Quantifying the Number of Lane Changes in Traffic
An empirical analysis

V. L. Knoop PhD
Delft University of Technology
Transport & Planning
Stevinweg 1
Delft, The Netherlands
+31 15 278 8413
v.l.knoop@tudelft.nl

S.P. Hoogendoorn PhD
Delft University of Technology
Transport & Planning
Stevinweg 1
Delft, The Netherlands
s.p.hoogendoorn@tudelft.nl

Y. Shiomi PhD
Kyoto University Katsura Nishikyo-ku,
Department of Urban Management
Kyoto, 615-8540 Japan
shiomi@trans.kuciv.kyoto-u.ac.jp

C. Buisson PhD
Senior Researcher
Université de Lyon, F-69622, Lyon, France
IFSTTAR, LICIT, F-69675 Bron
ENTPE, LICIT, F-69518 Vaux en Velin
christine.buisson@ifsttar.fr

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ABSTRACT

Lane changes are an important aspect of freeway flow. Most lane change models are microscopic, describing whether individual vehicles/drives will change lanes, and hence are calibrated microscopically. Macroscopic validation often is restricted to the distribution of vehicles across lanes. To the best of our knowledge, no systematic analysis has been made of the number of lane changes as function of the operational characteristics of the origin and target lane. This paper fills that gap, by analyzing the number of lane changes as function of several incentives. Based on data availability, two "simple" sites are selected, i.e. as close as possible to a straight continuous freeway. Statistically, we find that on the selected sites, drivers change lanes on average once per two kilometer driven. Furthermore, analyzing the number of lane changes (per kilometer per hour) as function of the density in the origin lane and in the target lane, we find, as expected, this increases with the density in the origin lane for a fixed density in the target lane. Surprisingly, it also increases with the density in the target lane for a fixed density in the origin lane. The underlying mechanism is therefore different than gap acceptance theory. The analyses presented in this paper can be used to qualitatively verify (microscopic and macroscopic) lane change models, and to propose better lane change models.

1 INTRODUCTION

Lane changes are important in traffic flow operations. They cause a synchronization of speeds (*1*), they might reduce the capacity (*2, 3*), and they are even showed to be the cause of stop-and-go waves (*4, 5*). Also accidents are often related to lane changes (*6*). However, little literature is available which presents empirical statistical studies on lane changing on freeways. Rarely the principles for the requirements for a desired lane change, as introduced by Gipps (*7*), are disputed: (1) inability to continue at desired speed in current lane, (2) speed advantage in the adjacent lane (3) a gap large enough to change lanes. In section 2 we will present several more recent models describing lane changing. They proposed generally a quantification of the principles.

This paper will study discretionary lane changes, but not propose a new model. Instead the general pattern of lane changing is studied using empirical data. We focus on the traffic conditions which lead to a number of lane changes. As will be shown below, several microscopic lane change models have been proposed, and using generally several dozens of parameters they can be calibrated such that the individual lane changes indeed can be found. For practitioners, however, it is useful to have a general idea of the number of lane changes, and moreover, whether the assumed explanatory variables (speed difference, density in origin lane and target lane) indeed play an important role.

In the remainder of this paper, first an overview of the literature on lane change models and the impact of lane changing is given. Section 3 then introduces the data which we will use for our analysis. We will use video data for one road stretch and microscopic data collected by closely spaced loops for the other. The results of the analyses, presented in section 4, consist mainly of the key statistics on the number of lane changes in the light of gap-acceptance theory: the density in origin and target lane. Additionally, the effect of speed and speed differences is studied and presented in section 4. Section 5 discusses the results and links them to other theories on lane changing. In particular, this section discusses the parts which remain unexplained by traditional gap-acceptance models. Finally, section 6 presents the conclusions.

2 LITERATURE OVERVIEW

In an early publication on lane change rates, in 1954, a dependency of overtakings and macroscopic density was hypothesized (*8*). From a theoretical and microscopic point of view, Wardrop derives

$$N = \frac{k^2\gamma(v)}{2} \tag{1}$$

in which N is the number of overtakings per space and time, k is the density, $\gamma(v)$ is the mean difference in speed. This equation captures the demand for overtaking, and does not take the restrictions in possibilities into account. It hence does not differentiate between the density in each lane. Another microscopic approach is to derive the microscopic requirements for a driver to change lane (*7*).

McDonald and Brackstone (*9*) were among the first to develop systematic empirical observations of lane-changes. This was achieved by manual analysis of video images from a three-lane freeway. They found that “it is extremely difficult to validate the (lane change) model over a wide range of flows and conditions”. Recently, Knoop et al. (*10*) have shown the number of lane changes as function of the road characteristics. However, that paper lacks the lane characteristics, which are expectedly relevant for a lane change. Microscopically, the characteristics of lane changes have been studied, showing for instance reasons and the duration (*11*); however, the authors do not propose a model to replicate the observations.

In the last decade, lane changes have been studied in relation to proposed lane change models, and individual lane change models have been calibrated. To the best of our knowledge, the first steps in lane change analyses were made by Worrall and Bullen (*12*), who proposed to estimate lane change rates, considering lane changes as individual, uncoupled events. This also resulted in a macroscopic model of lane

changes (13). In the past decade, there have been other studies on calibrating lane change models, starting by Sheu and Ritchie (*14*), studying conditions where an incident had taken place and other drivers had to avoid this site. Hidas (*15*) presents another study where lane changes are observed by video observations. He models, describes and observes the microscopic interactions between the vehicles. Gap creation, and speed adaptation are discussed, but also the size of the critical gap and it dependence on the relative speed. Choudhury et al. (*16*) presents another lane change model, where the desire to change lanes depends on the drivers' state. Different levels of gap acceptance distinguished in this paper are, in order from lower interference with other vehicles to more interference: normal gap acceptance, gap anticipation (similar to (*15*): relative speeds are important), courtesy merging and forced merging. This many-parameter model is calibrated on the maximum likelihood to find the correct vehicle trajectory. The model is also validated, using the likelihood of the trajectory (i.e., the lane choice). Kesting et al. (*17*) present another model where a lane change is valued according to the acceleration of the lane changer, but also of the surrounding vehicles. A lane change maneuver can influence the acceleration of the old and the new leader. In the model, the utilities of the others are considered as well before performing a lane change, but generally valued less than ones own benefit.

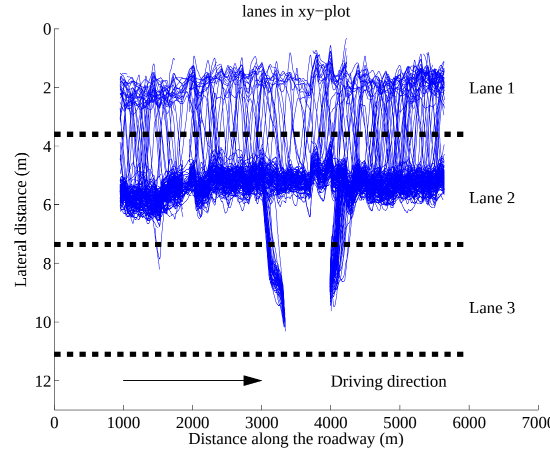
Toledo et al. (*18*) present a model where lateral and longitudinal driving behaviour are combined. The lane change decision depends on the possible longitudinal accelerations according to the longitudinal model. Later, the model is extended with several parts (*19*) and the final "integrated model" is presented. They calibrate the model on the likelihood to find the trajectory, and thus use this as objective function for the optimization of the parameters (*20*).

A behavioral theory on lane choice is presented by Daganzo (*21*). He introduces two driver types: *slugs* and *rabbits*. He poses that *slugs* only drive on the shoulder lane(s), and *rabbits* only on the median lane(s), as long as these are faster than the shoulder lane(s). In the sequel (*22*), the effect of on-ramps is shown, as well as how congestion sets in, all in theory. Patire and Cassidy (*23*) validate this theory with microscopic data. On a Japanese freeway the lane changes are studied in a qualitative way, and cumulative counts are used. The theory by Daganzo (*21*) has been validated in general terms, showing that the slower lanes are a release valve for traffic in the faster lanes.

There are other papers focusing on the effect of lane changes rather than the reason for the lane changes. For instance, Jin (*2*) gives a microscopic interpretation of the process of lane changing, where vehicles take two places (at two lanes) in the traffic stream. In Jin (*24*) this is translated into a macroscopic traffic description. For both, a calibration has been carried out based on the shape of the fundamental diagram, this using macroscopic quantities. Another approach for modeling the consequences of lane changing is shown by Laval and Daganzo (*25*), introducing the combination of demand and supply, of lane changes by the densities in both lanes. The lane change rate can be introduced into the macroscopic traffic equations. This can be extended in a hybrid representation of macroscopic and microscopic descriptions, including the time vehicles need to accelerate to higher speeds after a lane change (*26*). They show the validation thereof using cumulative counts, so similar to a flow distribution. The same type of data is used by Cassidy et al. (*4*) to show that lane changes reduce capacity. They state that reducing the number of lane changes thus can improve the capacity, as is shown empirically. The impact of a lane change at the level of a platoon is studied empirically, for instance by Ahn and Cassidy (*27*) or Duret et al. (*28*)

As the overview of literature shows, none of the proposed lane change models is tested on the lane change prediction as function of macroscopic properties, using real traffic data on freeways. Some principles are postulated without a model, but generally remain untested. This is possibly due to the lack of sufficient accurate (microscopic) data, which is available for this paper. The goal of this paper is twofold. First, it will give an order of magnitude for the number of lane changes, to give practitioners an idea of typical values. This is relevant for instance for capacity reductions due to lane changing. Secondly, it will show the influencing factors in lane changing. This will show the principles of lane changing and the elements required in a realistic lane change model. The observations from the empirical analyses will be discussed in

(a) Google maps



(b) Trajectories x-y plot

FIGURE 1 The layout of the A270 freeway

the light of lane change theories in section 5.

3 DATA COLLECTION AND TREATMENT

In this paper, two data sources are used. Both are individual traffic data, in order to capture the lane changes, and both are collected at freeways. They differ in location, and measurement type. Video-recorded trajectory data from the A270 near Eindhoven (the Netherlands) is used (section 3.1) and individual loop detector data from the M42 near Birmingham (United Kingdom) is used (see section 3.2).

3.1 A270 freeway near Eindhoven, the Netherlands

The A270 freeway is a urban freeway of approximately 6500 meters. It starts and ends at traffic lights and in the middle there is one crossing road, connected to the freeway by one off ramp and one on ramp with 300m slip lanes. The section is shown in figure 1a. The eastbound section is equipped with 55 cameras mounted at poles at the road side. They all cover a part of the freeway, and together the whole freeway is covered by the cameras. In real time, automatic vehicle detection algorithms are run and trajectories are obtained from the images. For the data set we have (partial) individual traffic trajectories with high precision in space (approximately 1m) and time (10 observations per second). The partial vehicle trajectories in the field of view of one camera are connected to the partial trajectories in the field of view of the next to come to complete vehicle trajectories. The tracking process have been validated, comparing the video images with the tracks. All vehicles in the "open area" have been tracked (under the overpass this reduced), but there were some problems of connecting the partial trajectories (approximately 1%). Since we are interested in the densities and speeds, this does not matter. Also, we will find all lane changes since there is an overlap of the cameras. Furthermore, due to different heights of the vehicles, there were problems in finding the exact right location of the vehicles: due to the angle of view, this could laterally be off for some decimeters, and longitudinally for up to a meter (when far away of the camera). This again, is well acceptable for the purpose we want to use the data for. Figure 1 shows the recovered trajectories in the x-y plane, which are smoothed with a moving average filter (*29*). The y-coordinate is calculated relative to the axis of the road. Two driving lanes are visible, as well as the off ramp and the on ramps. The figure also shows the used lane separation, using a lane width of 3.75 meters. From the y-position of the smoothed track of the vehicle the lane is determined, using the lane separation shown in figure 1.

The first part of the section (up to 2000 meters) is influenced by the traffic light at the beginning of the section, and is therefore discarded. At the end of the freeway, at 6500 meters, are traffic lights, which have an influence on traffic operations from 5500 meters. The stretch between 5500 and 6500 meters is therefore discarded as well. To avoid the influence of the ramp, we choose exclude also data in the section 3000 - 4500 meters.Consequently, two stretches remain in the data set: a stretch from 2000 to 3000 meters, upstream of the off ramp, and a stretch from 4500 to 5500 meter,s downstream of the on ramp. Note that there might be an influence of the off and on ramps, although they are still at least several hundreds of meters away. An earlier paper showed – for another road stretch – a difference in lane distribution upstream or downstream of the on-ramp (*30*).

For the analysis we use data from Monday 23 May 2011, from 12.00 noon to 20.00 h. This gives a relatively quiet periods and moderately loaded roads, with traffic volumes ranging from 200 to 2500 veh/h, and densities are up to approximately 25 veh/km over two lanes. The average speeds vary between 90 and 120 km/h. There is no congestion in the period for which data is available. The fundamental diagram of the traffic operations in the 2000-3000 m section is shown in figure 2a.

To find the number of lane changes, aggregation of data is required. The high quality of data allows us to proceed by the aggregation method proposed by Laval (*31*). The reason for this is – in short – to have more homogeneous traffic conditions within an aggregation area. Traffic characteristics move forward with approximately free-flow speed (90 km/h) in free flow, or backwards with approximately shockwave speed (18 km/h). If a parallelogram now is chosen with borders with the above-mentioned speeds, in either condition, free flow or congestion, traffic conditions are followed by the borders of the aggregation interval, and borders of traffic states will not cross the borders of the aggregation interval. Therefore, the intervals are more homogeneous. For a more detailed description, see (*31*). For the sake of simplicity, we approximate the values for the boundaries and we do not use individual vehicles as boundary for the aggregation interval. The aggregation areas have a length of 1000 meters in space (required by the data, see above) and 40 seconds in time, to well match the spatial component. Flow (q), density (k), and speed (v) are computed from the total distance driven (D), the total time spent (T) and area of the aggregation interval (A) in space-time, using Edie's (*32*) generalized definitions:

$$k = \frac{T}{A} \tag{2}$$

$$q = \frac{D}{A} \tag{3}$$

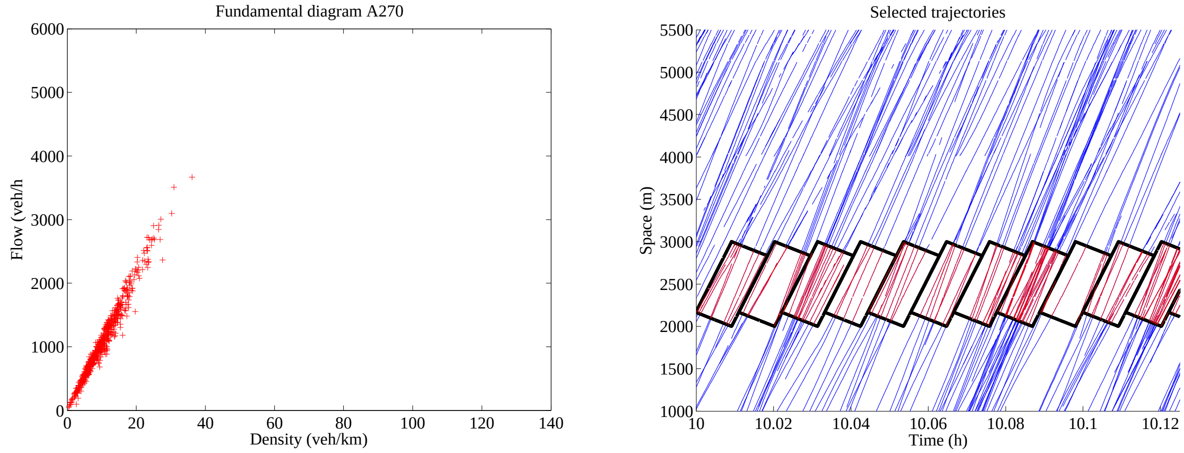
$$v = \frac{D}{T} \tag{4}$$

These are applied both on individual lanes and on the complete roadway.

Figure 2b shows these areas as well as the trajectories in the x-t plane. The combination of off ramp and on ramp is clearly visible by the lower number of traced vehicles between 3300 and 4000 meters. This is partially due to a number of vehicles that leave the freeway, and other vehicles that enter the freeway. Another part is due to the lower tracking rate of the vehicles under the overpass with the connecting road. This part is not in the selected sections.

3.2 M42 near Birmingham, United Kingdom

The data from the A270 are limited to one day, and for more detailed and accurate analyses, a larger amount of data is better. We therefore use data collected using an automated data collection method in the period 1 October 2008 - 30 November 2008. The data we use are individual loop data from the M42 freeway in the UK near Birmingham (*33*). The loops are placed approximately 100 meters apart, and for all vehicles the passing time, the lane, the speed and their length is recorded. It is a three lane freeway, and at the



(a) Fundamental diagram

(b) The trajectories in x-t plane of the vehicles in all lanes. A parallelogram is used as aggregation interval: in this 7,5 minute period 11 different aggregation areas are identified. Note that there are gaps and periods with vehicles with shorter headways, and that borders of the integration area is well aligned with the borders between traffic operations

FIGURE 2 The traffic operations.

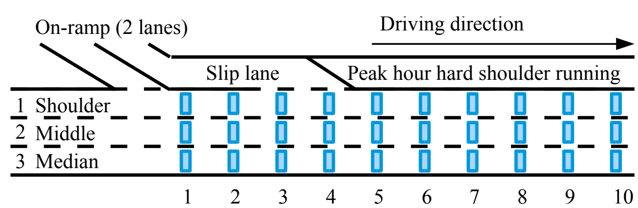


FIGURE 3 The layout of the freeway and the detectors. The detectors are placed at approximately 100 meter distances. Note that in the United Kingdom, people drive at the left hand side of the road. That means, left to right in this figure.

upstream end of the section is the downstream end of an slip lane from an on ramp, see figure 3. To avoid the impact of the merging as much as possible, the article will focus on sites 5-10. Figure 4 shows the occupancy over time for three sites. Since the passing times and the speeds, as well as the lengths and the lanes, are known for each vehicle at each site, the vehicles can be re-identified from one site to the next. If a vehicle is re-identified at the further downstream site at another lane, a lane change has taken place. The re-identification works very good in uncongested conditions. In fact, a re-identification rate of more than 999 out of 1000 vehicles is obtained (personal communication (*34*)), but the re-identification breaks completely in congestion. Then, the headways and speeds vary less over different, successive vehicles, and re-identification is impossible. Therefore, the data used in this study is limited to non-congested periods, here defined by speeds of 20 m/s (72 km/h) and higher. Additionally, the speed limit of 70 mph is lowered dynamically at high demand levels. The details of the system will not be presented here; for this paper, it suffices to state that the dynamic speed limits are recorded and the aggregation periods at which a dynamic speed limit was active are discarded.

Since the vehicle is re-identified at the following site, and it is known in which lane the vehicle has been driving at each of the sites, it is known whether the driver has performed a lane change between the two sites. It is assumed that no driver makes a lane change from his lane and back to his original lane within

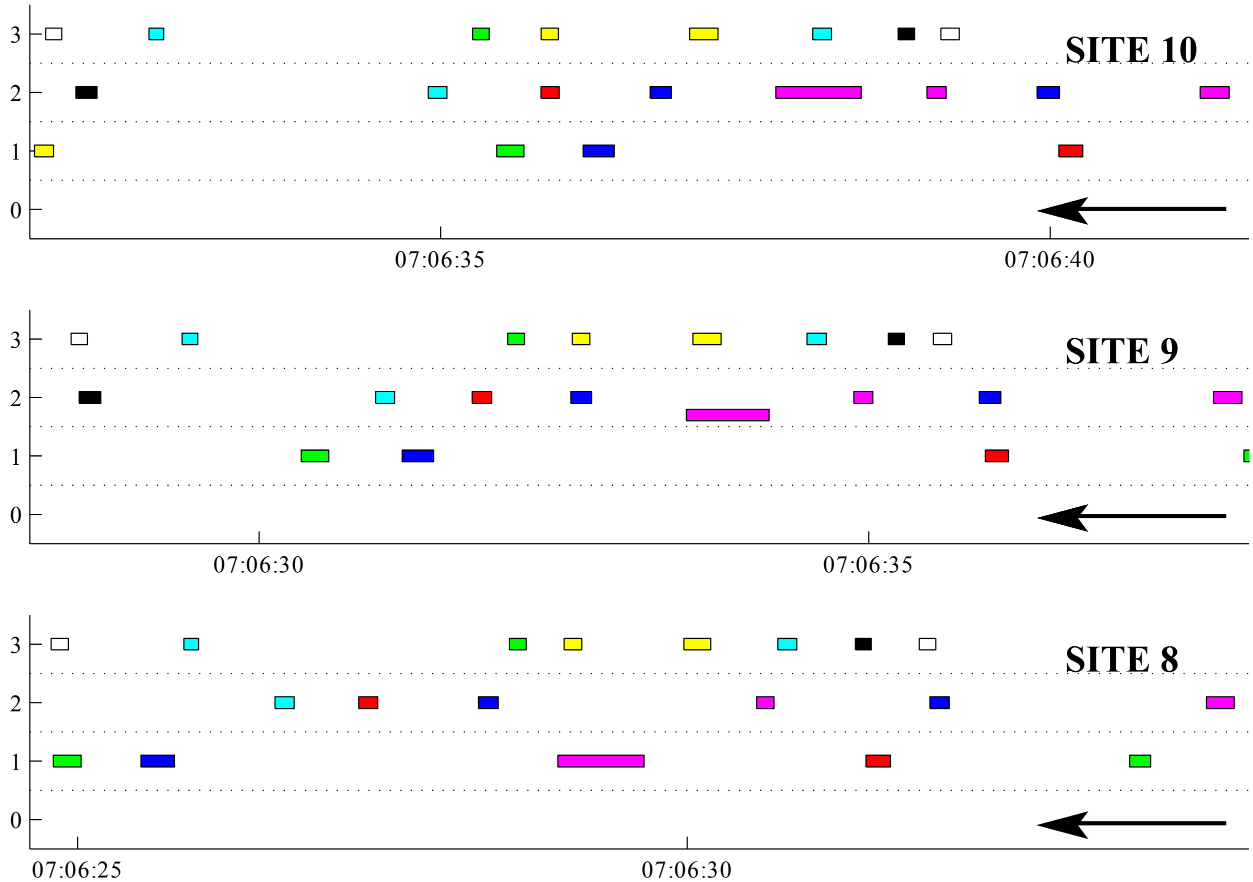
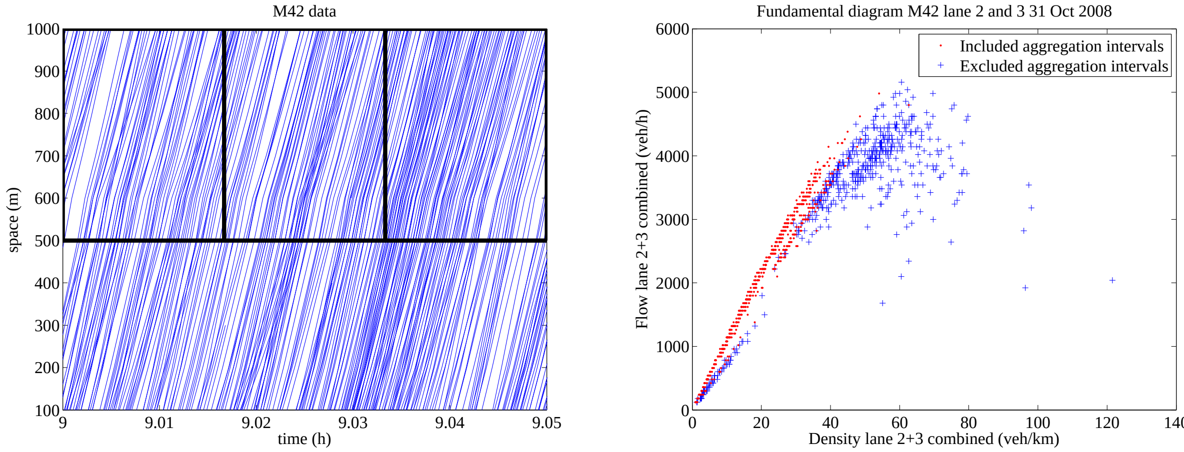


FIGURE 4 Detected vehicles over time. Since traffic drives from site 1 to site 10, vehicles will reach the later sites later in time, and thus they "move to the right" in the figures, since the horizontal axis denotes time. Note the truck in the midlle straddling at site 9 (it is detected at both lane 1 and 2), and then changing towards lane 2.

100 meters.

The data used does not give the trajectories very accurately, but only on a few seconds scale and 100-meter spatial resolution. We therefore have to approximate the trajectories, and hence the aggregation intervals cannot be calculated accurately in the same way as the platoons in the A270 dataset. For simplicity, we choose rectangular aggregation intervals in space-time: 500 meters (from site 5 to 10) in space and 1 minute in time. This is shown graphically in figure 5a.

After discarding the periods where re-identification was impossible, or dynamic speed limits were active, 38,064 aggregation intervals of 1 minute and 500 meters remain for further analysis. Lane changing is a complex process. Gaps created by a in lane i by lane change from lane i to lane j can be filled by changes towards lane i. On a two-lane freeway, this would be changes from lane j to lane i; on a three-lane freeway, a gap by a lane change from lane 2 to lane 3 can be filled by a vehicle changing from lane 1 to lane 2. This is a problem we cannot overcome by choosing our lanes clever. Another problem can be made less relevant, namely the influence of the on-ramp. We focus on the lane changes between lane 2 and 3 to reduce this influence – and mandatory lane changes – as much as possible. Figure 5b shows the fundamental diagram for lanes 2 and 3 combined, for the sake of readability limited to one day of data. Density in the available periods ranges from 0 to 60 veh/km over lanes 2 and 3 together, ans speeds are between 72 (exclusion



(a) Trajectories of vehicles in all lanes, with , and the black lines denoting the aggregation interval borders

(b) Fundamental diagram in flow-density plane

FIGURE 5 The data of the M42

criterion) and 120 km/h. The points in the congested part of the fundamental diagram and around the critical point are discarded due to too low speeds and the lack of possibilities to re-identify the vehicles due to a low the variation in headways and speeds.

4 RESULTS

This section presents the results of the lane change analyses for the three sections: the A270 upstream of the off ramp (section 4.1), the A270 downstream of the on ramp (section 4.2), and the M42 (section 4.3)

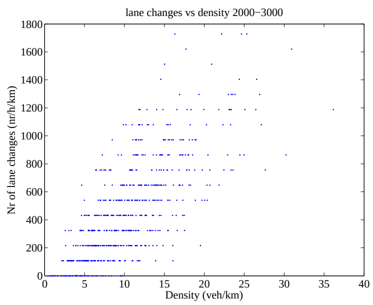
4.1 A270 upstream of off ramp

The results of the part upstream of the off ramps are shown in figure 6. Figure 6a shows the number of lane changes (per km.h) as a function of the roadway density. This number has been normalized for the total area of the aggregation interval in time-space, in this case the area of the parallelogram. As the density increases, the number of lane changes increases. This is in line with Wardrop (*8*), equation 1, although the increase is more linear than quadratic with the increase in density.

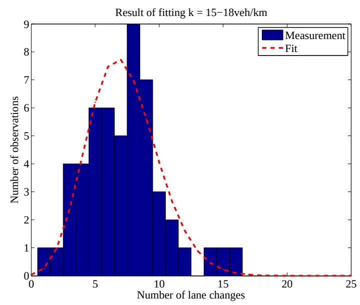
For aggregation intervals with similar traffic conditions (e.g., with similar density), we may view lane-changing as a stochastic process with a given rate parameter λ (that is consequently a function of the given density, so we may write $\lambda = \lambda(\rho)$). The number of lane changes depend on the traffic conditions, but in first order, we expect them not to depend on each other, i.e. we expect that drivers are not changing lanes because someone else changes lanes; we acknowledge that if studied in more detail, this assumption is not be valid, for instance if a slow vehicle causes multiple vehicles to change lanes. For the sake of simplicity, we assuming this independence, and the time between consecutive lane changes will be exponentially distributed, and the number of lane changes in any given aggregation interval will be distributed according to a Poisson process with rate λ. Thus the probability of n events in an aggregation interval of length T (in our case 1 minute) is given by

$$f(n) = \frac{(\lambda T)^n}{n!} \exp(-\lambda T). \tag{5}$$

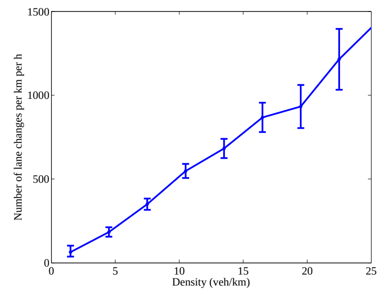
Since we have many aggregation intervals with common traffic conditions, the counts for lane changes for such intervals may be used to estimate λ according to equation 5. Formally, we use the Maximum



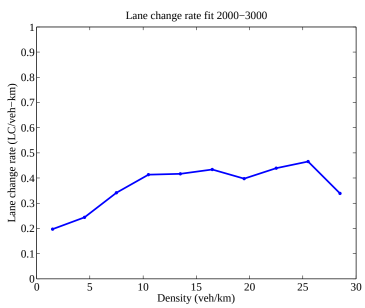
(a) nr of lane changes as function of road density



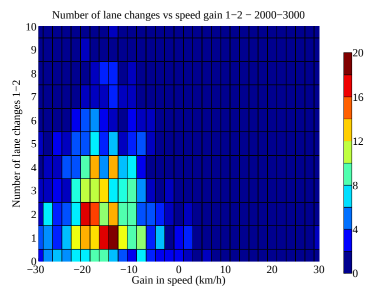
(b) Fit of one density bin



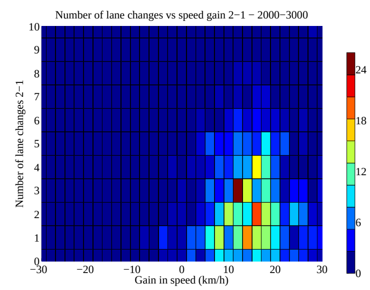
(c) Fit of rate per veh km



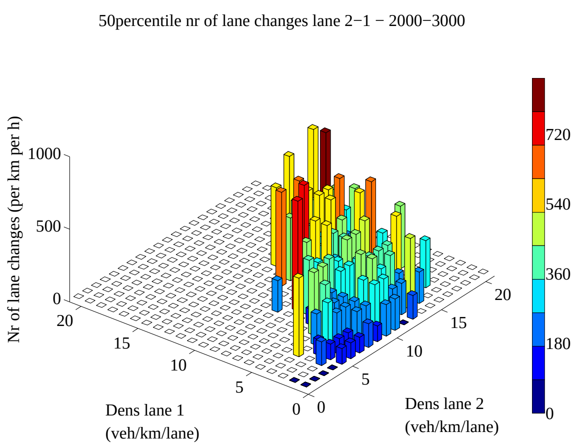
(d) Nr of lane changes per veh km



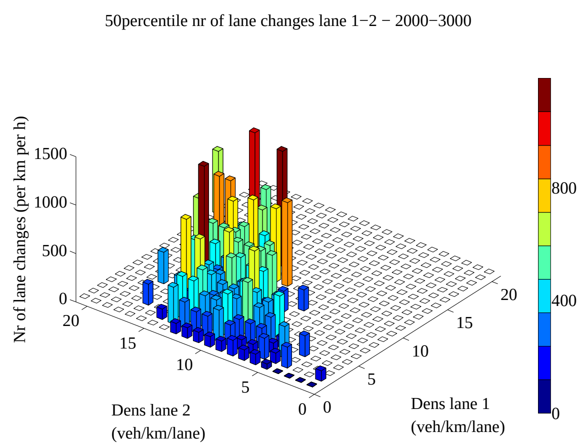
(e) Influence of the speed difference for lane changes 1-2



(f) Influence of the speed difference for lane changes 2-1



(g) Lane changes from lane 2 to lane 1



(h) Lane changes from lane 1 to lane 2

FIGURE 6 The number of lane changes for the part upstream of the off ramp on the A270

Likelihood Estimator (MLE) in which λT is simply the expected value of $f(n)$ according to the supplied the data. However, the use of MLE library routines also enables the calculation of error bars by using the Fisher information and the asymptotic normality of the estimator (*35*). The result of a fit for one density bin is shown in figure 6b. Figure 6c shows the best fit result, and the error bars of the fit for all density bins. Note that these error bars are *not* showing the errors of individual observations within the poisson distribution, but they show the 95% confidence intervals of the fit for the lane change rate λ.

This number of lane changes is remarkably linear. Note that the slope of the line in the number of lane changes vs density plot (figure 6c) is connected to the lane changes per vehicle kilometer (figure 6c) by the vehicle speed. In (*10*) it is shown that the number of lane changes can statistically best be expressed as rate per vehicle kilometer driven. Apart from being more intuitive, it is shown to be more constant measure. We follow(*10*) and fit a lognormal distribution to the average lane change rate per kilometer driven, one for each density bin. On this freeway stretch drivers change on average approximately 0.5 times per kilometer driven, (figure 6d), and that this value hardly depends on the density. This is in agreement with figure 6c. The line has a slope of approximately 1000 [lane changes/km/h] in 20 [veh/km], = 50 LC/veh/h. With a more or less constant speed of 100 km/h we find 0.5 LC/(veh-km).

Microscopically, no influence of the speed on the number of lane changes can be found (no figure due to space restriction). Macroscopically, the effects of the speed difference are shown in figure 6e and f. It shows simply that the speeds in lane 1 are higher. If people are changing towards this lane, there is a speed gain. If people change from the lane 1 to lane 2, there is a speed reduction on average. These are not individual speeds of the vehicle, but they are the average speed per lane for the aggregation interval, and hence show the influence of the driving conditions on the lane change. Note that people might anticipate on future conditions.

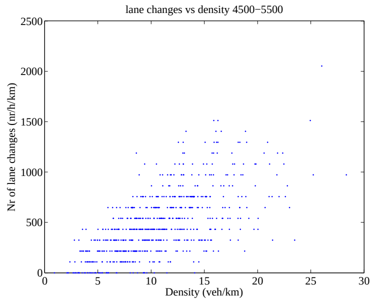
Now, we also show the influence of the density in the different lanes, rather than the density for the whole roadway, see figure 6g and h. It basically shows that with the increase in density in both the origin and the target lane, the number of lane changes increases. Note that not all combinations of density in origin lane and target lane occur, and hence not all bars of the figure could be made. The combinations of intervals for which there are measurements are combinations of density which occur, and thus are a result of the lane selection and lane changing process. Values (and thus observations) are lacking for many combinations with a higher density in lane 1 than in lane 2. This is in line with other measured values (e.g., (*30*)) of lane distributions.

Focusing on the effect of density, we find that an increase of lane density increases the number of lane changes from that lane – as was expected. With higher density, the distance to the predecessor decreases and the speed will slightly decrease (since we are in free flow conditions – more importantly, it will not increase with increasing density), which both are well-accepted elements for a desire to change lanes. However, with the increase of density in the target lane and a *constant density in the origin lane*, the number of lane changes from the origin lane to the target increases as well. This is surprising, since generally it means the speed is lower (hence there is less speed difference to gain by changing lanes) and the higher density means that there are less suitable gaps (in free flow, the speed changes little over the density range, so the time gap scales almost linearly with the space gap). This observation holds for lane changes from lane 1 to lane 2 and from lane 2 to lane 1. Section 5 will discuss some causes of this found behavior.

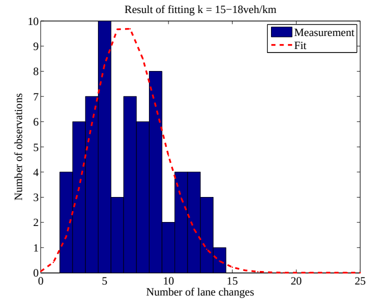
Apart from the similar pattern, we see a higher number of people changing from lane 1 to lane 2 than from lane 2 to lane 1. This is related to people leaving the freeway at the offramp downstream of this section.

4.2 A270 downstream of on ramp

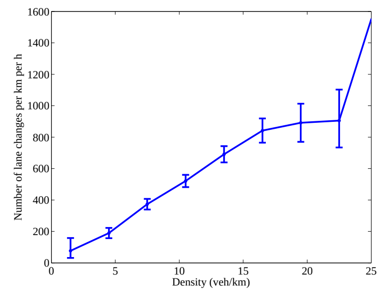
The results of the part upstream of the off ramps are shown in figure 7. Generally, the same pattern of lane changing is seen. The numbers of lane changes is more or less the same, increasing linearly from 0 to 1500



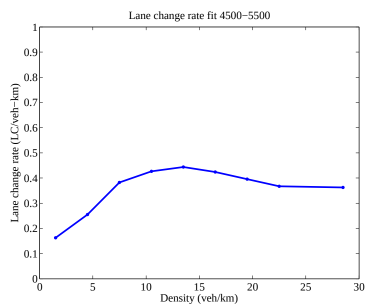
(a) nr of lane changes as function of road density



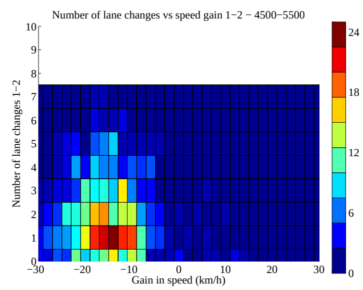
(b) Fit of one density bin



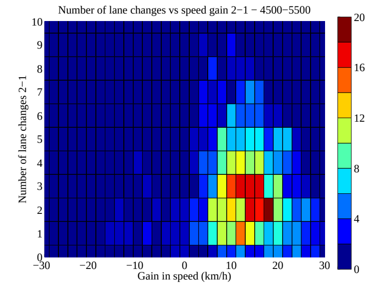
(c) Fit of rate per veh km



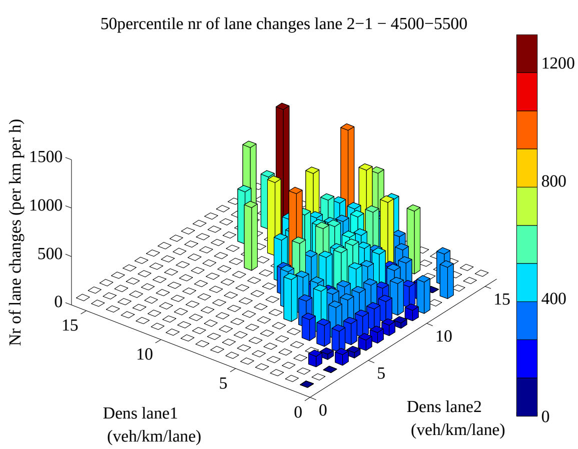
(d) Nr of lane changes per veh km



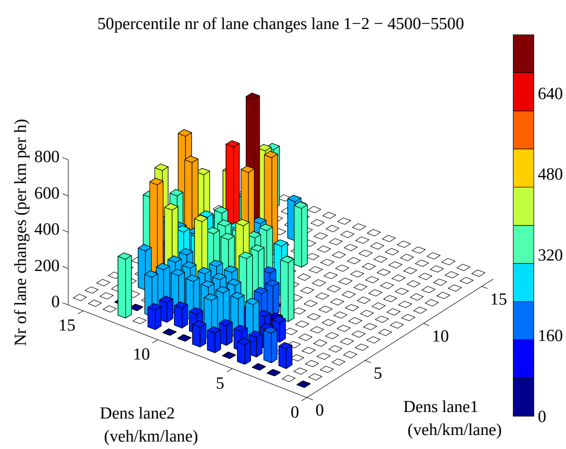
(e) Influence of the speed difference for lane changes 1-2



(f) Influence of the speed difference for lane changes 2-1



(g) Lane changes from the lane 2 to lane 1



(h) Lane changes from the lane 1 to lane 2

FIGURE 7 The number of lane changes for the part upstream of the off ramp on the A270

lane changes per km per hour over a density increase from 0 to 20 veh/km (figures 7a-c). The lane change rate is similar, at 0.4-0.5 lane change per vehicle kilometer (figure 7d). There is a small increase and a decrease over the 0-30 veh/km density range.

The speed differences for lane changing are also the same as upstream of the off ramp: negative for changing towards lane 2 (figure 7e) and positive for changing towards lane 1 (figure 7f).

The lane distribution can be derived from the combinations of density for which no measurements are made as is shown in figure 7g and h. These combinations of density are more or less the same as in figure 6g and h, meaning the same combinations of density do not occur. Whereas a close analysis (*30*) reveals a few base point difference in fraction of flow per lane, this is negligible for the analysis at hand. The lane change rates also show the same general pattern and typical values down stream of the on ramp as upstream of the on ramp. In both cases, we find an increase in the number of lane changes as function of the density in the origin lane and in the target lane, and an increase from 0 to 1000 lane changes per km per h. Contrary to the section upstream of the off ramp, we find here a higher number of lane changes towards lane 1. This confirms the hypothesis that the inequality ($1->2$ and $2->1$) is due to the ramp. The extra lane changes towards lane 1 here are due to the on ramp.

Congested periods, or even periods with near congestion, were not available in this dataset. However in the M42 dataset, there are observations up to capacity, and little over capacity.

4.3 M42

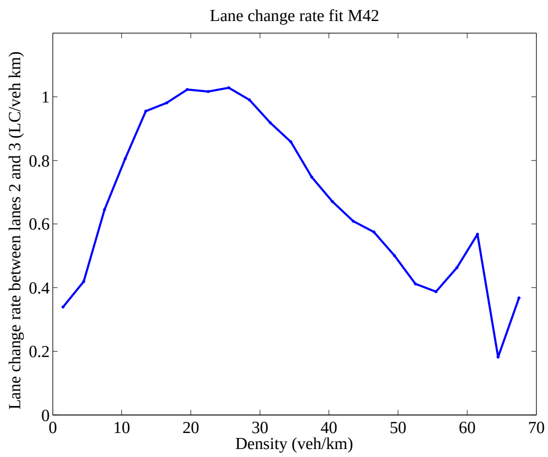
Figure 8a shows the number of lane changes as function of the roadway density. Note that the density range (and hence the scale of the x-axis) differs from the figures for the A270: in this case, data on a larger range of densities is collected. Since we are studying the lane changes between lane 2 and 3, the indicated density is the density of these 2 lanes combined. The number of lane changes per vehicle kilometer changes more than at the A270, and to higher values. This can be explained by the differences in layout. For the M42 we consider changes between lanes 2 and 3. Trucks are mainly in lane 1, and they do not change often. For the high densities, which are not available in the A270 dataset, there are also less lane changes, since people tend to “keep their position” in more dense traffic.

Analyzing the number of lane changes as function of the densities in both lanes, we first have to consider the number of aggregation intervals in each bin. This is depicted in figure 8b. The results in terms of number of lane changes per bin with similar density are shown in figure 8c and 8d. As has been shown for the A270 freeway (see above), the influence of the ramp is – in determining the general pattern – minor. This will be even less for lanes 2 and 3.

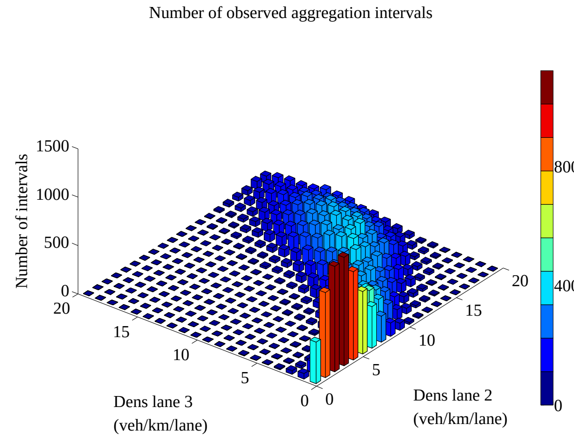
At the edges of the observed conditions where the number of observations is low (see figure 8b), the median value might be fluctuating more due to stochastic differences. Turning to the number of lane changes, we find a similar pattern to the A270 freeway. This holds both for the lane change rate (increasing from 0 to 1500 lane changes per kilometer per h) and for the dependencies (increasing with both density in the target lane and in the origin lane). This site is downstream of an on ramp, so here we also observe a (slightly) higher rate of lane changes from the center lane towards the median lane than vice versa.

5 DISCUSSION

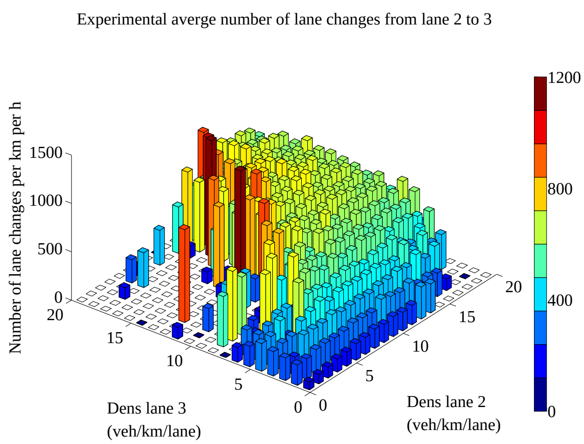
At the sites studied in this paper, it is found that the number of lane changes increases with the density in the origin lane, but, contrary to most theories, also increases with an increase in density in the target lane for a constant density in the origin lane. We are aware that these effects might be site specific. In this section we discuss other, non site-specific phenomena than immediate speed gain or gap-acceptance that play a role in lane-changing and cause these effects. This section discusses the results in the light of lane changing theories, and introduces possible explanatory behavioral elements for the observed results.



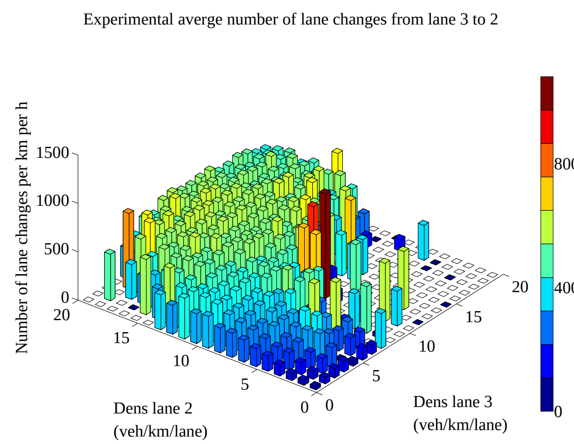
(a) Exponential fit for the lane change rate from lane 2 to 3



(b) number of observations



(c) lane 2 to 3



(d) lane 3 to 2

FIGURE 8 Measured number of lane changes on the M42

First a remark should be made on the road stretches. We used road stretches for which data are available. In more urban areas, the distance between ramps is never very long, and they will most likely have an influence on the number of lane changes. Not only directly the ramps influence the lane changes (mandatory lane changes towards an exit, or onto the freeway), but also other traffic will make room on the shoulder lanes to enable other traffic to enter the main roadway. In areas with longer freeway stretches with less ramps, the number of lane changes is therefore likely to be lower. Lane changes can also depend on gradients in the road, since these might increase the speed differences between the passenger cars and the trucks (*23*). Also driving regulations will influence the number of lane changes: keep your lane will lead to less lane changes than keep left/right except when overtaking. More heterogeneity in vehicle composition and driver population will also increase the number of lane changes. The number of lanes can have an effect as well. For the M42 motorway we chose the middle and the median lane to avoid lane changes from the on-ramp to the shoulder lane. Although the lane has been excluded from the analysis, drivers still have to consider the possible movements of other drivers from the motorway. So although it is not considered in the analysis, the shoulder lane has an influence. Finally, curvature might have an impact on lane changing behavior too.

Then, the applied methodology might play a role. We choose to bin all aggregation periods in bins of the same density in the origin and target lane. Alternatively, one might choose other variables to bin the data. Speed is likely to have an influence. However, an analysis of the speed differences in origin and target lanes did not show the incentive for the lane change. We choose to the analyze the number of lane changes as function of the density since the density fluctuates more in the level of service A-D than speed (the ranges considered here) and gap acceptance is more related to density than to speed. For other, more congested traffic conditions, one might include the speed explicitly as independent variable, as well as downstream conditions (speed or density).

A first explanation for the results is that the above reasoning explains lane changes based on the *actual* and *local* situation. However, other lane change incentives are possible: drivers can look ahead (downstream) for a future traffic situation (e.g., (*36*)). For instance, there might be a truck in the middle lane, or a possible acceleration wave both further downstream, in the fast lane, which make drivers in the middle lane change towards the fast lane, also if the speed in the middle lane has not reduced yet (distance to the truck is still large) or if the speed in the fast lane has not increased yet (wave is yet to arrive). Empirically, such counter-intuitive results are also found by (*37*). They show, using microscopic observations from a driving simulator, that the number of lane changes varies with the fluctuation of speed, and, moreover, that drivers tend to overtake if the leading vehicle drives *faster*. This can possibly have the same origin as the results found here: the traffic conditions at the moment of the maneuver (lane changing or overtaking) are not the same as the traffic conditions which drivers account for when they perform the maneuver (time to take perform the action or look-ahead).

Also, the number of lane changes from a lane and towards a lane are possibly not completely independent. A lane change from one lane will leave a gap in the origin lane, which might be used as gap to merge into for another vehicle. More vehicles in the target lane would in first order mean that more vehicles change out of the target lane in the first place. This leaves room for vehicles in the origin lane to change towards the target lane. This theory would hold more in higher density situations, where vehicles are waiting for a gap and use this as soon as it will be available.

Furthermore, the separation of density in the origin lane and density in the target lane is therefore possibly a bit artificial, since these are not equilibrium situations. In a way, the shown lane change rates might show the consequences rather than the causes of the lane changes. For some deeper reason than the immediate traffic conditions the drivers choose a particular lane. The collective behavior, however, is the same. So if the fast lane, for some reason, is more attractive, there are more people changing towards this lane, and in the meantime it gets busier. Even if it gets busier, the reason to go there is still valid, so people still move there.

Another theory which can explain the effects, is related to the theory of slugs and rabbits, formulated by Daganzo (*21, 22*). He states that *rabbits* will move to the faster lanes as long as the speeds are higher. In non-congested conditions vehicles in the middle lane are not allowed to overtake vehicles in the fast lane (European driving rules, contrary to for instance US driving rules). This means that drivers wanting to go faster, have to move towards the faster lane anyway. This will always be faster in the longer run, since the middle lane, by regulation, cannot be faster. Thus, faster drivers want to claim a position in the fast lane. The busier the fast lane becomes, the more difficult it might be to obtain this spot in the fast lane. With a game-theoretical idea, the more dense the fast lane is, the higher is the wish to claim a position in that lane. That can explain why for a fixed density in the middle lane, at increasing density in the fast lane an increasing number of lane changes from the middle to the fast lane is found.

A future lane change model should be able to predict the number of lane changes, but also the equilibrium situation (i.e., the lane flow distribution) must follow from a lane change model. Using lane change data, this equilibrium line can be found. In principle, one can find the number of lane changes towards a lane and from a lane under a specific set of conditions. One can define an effective lateral inflow towards lane j, as the sum of the lane changes from the adjacent lane(s) minus the sum of the lane changes towards the

adjacent lane(s). Since these can be expressed as function of the density, one can find conditions for which the effective lateral flow towards lane j equals the effective lateral flow from lane j. These conditions are equilibrium conditions, which can be derived from the lane change functions. These equilibrium conditions, in turn, should give the equilibrium lane distribution, as can be measured using inductive loop detector data. Note that the equilibrium conditions can be derived from the lane change dynamics, but the equilibrium conditions do not imply lane change rates, hence a confirming a lane change model is not possible using only a lane distribution.

6 CONCLUSIONS

The often assumed steps of lane changing (slower moving vehicle in the same lane, other lane is moving faster and a gap in the adjacent lane) are not found in the data analyzed here. The process of lane changing is more complicated than these simple steps describe. Not only does this require models which describe this process better, but it also shows that the lane change models need a qualitative calibration based on the number of lane changes from lane to lane, binned per condition, before fitting the model parameters to find a reasonable number of lane changes in total.

Generally, it is found that the number of lane changes (measured per kilometer per hour) increases with the density of the vehicles in the origin lane. Surprisingly, it also increases with the density in the target lane. On average, lane change rates of approximately 0.4-0.5 lane change per vehicle-kilometer were found. It is finally shown that ramps have an influence on the lane change rate on the main road. The lane change rate to the shoulder lane is higher than towards the median lane upstream of an off ramp. Similarly, the lane change rate towards the median lane is higher than towards the shoulder lane(s) downstream of an on ramp. This influence is observed also at distances of 500-1500 meter upstream of the upstream end of the slip lane of the off ramp and 500-1500 meter downstream of the downstream end of the slip lane on ramp.

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