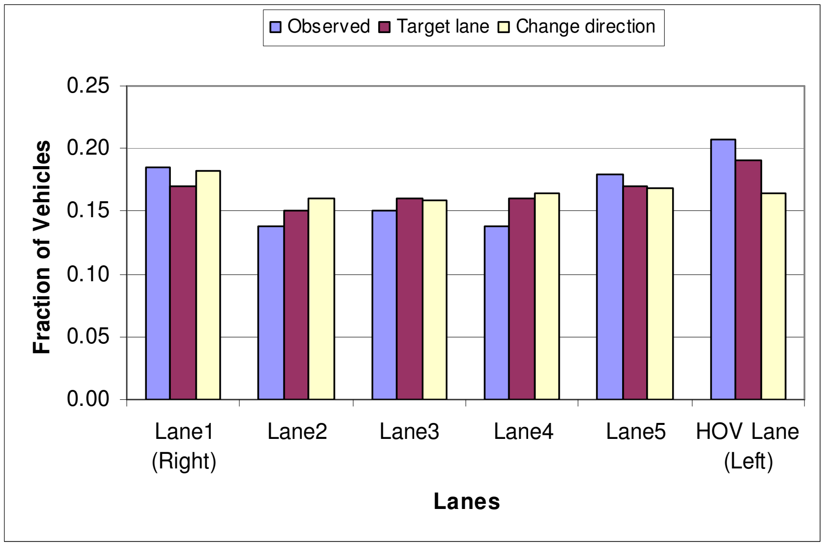


Fig. 7. Observed and simulated distributions of vehicles among lanes in the I-80 section

Cooperative and Forced Gap acceptance

The models discussed so far assume that lane changing is executed through gap acceptance. However, in congested traffic conditions, acceptable gaps may not be available, and so other mechanisms for lane changing are required. For example, drivers may change lanes through courtesy and cooperation of the lag vehicles on the target lane as a result of the latter slowing down to accommodate the lane change. In other cases, certain drivers may become impatient and decide to force their way into the target lane thus compelling the lag vehicle to slow down.

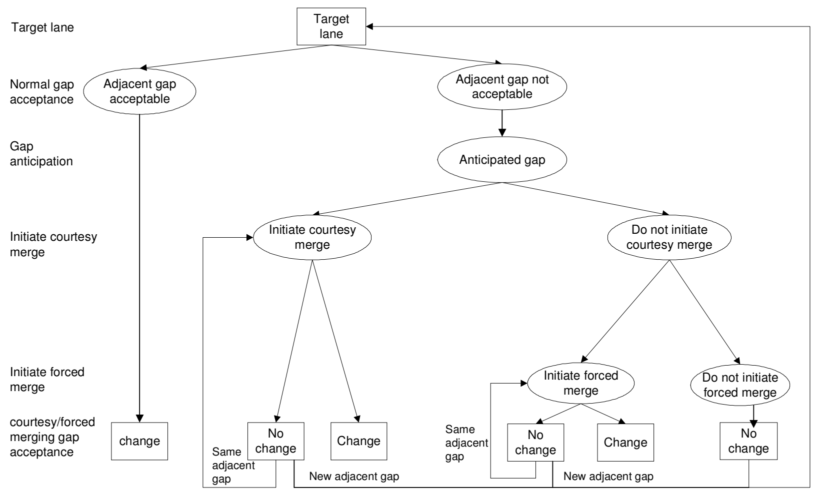


Fig. 8. Structure of a merging model that integrates courtesy and forced merging

The model shown in Figure 8, which was developed for a merging situation, integrates courtesy and forced merging mechanisms with “normal” gap acceptance. This integrated model captures the transitions from one type of merging to the other and the merging driver first evaluates whether or not the available adjacent gap is acceptable. This decision is modeled with standard gap acceptance models that com- pare the lead and lag gaps with the corresponding critical gaps. If the available gap is acceptable, the driver merges to the mainline. If, on the other hand, the available gap is unacceptable, the driver anticipates what the magnitude of the adjacent gap will be in a short time horizon. The anticipated gap is evaluated based on the magnitude of the available gap and the current speed and acceleration of the lag vehicle. The time horizon over which the driver anticipates the gap may vary across the driver population so as to capture differences in perception and planning abilities among drivers. The anticipated gap reflects the drivers’ perception of the courtesy or discourtesy of the lag vehicle. The driver then evaluates whether the anticipated gap is acceptable or not. An acceptable anticipated gap implies that the lag vehicle is providing courtesy to the merging vehicle, and so the driver can initiate a courtesy merge. If the anticipated gap is not acceptable, the lag vehicle is not providing courtesy, in which situation the merging driver may choose whether or not to begin forcing his way into the mainline and compel the lag vehicle to slow down.

A driver that has initiated courtesy yielding or forced merging completes the merge when the available gap is acceptable. Thus, the lane change may not be completed when initiated, but it may rather take more time. However, the model assumes that a driver that has initiated a courtesy or forced merge will continue to use this mechanism until the lane change is complete, or if unsuccessful until the adjacent gap is no longer available (e.g., having been overtaken by the lag vehicle). Critical gaps for courtesy or forced merging may differ from the ones used in normal lane changing.

Estimation results for this model (Choudhury et al., 2007b) showed that the inclusion of the three merging mechanisms were justified by the data and significantly improved the fit of the model. Critical gaps differed in the various merging mechanisms. In general, the results showed that drivers were willing to accept smaller lead and lag gaps if they perceived that the lag vehicle was courtesy yielding.

To demonstrate the impact of the inclusion of courtesy and forced merging in the model, a version of MITSIMLab implementing this model was compared with one that only included a standard lane-changing model (Lee, 2006) similar to the one described in the previous section. The network used in the validation was a section of US101 in Los Angeles California, displayed in Figure 9. This section generally experiences high congestion during the peak period that was modeled in this case study. Figure 10 shows the distribution of locations of merges as a function of the remaining distance to the end of the merging lane, which was observed in the data and predicted by the two MITSIMLab versions. The results indicated that the full model, which incorporated courtesy and forced merging, was able to better match the locations of merges as compared to the model that only captured "normal" lane-changing. Particularly, with the simple model, vehicles were unable to change lanes by accepting available gaps. Therefore, a large share of the merges occurred very late (81% occurred less than 100 meters from the end of the merging lane). This may result in the formation of queues on the ramp and an over-prediction of delays to both ramp and mainline vehicles. With the full model, the addition of the courtesy and forced merging mechanisms allowed drivers to merge more quickly and with greater ease, and thus only 47% of the merges occurred within 100 meters from the end of the ramp. This value is significantly closer to the observed 44%.

Comparisons of lane-specific flows from both versions of MITSIMLab are presented in Table 1. The results show that the full model was able to provide a better match to the actual flows. Thus, the improved realism of the model at the microscopic level was also translated into an improved fit to the aggregate (or macroscopic) traffic flow characteristics, which are most often the statistics of interest in a simulation application.

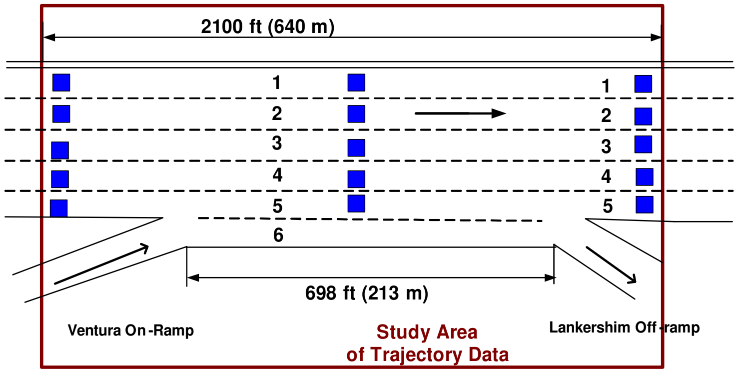


Fig. 9. The US101 site, Los Angeles California

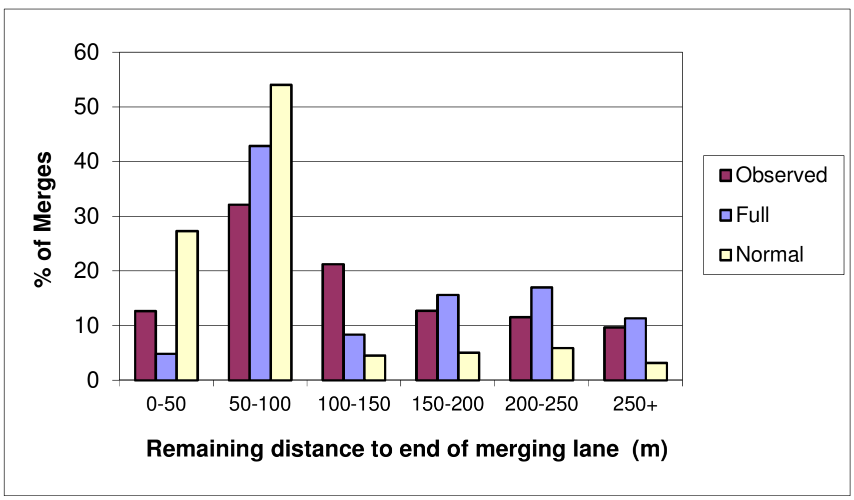


Fig. 10. Observed and predicted merge locations

Table 1- Comparison of Lane-Specific Flows

	Normal	Full	Improvement
RMSE (vehicles/5 mins)	19.18	13.22	31.07%
RMSPE	12.18%	7.52%	38.26%

Accounting for heterogeneity

All the lane-changing models discussed above incorporate decisions that drivers make over several choice dimensions (e.g., the choice of target lane, gap acceptance). Moreover, these decisions are repeated over time. Invariant characteristics of the drivers and their vehicles, such as aggressiveness, their level of driving skill and the vehicle's speed and acceleration capabilities, create correlations among the choices made by a given driver over time and choice dimensions. It is important to capture these correlations in the utility functions. However, the data available for model estimation does not comprehend information about these characteristics. Therefore, a model specification including individual-specific latent variables in the various utilities in order to capture these correlations was utilized. This individual-specific term appears in the utilities of all the various alternatives that a driver has in all his choices and in all time periods. The model assumes that, conditional on the value of this latent variable, the error terms of different utilities are independent. This specification is given by:

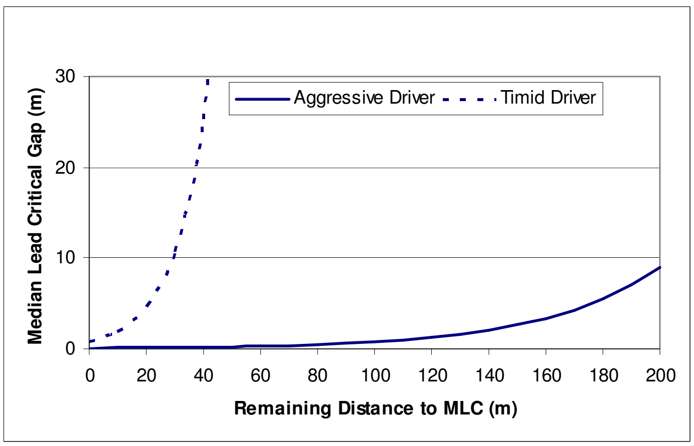
$$U_{int}^{c} = \beta_i^{c^T} X_{int}^{c} + \alpha_i^c \upsilon_n + \varepsilon_{int}^{c} \qquad (1)$$

U_{int}^{c} is the utility of alternative *i* of choice dimension *c* to individual *n* at time *t*. X_{int}^{c} is a vector of explanatory variable. β_i^c is a vector of parameters. υ_n is an individual-specific latent variable assumed to follow some distribution in the population. α_i^c is the parameter of υ_n. ε_{int}^{c} is a generic random term with independently and identically distributed (i.i.d.) across alternatives, individuals and time. ε_{int}^{c} and υ_n are independent of each other.

The resulting error structure (see Heckman 1981, Walker 2001 for a detailed discussion) is given by:

$$cov\left(U_{int}^{c},U_{i'n't'}^{c'}\right)=\begin{cases}\left(\alpha_i^c\right)^2+\left(\sigma_i^c\right)^2 & if\ n=n',\ c=c',\ i=i'\ and\ t=t' \\ \alpha_i^c\alpha_{i'}^{c'} & if\ n=n',\ c\neq c'\ and/or\ i\neq i'\ and/or\ t\neq t' \\ 0 & if\ n\neq n'\end{cases} \quad (2)$$

σ_i^c is the standard deviation of ε_{int}^c.



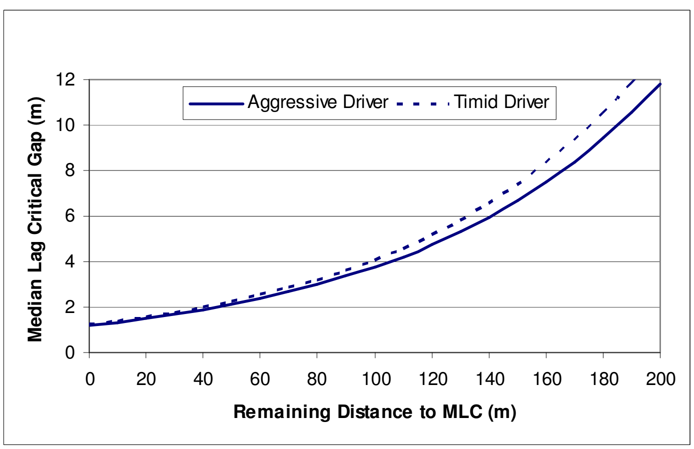


Fig. 11. Median lead and lag critical gaps as a function of the distance to the end of the merging lane

The impact of this formulation on the resulting behavior is demonstrated with the application in the lead and lag critical gaps of the merging model described in this model. Here, critical gaps depend on the remaining distance to the end of the merging lane. The individual specific random term was introduced in the coefficient of the remaining distance in both the lead and lag critical gaps (as well as in other parts of the model). This variable was interpreted as representing the range of drivers' behavior from timid to aggressive. Figure 11 demonstrates critical lead and lag gaps for timid and aggressive drivers. Everything else being equal, aggressive drivers had lower critical gaps as compared to their more timid counterparts. Furthermore, the difference in critical gaps increased when the merge became more urgent, as the vehicle approached the end of the merging lane. The use of the same individual-specific latent variable in both critical gaps also ensured that the behavior was consistent, and consequently, a driver who is aggressive in one dimension (e.g., has a small critical lag gap) would also be aggressive in other dimensions (e.g., would have a small critical lead gap as well).

Conclusion

Lane-changing is an important component of microscopic traffic simulation models, and has a significant impact on the results of analyses employing these tools. In recent years, the interest in the development of lane-changing models and their implementation in traffic simulators has increased dramatically. This paper presents several enhancements to the basic lane-changing model that has been utilized, with some variations, in several simulators. These enhancements have been intended to form a more comprehensive modeling framework for the integration of various aspects of the lane-changing behavior, such as MLC and DLC, and other lane changing mechanisms, including courtesy and forced gap acceptance. Estimation results and validation case studies demonstrated significant improvements in the ability of the enhanced lane-changing models to replicate observed behavior and traffic patterns as compared to the simple generic model. The extent of the improvement obtained with the enhancements presented herein leads us to believe that further advances in lane- changing models may give rise to additional improvements in their ability to replicate reality. In particular, two areas of improvement may be useful in that respect:

Integrating acceleration behavior in lane-changing models. Drivers' acceleration may be affected by their lane changing behavior. For example, drivers may accelerate or decelerate in order to position their vehicles such that they are able to accept available gaps. This type of behavior, if implemented in traffic simulators, may have a significant impact on simulated traffic flow characteristics. Some research in this direction, with promising results, has been conducted by Zhang et al. (1998) and Toledo (2002). However, further research to experiment with various model structures and specifications as well as to use more datasets from diverse locations and traffic conditions, is required in order to better understand the inter-dependencies among lane changing and acceleration behaviors.

Lane-changing behavior in arterial streets. All the results presented in this paper and most of the research in this field in general are based on data collected from freeway sections. While the structures of these models are common enough to be applied on traffic in urban arterials, some factors affecting the lane-changing behavior in urban streets may not be present in freeway traffic. For example, the impact of buses and bus stops, paring activity, traffic signals and the queues that form behind them are important in urban streets but cannot be observed in data collected from freeway sections.

Furthermore, a significant proportion of lane changes in urban arterials may occur at intersections and not in the sections themselves. Research in this direction has been conducted by Wei et al. (2000). In an on-going effort sponsored by the NGSIM project, data collected in an arterial street in Los Angeles California is used for this purpose.

Acknowledgments

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