Modeling Duration of Lane Changes

Tomer Toledo and David Zohar

Lane changes significantly affect the characteristics of traffic flow. Lane-changing models are therefore important in microscopic traffic simulation. Existing lane-changing models emphasize the decision-making aspects of the task but generally neglect the detailed modeling of the lane-changing action itself and model it only as an instantaneous event. However, research indicates that lane-changing durations are on average in the range of 5 to 6 s. The omission of lane-changing durations from simulation models may have a significant impact on simulation outputs. Models of the duration of lane changes are presented. These models are estimated by using detailed vehicle trajectory data that were collected in naturalistic driving with high-mounted video cameras. Separate models are presented for passenger cars and for heavy vehicles and statistical tests are conducted for the similarity between the lane-change durations of the two vehicle types.

Lane changes have a significant impact on the characteristics of traffic flow (*1, 2*). Lane-changing models are therefore important in microscopic traffic simulation. In recent years, following the emergence of traffic simulation models as useful tools for the analysis of transportation systems, interest in the development of more reliable lane-changing models has increased [see work by Kitamura and Kuwahara (*3*) and Toledo (*4*) and the references therein]. Existing models of lane-changing behavior emphasize the decision-making aspects of the task but generally neglect the detailed modeling of the lane-changing action itself and only model it as an instantaneous event. However, this assumption contradicts research findings showing that average lane-changing durations are in the range of 5 to 6 s. The acceleration behavior of the vehicle changing lanes and of other vehicles around it may be affected during the execution of lane changes. Therefore, the omission of lane-changing duration from microscopic simulations may have a significant effect on simulation outputs. Here models of the duration of lane changes are presented. Detailed vehicle trajectory data are used to estimate the parameters of these models.

MODELS OF LANE-CHANGING DURATION

Only a limited number of studies that address the question of duration of lane changes have been presented in the literature. Worrall and Bullen (*5*) used aerial photographs to estimate lane-change durations, which split into two parts: the time in the initial lane and the time in the target lane. The mean durations were 1.25 and 1.95 s, respectively. The respective standard deviations were 0.4 and 0.5 s. However, later research (*6*) suggested that lane-change durations were underestimated in this study because of the limitations of the technology that was used. Finnegan and Green (*7*) reviewed relevant research conducted in the 1970s and 1980s. They report that lane changes, including visual search time, took between 4.9 and 7.6 s depending on the presence of traffic and the direction of change. However, they point out that the use of obtrusive equipment, such as eye markers and helmets, may have interfered with drivers' behavior.

Tijerina et al. (*8*) used observers who accompanied the driver in the vehicle. The observers gave driving instructions and recorded drivers' actions. The study included 39 drivers who drove both on highways and on urban streets. For the urban streets, lane-change durations were between 3.5 and 6.5 s, with a mean of 5.0 s. For highways the duration ranged from 3.5 s to 8.5 s with a mean of 5.8 s. Hetrick (*9*) also used observers to collect data in the vehicle. Sixteen participants drove an instrumented vehicle with an observer for 1.5 h on urban streets and on highways. Lane-change durations ranged from 3.4 s to 13.6 s. Young drivers tended to have short lane-change durations, whereas elderly drivers took longer times to change lanes. The mean lane-change duration was 6.0 s. Lee et al. (*10*) point out that the presence of the observer in these studies may have influenced drivers' behavior, resulting in a lack of natural driving behavior.

Hanowski (*11*) used instrumented short-haul trucks to record, among other things, the durations of lane changes in a study designed to evaluate the impact of fatigue. He found that for the 42 drivers who participated in the experiment, lane-change durations ranged from 1.1 s to 16.5 s. The mean and standard deviation were 4.52 s and 1.71 s, respectively [results reported by Lee et al. (*10*)]. The lane-change initiation was defined by the time when the wheel crossed the lane line. Lee et al. (*10*) point out that this definition differs from earlier results and that on the basis of the study by Worrall and Bullen (*5*), 1.25 s should be added to these durations.

Lee et al. (*10*) conducted another experiment with instrumented vehicles that were equipped to automatically gather data on lane changing, and so the presence of an observer was not required. Two vehicles were used: a sedan and a sport utility vehicle. Sixteen drivers who normally commuted more than 40 km every day drove each vehicle for 10 days. The initiation of lane changes was defined by the point in time when vehicles began to move laterally. The completion of lane changes was defined by the points in time when the centers of the vehicles were in the destination lane. With these definitions, the mean duration of single-lane changes observed in the experiment was 6.3 s with a standard deviation of 2.0 s. They also found that lane changes to the left took longer to complete compared with lane changes to the right but found no significant differences between lane changes taken in the two vehicles.

A different approach was applied by Salvucci and Liu (*12*), who used a driving simulator to evaluate drivers' lane-changing behavior. The 11 participants in the experiment were asked to drive through a

T. Toledo, Faculty of Civil and Environmental Engineering, Technion–Israel Institute of Technology, Haifa 32000, Israel. D. Zohar, Cardno Eppell Olsen, 243 Riverside Drive, South Brisbane, Q 4101, Australia. Corresponding author: T. Toledo, toledo@technion.ac.il.

Transportation Research Record: Journal of the Transportation Research Board, No. 1999, Transportation Research Board of the National Academies, Washington, D.C., 2007, pp. 71–78.
DOI: 10.3141/1999-08

multilane highway in a fixed-base medium-fidelity driving simulator. Subjects were asked to report the intention to make a lane change and also the completion of a lane change. On the basis of these observations, the mean duration of lane changes was estimated at 5.14 s with a standard deviation of 0.86 s. The limited realism of the driving simulator may have biased the results. In addition, obtrusive equipment was used, which may have made the driving task unnatural.

Although the methods used in the studies just reviewed vary, they all demonstrate that lane changes are not instantaneous events but make take up to 16 s, with mean durations in the range of 5 to 6 s. However, there are significant limitations and potential biases in these studies. In most cases, human observers or obtrusive equipment, such as eye markers, were used to collect data. Their presence may have affected driver's behavior and biased the results. In one case, data were collected by using a driving simulator and not in naturalistic driving, which may negatively affect the realism of the driving experience and the fidelity of the data collected.

Another difficulty is that the definitions of the initiation and completion of lane changes differ in the various studies. For example, in some cases it is assumed that lane changes are initiated when the driver decides to change lanes. This ambiguous definition may be interpreted differently by different drivers and lead to larger variability of the lane-changing durations. Moreover, this definition is not appropriate for use in microscopic traffic simulation, in which driving behavior models are mostly based on the observable positions and speeds of vehicles and not on their intentions. Human factors used in some of the studies to explain lane-change durations, such as eye and head movements, are also not applicable in the context of traffic simulation.

Finally, the cost associated with the use of driving simulators and equipped vehicles is high. Therefore, only small samples of drivers could be used, which made it difficult to draw statistically significant conclusions from the results. It is therefore not surprising that Chovan et al. (*6*) and Lee et al. (*10*) both point out the lack of on-road lane-changing duration data as an important limitation to studies that use these data to develop and evaluate driver assistance systems.

Models for the durations of lane changes are developed here that address some of these limitations by using a large set of trajectory data at a high time resolution that was collected by high-mounted video cameras in naturalistic driving conditions and without the use of obtrusive equipment or even the knowledge of the drivers.

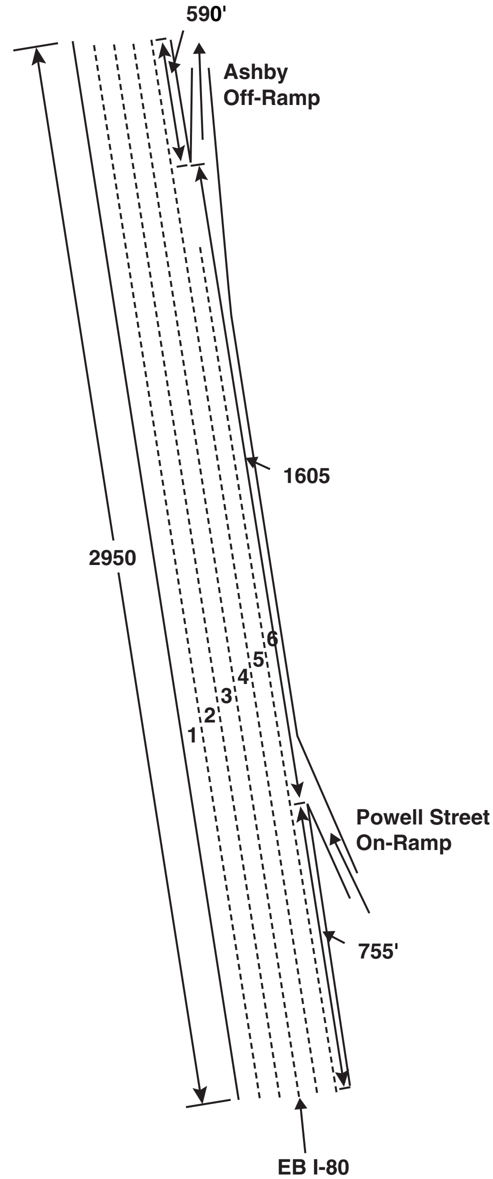

FIGURE 1 Data collection site (*13*).

TRAJECTORY DATA SET

The trajectory data set used in this study was collected on two different days on an eastbound section of I-80 in Emeryville, California, with video cameras mounted on a nearby high-rise building. Details of the collection effort may be found elsewhere (*13, 14*). The collection site is shown schematically in Figure 1, where distances are in feet. The entire section is approximately 899 m (2,950 ft) long and includes a weaving section between the on-ramp at Powell Street and the off-ramp at Ashby Avenue. The leftmost lane (Lane 1) is a high-occupancy-vehicle lane. The trajectories of all the vehicles that traveled on this section were extracted from the video files. The data include observations on the physical dimensions of all vehicles and the positions and lanes they travel in at a time resolution of 10 or 15 observations per second, depending on the date of collection. The data were collected at three separate time periods, which cover a wide range of traffic conditions:

1. Off-peak period, between 2:35 p.m. and 3:05 p.m. on December 3, 2003: Relatively low traffic densities and high travel speeds were observed during this period. The data were recorded at a rate of 15 frames per second.
2. Transition period, between 4:00 p.m. and 4:15 p.m. on April 13, 2005: This period represents conditions during the buildup to congestion. On this date, data were recorded for a shorter section 503 m (1,650 ft) long, up to the Ashby off-ramp, at a rate of 10 frames per second.
3. Peak period, between 5:00 p.m. and 5:30 p.m. on April 13, 2005: Congested traffic conditions were observed during this period.

The weather was clear with no precipitation, good visibility, and dry pavement conditions during the data collection periods. Furthermore, there were no incidents or events within the section during these periods. Table 1 summarizes the traffic flow characteristics in the three collection periods.

TABLE 1 Average Traffic Flow Characteristics During Data Collection

	Number of Vehicles	Density (veh/km/lane)	Speed (km/h)	Flow (vph)	Heavy Vehicles (%)
Off-peak	4,733	19.7	80.1	9,466	4.3
Transition	2,052	47.3	28.7	8,144	4.7
Peak	3,626	56.3	21.2	7,168	3.2
Overall	10,411	39.9	34.6	8,282	4.1

The resulting data set includes the trajectories of 10,411 vehicles, with a total of about 7 million observations. These data were analyzed to detect all lane changes that took place. In order to be consistent with the way lane changes are handled in traffic simulation models, a lane change is defined as the passing from one lane to the lane immediately next to it. Vehicles that cross two or more lanes in a sequence are considered to make multiple-lane changes.

A total of 1,790 successful lane changes were identified. Of the lane-changing vehicles 112 (6.3%) are classified as heavy vehicles, and the rest are passenger cars. The lane changes to the left totaled 1,258 (70.3%), 1,218 (72.6%) by passenger cars and 40 (35.7%) by heavy vehicles. For each lane change the initiation and completion points in time were identified, which are defined as the time instances when the lateral movement of the subject vehicle begins and ends, respectively. Figure 2 demonstrates these points on the trajectory of one of the vehicles in the data set. The lane-change duration is the time lapse between its initiation and completion.

In addition, other variables that may be used to explain lane-change durations were generated. These variables include traffic characteristics (e.g., lane densities and average speeds), the characteristics and state of the subject vehicles (e.g., vehicle types, speeds), and their relations to other vehicles around them (e.g., spacing and relative positions with respect to the vehicles in front and the lead and lag vehicles in the lanes to which they are changing). In all cases, the values of these variables at the time of the lane-change initiation were associated with the lane change. Summary statistics of the lane-change durations and other relevant variables in the data set are presented in Table 2. The subject vehicle, the vehicles around it, and the variables that define the relations between them are shown in Figure 3. The front-vehicle relative speed is calculated as the speed of the front vehicle less the speed of the subject vehicle. The lag-minus-lead relative speed is calculated as the speed of the lag vehicle less the speed of the lead vehicle.

The distribution of lane-change durations in the sample is shown in Figure 4, which also shows a lognormal distribution that was fitted to the data ($\mu = 1.376$, $\sigma = 0.550$). The lognormal distribution guarantees that lane-change durations are nonnegative.

The models presented in the literature generally only refer to a single type of vehicle, in most cases passenger cars. A priori it was expected that the lane-change durations of heavy vehicles might differ significantly. In order to test that belief, a two-tailed two-sample Kolmogorov–Smirnov test was conducted on the null hypothesis that the distributions of lane-change durations of passenger cars and heavy vehicles are equal. With a D-statistic value of 2.32, the equality of the two distributions can be rejected with a 99% confidence level. Therefore, the presentation of lane-change duration models in the next section begins with a model for passenger cars only. Observations of lane changes by heavy vehicles are then added and different specifications of their behavior are tested, which range from assuming that they are identical to passenger cars to developing completely separate models for the two vehicle types.

RESULTS

Lane-change durations may depend on various factors, such as traffic conditions and the relations of the subject vehicle with other vehicles around it (i.e., the vehicle in front of it and the lead and lag vehicles in the lane to which it is changing). Lane-change durations

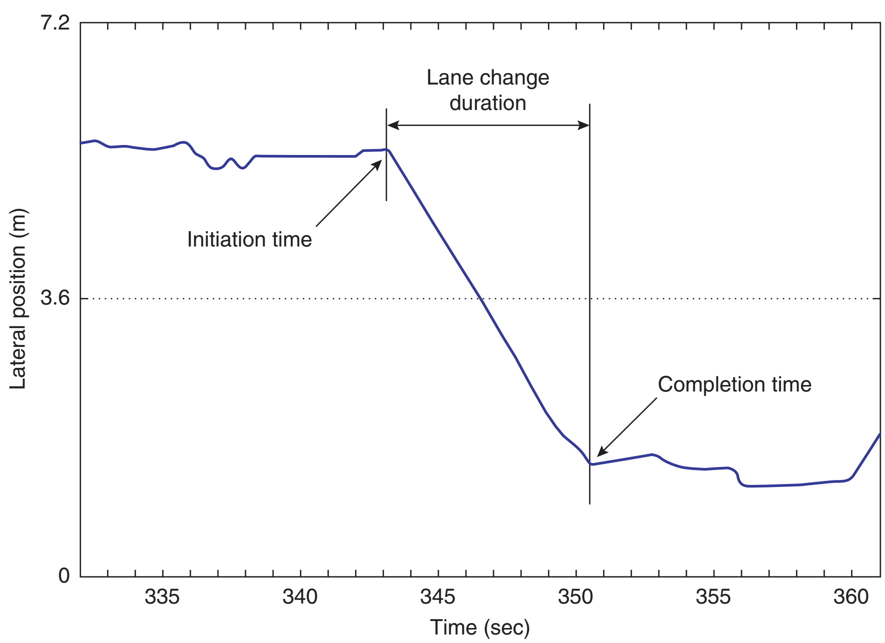

FIGURE 2 Definition of lane-change initiation and completion time points.

TABLE 2 Summary Statistics of Lane-Change Duration and Related Variables

Variable	Mean	Median	Standard Deviation	Minimum	Maximum
Lane-change duration (s)					
All	4.6	4.2	2.3	1.0	13.3
To the left	4.6	4.4	2.3	1.0	13.2
To the right	4.4	3.9	2.4	1.0	13.3
Passenger cars	4.6	4.3	2.3	1.0	13.3
Heavy vehicles	3.8	2.9	2.4	1.1	11.8
Off-peak	3.6	3.2	1.8	1.0	9.7
Transition	5.9	5.9	2.3	1.4	13.2
Peak	5.8	5.6	2.3	1.3	13.3
Other variables					
Subject speed (m/s)	16.7	17.6	10.4	0.0	41.5
Front vehicle spacing (m)	30.0	18.4	31.9	0.1	274.6
Front vehicle relative speed (m/s)	–0.6	–0.4	3.2	–16.7	17.1
Lag–lead spacing (m)	63.6	43.4	59.0	0.4	456.6
Lag–lead relative speed (m/s)	0.2	–0.1	5.5	–26.1	15.2

are by definition nonnegative. In order to ensure that predicted lane-change durations are also nonnegative, the following model specification was used:

$$\ln\left(d_n\right) = \beta X_n + \epsilon_n \quad (1)$$

where

d_n = lane-change duration for driver n,
X_n = vector of explanatory variables,
β = corresponding parameters, and
ϵ_n = error term associated with observation n.

Passenger Car Model

Estimation results of the passenger car lane-change duration model are presented in Table 3. $\Delta V_n^{\text{front}}$ is the front-vehicle relative speed, and $\Delta V_n^{\text{lag,lead}}$ is the lag-minus-lead relative speed. All but two of the estimated coefficients are significant at the 95% confidence level and all are significant at 90% confidence. Figure 5 demonstrates the effect of the explanatory variables on the lane-change durations of passenger cars. When these variables were not varied, the figure was generated assuming that the change is to the right with a traffic density of 30 veh/km/lane, zero speed differences between the various vehicles, front spacing of 30 m, and gap size of 60 m.

The most important variable, both in terms of relative magnitude and statistical significance, is traffic density, which captures the impact of traffic conditions. Densities were calculated as averages over a period of 1 min. Lane-change durations increase when traffic density is higher since it becomes more difficult and risky to undertake the lane-changing action.

The coefficient of the lane-change direction variable is positive, which indicates that drivers take longer to change lanes to the left compared with the right. This result is consistent with results reported by Lee et al. (*10*). For the mean lane-change duration, the difference between the directions is about 0.3 s. A possible explanation may be that in the data collection site, as in most cases, traffic is faster in the left lanes. As a result, drivers changing to the left are slower than passing traffic, which makes the lane change riskier. Drivers are then more cautious in changing lanes and so take longer to complete the maneuver.

Risk aversion is also an important factor in the relations of the subject vehicle and the vehicle in front. The variable min $[0, \Delta V_n^{\text{front}}]$ captures the impact of the front-vehicle relative speed in the case that the subject is faster; that is, it is approaching the vehicle in front. In this case the completion of the lane change is more urgent since it is safer to complete the change sooner in order to reduce the risk of collision. The estimated parameter of this variable is positive, which indicates shorter lane-change durations (the variable itself is always nonpositive). Similarly, lane-change durations decrease

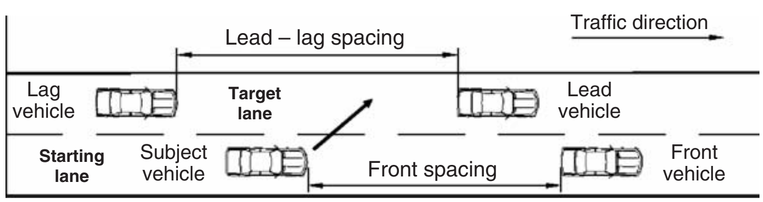

FIGURE 3 Definitions of subject vehicle, vehicles around it, and relations between them.

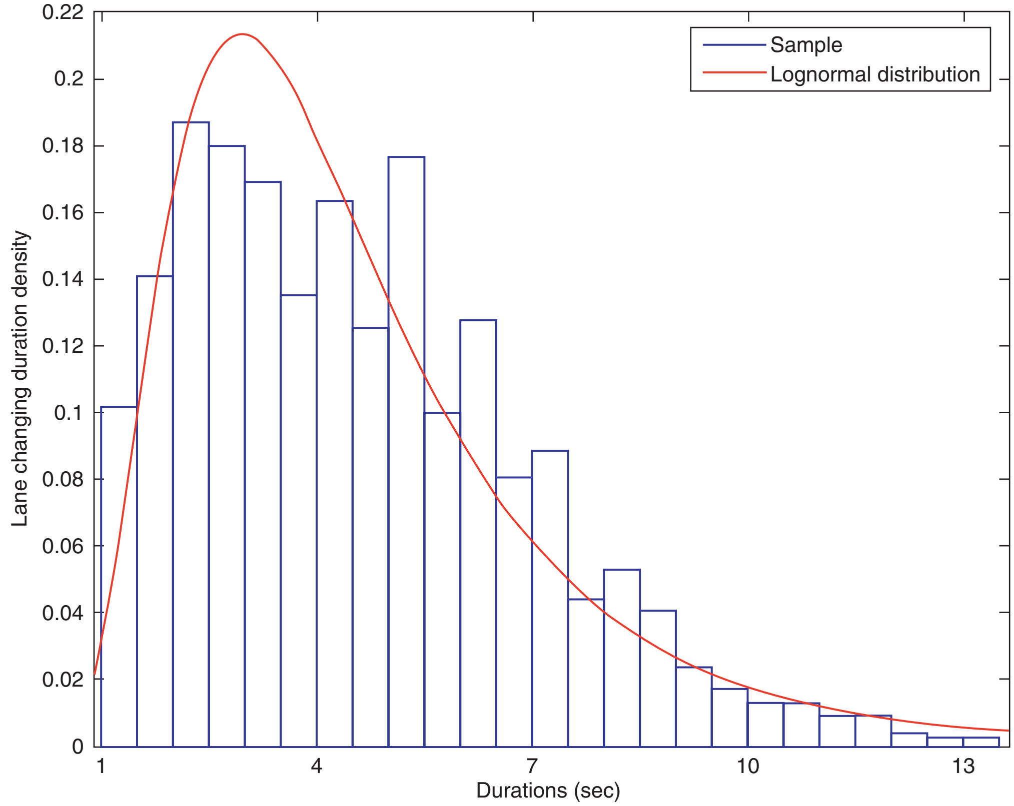

FIGURE 4 Distribution of lane-changing duration.

when the front-vehicle spacing decreases. With shorter spacing the collision risk is higher, and so lane-change durations are shorter in order to reduce this risk. With large spacing the lane-change urgency reduces and so drivers can take longer to complete the maneuver.

The other two important vehicles in the lane-changing maneuver are the lead and lag vehicles. The model captures their impact through the spacing between them (the size of the gap into which the subject is changing) and their relative speed, which indicates whether this gap is increasing or decreasing. The lane-change duration is longest when the speeds of the lead and the lag vehicles are equal. As with other variables when speeds vary, the risk and urgency associated with the lane change are affected and affect its duration. When the lag vehicle is faster—that is, the gap into which the vehicle is changing is getting smaller—there may be urgency on the part of drivers to complete the lane change before the opportunity to do so disappears. The situation in which the lead vehicle is faster (i.e., the gap into which the subject is changing into is getting larger) is simpler in terms of the risk associated with the lane change. Therefore, drivers may be able to complete the lane change faster. The lane-change duration increases when the size of the gap between the lead and lag vehicles decreases. A smaller gap implies higher risk for lane changing. Consistent with the interpretation of other parameters, drivers may chose to change lanes more cautiously and take longer when the associated risk is higher.

Interestingly, variables related to the nature of the lane change (e.g., mandatory lane changes that are taken by vehicles exiting the freeway and drivers that make multiple lane changes in a sequence) and its urgency (e.g., the distance to the exit point) were not statistically significant in the model and therefore were omitted. A possible reason for this result is that most of the vehicles making mandatory lane changes already positioned themselves on the rightmost lane or the lane next to it at the upstream end of the section, and so only 48 vehicles were observed making more than one lane change within the section.

TABLE 3 Estimation Results of Passenger Car Lane-Changing Duration Model

Variable	Parameter Value	*t*-Statistic
Constant	1.114	19.8
Traffic density (veh/km/lane)	0.01001	10.5
Change direction (left = 1, right = 0)	0.06314	2.04
min [0, $\Delta V_n^{\text{front}}$] (m/s)	0.02470	3.99
Front vehicle spacing (m)	–0.0009627	1.93
min [0, $\Delta V_n^{\text{lag,lead}}$] (m/s)	0.01516	2.17
max [0, $\Delta V_n^{\text{lag,lead}}$] (m/s)	–0.01187	–1.81
Lag–lead spacing (m)	–0.001064	–3.83

Number of observations = 1,518, R^2 = 0.205, adj R^2 = 0.201.

Treatment of Heavy Vehicles

As discussed earlier, the lane-changing behavior of heavy vehicles may differ from that of passenger cars. In this section this hypothesis is tested. Starting with the model presented for passenger cars, three models were estimated with an increasing level of separation between passenger cars and heavy vehicles:

Model 1. The same model specification that was used for passenger cars was estimated for all observations, including those of heavy

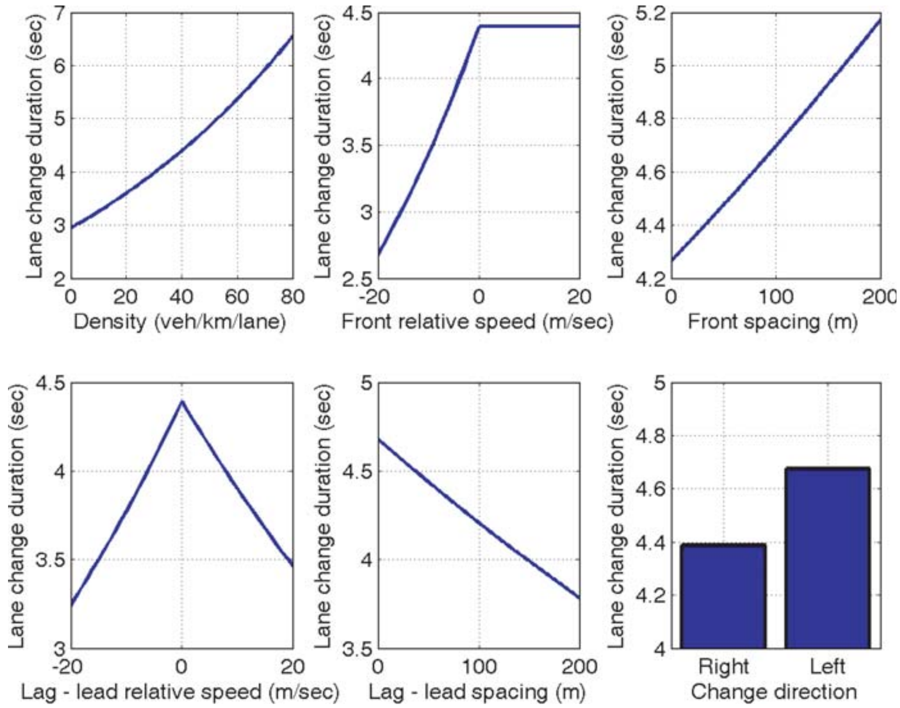

FIGURE 5 Effect of explanatory variables on passenger car lane-change durations.

vehicles. All parameters are common for the two vehicle types. The assumption in this model is that there is no difference between the lane-change durations of the two vehicle types.

Model 2. Model 2 extends Model 1 by assuming that the regression constant is vehicle-type-specific. All other parameters in the model are common to the two vehicle types. This model implies that the difference between lane-changing durations of passenger cars and heavy vehicles is systematic and constant.

Model 3. Model 3 assumes that the lane-change durations of the two vehicle types are completely different, and so all parameters for the two vehicles types may differ. It was estimated as two separate models: one for passenger cars and another for heavy vehicles.

To select among these alternative models, F-tests were conducted on the restrictions imposed on the models in which lane-change durations of passenger cars and heavy vehicles are similar compared with the more general models, in which they are allowed to differ. The F-test statistics for these tests are calculated as follows:

$$F_{q,N-k} = \frac{\mathrm{ESS}_R - \mathrm{ESS}_U}{\mathrm{ESS}_U} \; \frac{N-k}{q} \tag{2}$$

where

ESS_R, ESS_U = sums of squared regression residuals for restricted and unrestricted models, respectively;
N, k = number of observations in sample and number of parameters in unrestricted model, respectively; and
q = number of restrictions made.

The regression statistics for the three models and the test statistics and results are shown in Table 4. The first test was on the null hypothesis stating that the restriction that the constants for the two vehicle types are the same, which was imposed on Model 1 compared with Model 2, is justified. The result is that the restricted model can be rejected with a confidence level of more than 98% and the unrestricted Model 2 is adopted. Then Model 2 was tested against the more general Model 3, which allows all parameters of the model to differ between passenger cars and heavy vehicles. For the unrestricted model, ESS_U, N, and k are calculated as the respective sums over the two separate models. The test result is that the restricted Model 2 can be rejected at 95% confidence. The conclusion is therefore that the lane-change durations of passenger cars and heavy vehicles are different and should be modeled separately.

TABLE 4 Estimation Results and Statistical Tests for Three Models

Model	N	k	R^2	ESS	q	F	P-Value
1	1,617	7	0.208	381.47	—	—	—
2	1,617	8	0.211	380.01	Against model 1		0.013
					1	6.18	
3	1,518	7 (cars)	0.205	352.78	Against model 2		0.049
	99	7 (heavy)	0.232	24.26	6	2.11	

TABLE 5 Estimation Results of Heavy-Vehicle Lane-Changing Duration Model

Variable	Parameter Value	t-Statistic
Constant	0.790	6.25
Traffic density (veh/km/lane)	0.02104	5.50
Change direction (left = 1, right = 0)	–0.178	–1.76
max [0, $\Delta V_n^{\text{front}}$] (m/s)	–0.04775	–2.91
ΔV_n^{ave} (m/s)	0.02972	2.13

Number of observations = 112, $R^2 = 0.300$, adj $R^2 = 0.274$.

Heavy-Vehicle Model

Various specifications of models for the lane-change durations of heavy vehicles were tested. The final estimation results are presented in Table 5, where ΔV_n^{ave} is the subject relative speed with respect to the average speed in the section (i.e., the average speed less the subject speed). All estimated coefficients except the one for the change direction are significant at 95% confidence, and all are significant at 90% confidence. Figure 6 demonstrates the effect of the explanatory variables on the lane-change durations of heavy vehicles. The values of the various variables that were used to generate Figure 6 are identical to those used with the passenger car model.

The mean duration of lane changes for heavy vehicles is shorter compared with passenger cars. This finding may be because heavy-vehicle drivers are usually professional drivers. As with the passenger car model, lane-change durations increase with traffic density. However, the magnitude of the impact on durations here is larger. Unlike passenger cars, heavy vehicles take longer to change lanes to the right compared with the left. The reason for this finding may be that because of the dimensions of the vehicles, heavy-vehicle drivers have a good field of view to their left but only limited sight on their right. Similar risk aversion behavior can also explain the impact of the difference between the average speed and the subject's speed on the lane-change durations. As this difference increases (i.e., the subject is slower compared with the prevailing traffic speed), lane changes become riskier and so drivers take longer to complete them. The impact of the relative speed of the front vehicle indicates that drivers may be able to change lanes in a shorter time when the task is easier. When the relative front speed increases, the subject need not be concerned with the front vehicle and so can focus on the lane change itself and complete it sooner.

The variables related to the lead and lag vehicles, which were significant in the passenger car model, were not in the heavy-vehicle model. A possible explanation may be that the maneuverability of heavy vehicles is lower and so they cannot respond to these vehicles after they initiate the lane change. Furthermore, these vehicles may be more cautious toward the heavy vehicle and are therefore the ones making changes in their behavior to accommodate the lane change. As with the passenger car model, the lane-change urgency was not significant in this model.

CONCLUSIONS

Lane changes have a significant impact on the characteristics of traffic flow. However, lane-changing models used in microscopic traffic simulation models emphasize the decision-making aspects of the task but generally neglect the detailed modeling of the lane-changing action and its duration. In the past, data that were used to estimate lane-change durations were mostly collected in small samples by using instrumented vehicles or driving simulators, which may introduce biases in drivers' behavior. In this paper, trajectory data at a high time resolution were used that were collected from high-mounted cameras to estimate lane-change duration models. The

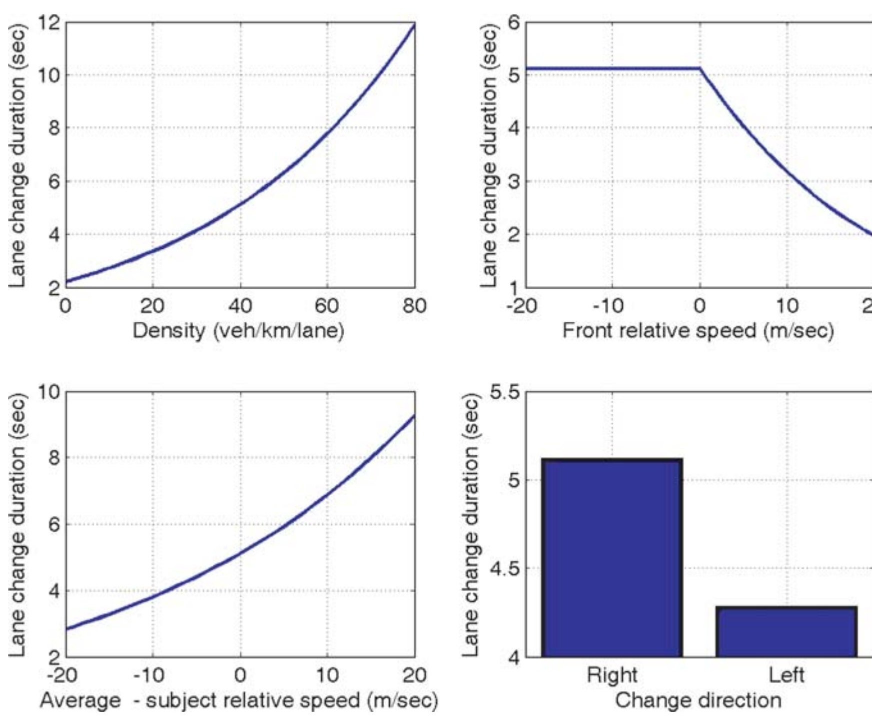

FIGURE 6 Effect of explanatory variables on heavy-vehicle lane-change durations.

results indicate that lane changes are not instantaneous events as most microscopic traffic simulations model them but may have durations in the range of 1.0 to 13.3 s, with a mean of 4.6 s. Lane-change durations are affected by traffic conditions captured by the traffic density, by the direction of the change, and by other vehicles around the subject vehicle.

These results indicate that the lane-change durations for passenger cars and for heavy vehicles differ significantly. However, with both vehicle types, lane-change durations are longer when the maneuver is riskier or when the task is complicated by the relation of the subject vehicle with other vehicles. Further research with more data sets is required in order to identify geometry and other site-specific effects as well as differences between behaviors in different regions and countries and to study the impact of the lane-changing action on traffic flow by incorporating these models into microscopic traffic simulators. In order to be useful in simulation models, additional models need to be developed that describe the behavior of the subject vehicle and the response of other vehicles around it during the lane change (e.g., in terms of speed and acceleration).

ACKNOWLEDGMENTS

The first author is a Horev Fellow supported by the Taub and Shalom Foundations. His work was partially supported by the European Commission under a Marie Curie Grant. The authors thank the anonymous referees for their comments, which helped improve the quality of this paper.

REFERENCES

1. Sparmann, U. The Importance of Lane Changing on Motorways. *Traffic Engineering and Control,* Vol. 20, 1979, pp. 320–323.
2. Ferrari, P. The Effect of Driver Behavior on Motorway Reliability. *Transportation Research B,* Vol. 23, 1989, pp. 139–150.
3. Kitamura, R., and M. Kuwahara, eds. *Simulation Approaches in Transportation Analysis.* Springer, New York, 2005.
4. Toledo, T. Driving Behaviors: Models and Research Directions. *Transport Reviews,* Vol. 27, 2007, pp. 65–84.
5. Worrall, R. D., and A. G. R. Bullen. An Empirical Analysis of Lane Changing on Multilane Highways. In *Highway Research Record 303,* HRB, National Research Council, Washington, D.C., 1970, pp. 30–43.
6. Chovan, J. D., L. Tijerina, G. Alexander, and D. L. Hendricks. *Examination of Lane Change Crashes and Potential IVHS Countermeasures.* Report DOT HS-808-071. NHTSA, U.S. Department of Transportation, 1994.
7. Finnegan, P., and P. Green. *The Time to Change Lanes: A Literature Review.* IVHS Technical Report 90-13. Transportation Research Institute, University of Michigan, Ann Arbor, 1990.
8. Tijerina, L., W. R. Garrott, M. Glecker, D. Stoltzfus, and E. Parmer. *Van and Passenger Car Driver Eye Glance Behavior During Lane Change Decision Phase, Interim Report.* Transportation Research Center Report. NHTSA, U.S. Department of Transportation, 1997.
9. Hetrick, S. *Examination of Driver Lane Change Behavior and the Potential Effectiveness of Warning Onset Rules for Lane Change or "Side" Crash Avoidance Systems.* M.Sc. thesis. Industrial and Systems Engineering, Virginia Polytechnic Institute and State University, Blacksburg, 1997.
10. Lee, S. E., E. C. B. Olsen, and W. W. Wierwille. *A Comprehensive Examination of Naturalistic Lane Changes.* Report DTNH 22-00-C07007, Task Order 4. NHTSA, U.S. Department of Transportation, 2003.
11. Hanowski, R. J. *The Impact of Local/Short Haul Operations on Driver Fatigue.* Ph.D. dissertation. Industrial and Systems Engineering, Virginia Polytechnic Institute and State University, Blacksburg, 2000.
12. Salvucci, D. D., and A. Liu. The Time Course of a Lane Change: Driver Control and Eye Movement Behavior. *Transportation Research F,* Vol. 5, 2002, pp. 123–132.
13. Cambridge Systematics. *NGSIM BHL Data Analysis, Summary Report.* FHWA, U.S. Department of Transportation, 2004. Available at http://ngsim. camsys.com.
14. Cambridge Systematics. *NGSIM I-80 Data Analysis, Summary Reports.* FHWA, U.S. Department of Transportation, 2005. Available at ngsim. camsys.com.

The Traffic Flow Theory and Characteristics Committee sponsored publication of this paper.