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Categorization of the lane change decision process on freeways

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A B S T R A C T

Traffic operations for new road layouts are often simulated using microscopic traffic simulation packages. These traffic simulation packages usually simulate traffic on freeways by a combination of a car-following model and a lane change model. The car-following models have gained attention of researchers and are well calibrated versus data. The proposed lane change models are often representations of assumed reasonable behavior, not necessarily corresponding to reality. The current simulation packages apply solely one specific type of model for car-following or lane changing for all vehicles during the simulation. This paper investigates the decision process of lane changing maneuvers for a variety of drivers based on a two-stage test-drive. Participants are asked to take a drive on a freeway in the Netherlands in a camera-equipped vehicle. Afterwards, the drivers are asked to comment on their choices related to lane and speed choice, while watching the video. This paper reveals that different drivers have completely different strategies to choose lanes, and the choices to change lane are related to their speed choice. Four distinct strategies are empirically found. These strategies differ not only in parameter values, as is currently being modeled in most simulation packages, but also in their reasoning. Most remarkably, all drivers perceive their strategy as an obvious behavior and expect all other drivers to drive in a similar way. In addition to the interviews of the participants in the test-drive, 11 people who did not take part in the experiment were interviewed and questioned on lane change decisions. Moreover, the findings of this study have been presented to various groups of audience with different backgrounds (about 150 people). Their comments and feedback on the derived driving strategies have added some value to this study. The findings in this paper form a starting point for developing a novel lane change model which considers four different driving strategies among the drivers on freeway. This is a significant contribution in the area of driving behavior modeling, since the existing microscopic simulators consider only one type of lane change models for all drivers during the simulation. This could lead to significant changes in the way lane changes on freeways are modeled.

1. Introduction

In recent years, due to the growing application of microscopic simulators for the analysis of transportation systems as well as traffic control, interests in developing more reliable driving behavior models and in particular lane changing and car-following models have increased significantly. Existing simulation packages that represent the state-of-the-practice are widely criticized as insufficient (Prevedouros and Wang, 1999; Hidas, 2005; Laval and Daganzo, 2006). In practice, microscopic simulation packages are being used to assess the quality of the traffic flow, as well as delays and emissions.

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0968-090X/

The modeling core of the movement of vehicles on freeways is formed by a combination of two sub-models, a longitudinal and a lateral sub-model. The model for the longitudinal movement either describes the car-following behavior or considers the free-flow speed of drivers. The lateral model describes when and how vehicles change lane. For ex-ante evaluations of traffic measures, it is important that the model predicts the driving behavior via a mechanism reflecting real-life driver behavior. This might be achieved by considering a comprehensive driving behavior modeling structure including the decision process, psychological and perceptional information of the driver, etc. This holds for both longitudinal as well as lateral actions.

Despite its great importance, lane changing has not been studied nearly as extensively as longitudinal acceleration and deceleration behavior. This could be due to insufficiency of reliable data (e.g. cross-sectional data from detectors (Hidas and Wagner, 2004)). Clearly, a traffic modeling tool that fully describes lane changing is still lacking. However, in recent years, interest in the development of lane changing models and their implementation in traffic simulators has increased drastically. The modeling efforts in the literature are roughly categorized as: modeling the lane change decision-making process, and modeling the impact of lane changes on surrounding traffic (Zheng, 2014). Zheng et al. (2013) studied the impacts of lane change maneuvers on the immediate follower in the target lane. Some models (e.g. Laval and Daganzo, 2006) emphasize on driver's decision-making process, which contains the decision to consider a lane change, choice of a target lane (i.e. unobservable), and gap acceptance steps. These models generally neglect the detailed modeling of the lane change action itself and model it as an instantaneous action. Current lane changing models are unable to describe correctly the lane changes found in traffic. Understanding lane changing behavior is important in several application fields such as capacity analysis and safety studies (Zheng et al., 2010). Approximately 539,000 two-vehicle lane change crashes occurred in the U.S. in 1999 (Sen et al., 2003). For traffic operations in multi-lane traffic facilities, lane changing is essential. The negative impact of lane changes on traffic breakdowns and bottleneck discharge rate reduction at the onset of congestion (i.e., capacity drop) is reported in Cassidy and Rudjanakanoknad (2005). The significant roles played by lane change in formation and propagation of stop-and-go oscillations have also been revealed (Kerner and Rehborn, 1996; Mauch and Cassidy, 2002; Ahn and Cassidy, 2007). Laval and Daganzo (2006) addressed that lane changes cause disruptions and might influence the capacity of the road by leaving voids.

Recent works studied also the driving behavior of heavy vehicles when making a decision or executing a lane changing maneuver on freeways (Aghabayk et al., 2011). Moridpour et al. (2012) addressed that applying an exclusive heavy vehicle lane changing decision model can raise the precision of the microscopic traffic simulation software in estimating the macroscopic traffic flow measurements.

After Gipps' lane change model (Gipps, 1986), in most lane changing models, the lane changes are classified based on the reason for which the lane changes are performed (e.g. mandatory, discretionary). Mandatory lane changes (MLC) occur when a driver must change lane to follow a path to reach his/her destination. Discretionary lane changes (DLC) occur when a driver changes lane to improve his driving condition (e.g. for higher speed). In most lane changing models (e.g. Kesting et al., 2007; Laval and Daganzo, 2006) discretionary lane changes only look at speed as an incentive to change lane. It should be noted that classifying the lane changing in MLC and DLC may lead to a rigid behavior structure which does not consider the trade-offs between these two. Toledo et al. (2003) developed a model that integrates MLC and DLC in a single utility framework. Toledo's lane changing process consists of two steps: choice of target lanes and gap acceptance decisions. The basic requirements for DLC are as follows: (1) a driver cannot drive with its intended speed in its current lane; (2) the speed in the adjacent lane is preferred over the speed in the current lane; (3) there should be a gap, large enough, in the adjacent lane. These requirements can be found in Gipps (1986). This has been formalized, for instance by the MOBIL (Kesting et al., 2007) lane change model. The fundamental idea behind MOBIL is to include both the appeal of a given lane (i.e., its utility) and the discomfort associated with lane changes in terms of accelerations. That model compares each time-step the utilities, defined as accelerations, of the vehicles involved in a lane change. For each time step, the model calculates the weighted sum of accelerations of the considered vehicle and the other drivers. If this exceeds a threshold value, the lane change is performed. To calculate the expected accelerations a car-following model is applied (e.g. IDM (Treiber et al., 2000)). None of these models provide a full explanation for the phenomena seen in practice where it is for instance observed that the number of lane changes to a certain lane increases if that lane has a higher density (Knoop et al., 2012).

Gap acceptance models (Kita and Fukuyama, 1999) are often applied in MLC models. These models are also not able to describe the observed gap choices in merging areas (Daamen et al., 2010). Marczak et al. (2013) analyzed merging behavior on a freeway using two empirical trajectory data sets (i.e. in France and in the Netherlands). They created a logistic regression model to predict the acceptance of a given gap. Other attempts have been made by modeling gap choice behavior. In all these studies, no questions were asked regarding the incentives of the drivers. Only by asking people, we may get an insight of their intrinsic motivations for merging or not merging into a particular gap.

Empirically, it is shown that for merging traffic, drivers may apply small decelerations and accept smaller time headways (Daamen et al., 2010) than for discretionary lane changes which is called relaxation phenomenon. Also, vehicle speeds are synchronized such that a driver adapts its speed to the speed of the neighboring lane. This is modeled in LMRS lane change model (Schakel et al., 2012), which includes relaxation and synchronization. Generally, this model may be employed with any car-following model which calculates the vehicle acceleration. It basically accounts for the fact that drivers sometimes merge into gaps which are too small, and then create a larger gap. Toledo et al. (2007) introduced a model which integrates the various decisions, such as acceleration, lane changing and gap acceptance. MOBIL provides a lane change using the possible acceleration in the current lane and after a lane change. The integrated model by Toledo et al. (2007) does the opposite, by taking the lane change decision as leading and determining the acceleration. LMRS accounts for accelerations related to a lane change, both for the lane changer and the presumptive follower.

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There are large discrepancies between the principles modeled and the observations, both for DLC (Knoop et al., 2012) and for MLC in case of merging (Daamen et al., 2010). Knoop et al. (2012) utilized inductive loop detector data to find the lane changes on a microscopic scale. This provided a very large number of observations, but not real insights into the motivations behind these lane changes. Daamen et al. (2010) used video recordings from a helicopter to derive vehicle trajectories with a higher resolution on drivers actions, but still the motivations and reasoning of the lane changes were not investigated. This implies that current models do not properly describe the various motive and stimulus behind lane change decision process (i.e. different lane change strategies).

Kondyli and Elefteriadou (2009) applied interview techniques for a study on driving behavior in merging area. Later, the same authors conducted a test-drive with an instrumented vehicle (Kondyli and Elefteriadou, 2011). Note that in the last-mentioned study, the drivers commented in real-time on their behavior and were aware of their actions. They made all driving actions consciously, and had to actively think on all actions. This might lead to a driving behavior which might not be the reflection of reality. Experienced drivers might in other situations drive using "intuition" or act differently in order not to have to explain potentially debatable decisions. Sun and Elefteriadou (2011) conducted a focus group study (as in Kondyli and Elefteriadou (2009)) with 17 participants to identify important factors that they frequently considered during their lane change experiences. Despite some limitations in this study, it is one of the very few studies in the lane change literature that used non-vehicular data. Zheng (2014) proposed to implement the data collection methods that are commonly used in the social science disciplines to gather psychological, perceptional, and cognitive information for completing the vehicular data during lane change.

Since both the interview and the set-up of natural driving in an instrumented vehicle is promising, we decided to integrate these two in our study. This paper tries to shed some light on the driving behavior strategies that play a role in lane changing and seem hidden from the current literature. Moreover, this work investigates the effect of lane changes on speed choice. To the best of our knowledge, combining speed choice and lane preference is currently not considered in most driving behavior models. On the other hand, simulation packages use one specific type of model for car-following or lane changing, although there are many models available. For the car-following behavior, Ossen et al. (2006) has shown that different drivers drive differently. In the current paper, we demonstrate to which extent the strategies related to lane changing behavior are also different for different drivers. For this, test-persons are asked to drive on freeway sketch (A13 in the Netherlands) in a vehicle equipped with video cameras. Right after the test, the participants are interviewed and questioned regarding their decisions (i.e. for changing lane or not) during the test. Subsequently, the test-drive is carried out under a naturalistic driving behavior with an insight of drivers' motivation, which is crucial for scrutinizing the strategies. In addition, 11 in-depth interviews on the lane change decisions without test-drive have been performed. In open-question interviews, drivers commented on their driving behavior on freeways. The outcome of these interviews confirmed the derived lane change behavior framework in this paper. Moreover, preliminary results of this study have been presented to approximately 150 people, and their comments on the strategies were asked. They could find themselves in one or more of the strategies, and their comments consisted of reasons why they would adhere to one of the found strategies.

The remainder of this paper is set up as follows. In Section 2, the methodology implemented in this study is addressed in details. This includes the test-drive (i.e. participants, test-bed, interviews and data analysis). Section 3 discusses the results and strategies derived for traffic operations on mainstream with discretionary lane changes. In Section 4, the decisions related to merging and diverging maneuvers (i.e. mandatory lane changes) are presented. Finally, discussion and conclusions are included in Sections 5 and 6, respectively.

2. Methodology

In our study, we combine the interview-based study with a test-drive under natural driving behavior condition. We explore the strategies underlying the actions by discussing the actions (decision process) after the test-drive during the interviews. Another difference with the aforementioned studies is that the scope of our study is broader, including lane choices on freeways and not only merges. This way, we aim to get an overview of the strategies drivers follow when driving on multi-lane freeways. In the test-drive, the drivers show their normal driving style (naturalistic driving) and the usual way of making decisions (revealed preference). These decisions are being discussed based on the video-recorded test-drive right after the experiment. The drivers are also being asked what they would have done in different situations if that is relevant (stated preference). This section, first describes the test-drive along with the related components (i.e., test-person, test-bed, interviews and data analysis). In the test-drives, drivers (i.e., 10 participants) could comment on their decisions, and as it will be addressed in Section 3, the driving strategies differed considerably. To enlarge the number of participants, we set up further interviews in which we questioned drivers (i.e., 11 people) without showing them the results of the found strategies (see Section 2.2 for more details). Moreover, when the set seemed complete, we asked a larger group (around 150 people) for additions to the strategies. This is described in Section 2.3.

2.1. Test-drive

The 2013 Toyota Prius of the Department of Transport and Planning, Delft University of Technology (TU Delft), is used as the test-car. The vehicle is equipped with two high resolution wide angle video cameras, monitoring the front and rear view of the car at a 25 Hz frequency. The cameras are installed at the left side of the windshield and rear window of the car (see Fig. 1 for a screen shot of the rear view and Fig. 2 for the front view). In the images a synchronized time is shown, such that the front and back images can be matched. In the front image, the speed of the head up display was being recorded in the image (see the green[1] digits in Fig. 2). The cameras observe the traffic states rear and the front of the test-car (e.g. gap with the front cars, existence of vehicles in the adjacent lanes, capturing the lane change actions, lane change duration, speed choice). Having a short test-drive might be considered to some extent a disadvantage (not all different situations might come up), but on the other hand, it can be beneficial for the drivers to recall all situations during the test and may help them to comment on the rationale behind their actions. In addition, by playing back the recorded video, they could see their actions and remember the situations easier. The two aforementioned factors assured us, with a high rate of confidence, that the drivers were able to describe precisely their course of actions. The drivers are informed that they participate in a test where their driving behavior will be analyzed and discussed after the driving. However, no further details are provided on beforehand regarding the main purpose of the experiment. The drivers are instructed to drive as they normally would do. The route has been programmed in the in-car satellite navigation system. The cameras are installed such that they are not hindering the view of the participants; especially the backwards looking camera is hardly visible. The total test took approximately one hour per person (i.e., 10 min instructions, 25 min test-drive and 25 min discussion and interview). The participant was accompanied by a technician sitting on the back seat of the test-car. He was instructed to be silent during the test-drive and not to give any guidance to the test-person.

2.1.1. Participants

Ten test-persons (i.e. 8 male and 2 female) were recruited using oral communication and digital media (e.g. Facebook, Twitter). The recruitment has a direct link to the university, which is being reflected in the test-persons' characteristics. A 15-euro gift card was awarded to each driver at the end of the test. The average age is 28 years old. The annual mileage varies from 30 to 12,000 km. The median annual mileage is 4000 km/year. Generally, most drivers addressed that they were familiar with the stretch since it is close to the university. Two participants were unfamiliar with the particular road stretch. Most of the test persons had finished higher education or were in the process of getting a degree. Seven test-drivers passed their driving test in the Netherlands 2 in Spain, and 1 in middle east. All hold a driving license which is valid in the Netherlands. A large part of the test persons were students (Master degree, or post-master, PhD students), and the rest administrative staff related to the university. One person was also a part-time professional private driver, for which he had received additional training. Clearly, this is not a representative sample for all drivers. The number of drivers is too small to draw conclusions on the whole, but it does give a good starting point for the identification of driving strategies. The sample has been boosted by adding other interview (without test-drive) and information of the presentations (see Sections 2.2 and 2.3).

2.1.2. Test-bed

The experiment took place on the A13 freeway stretch between Delft and Rotterdam on May 26, 2014 (see Fig. 3 for the road layout). The trip involves 11 km of freeway driving on multi-lane freeways in total. The selected freeway is equipped with dual loop detectors at 500 m intervals. The complete round trip starting at the TU Delft campus was 14 km and took about 25 min on average.

The freeway in southbound direction has three driving lanes available. The northbound stretch contains three regular driving lanes, as well as an emergency lane at the right of the driving lanes, which is being opened in peak hours with high demand (indicated by PHEL in Fig. 4). The configuration of the lanes is demonstrated in Fig. 4. Note that further details regarding the indicated MLC maneuvers in Fig. 4 will be discussed in Section 4.

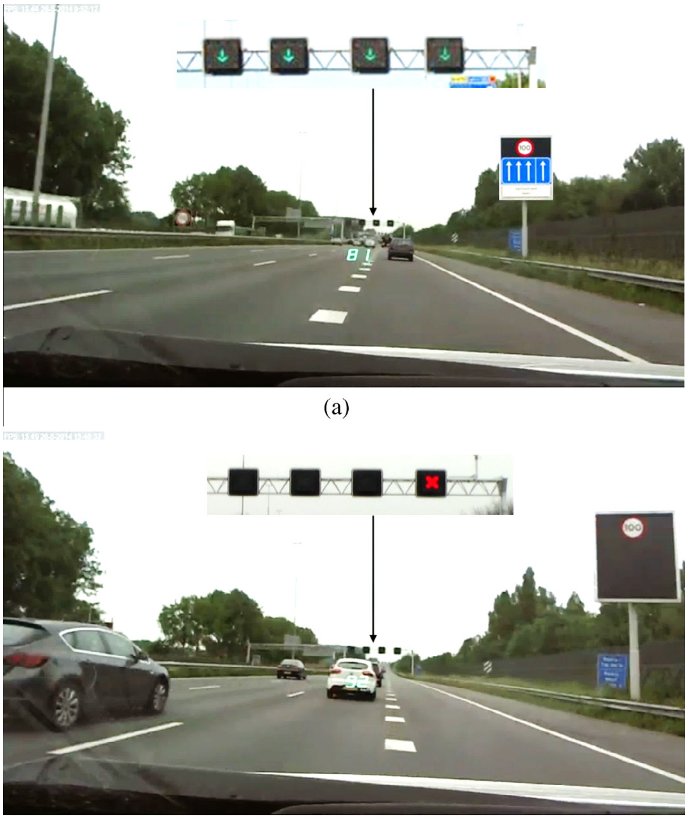
Dutch driving regulations indicate that drivers should keep right unless overtaking. In the late 1990, the peak hour lanes were constructed in the Netherlands. Especially in the period 2005–2011, many peak hour lanes were created and became common in the Dutch freeways. During peak hours, traffic is allowed to use the shoulder as an additional lane. On the overhead gantries a red cross or a green arrow indicates whether the lane is open or closed to the traffic. Besides, a sign at the side of the road indicates the opening of the lanes (see Fig. 2).

The speed limit for this stretch is 100 km/h; during the tests (9:45–16:00), the road was in free flow conditions in both directions. This is obviously concluded from the speed contour plot (e.g. see Fig. 5. for the northbound and the southbound) derived from the loop detector data showing the average traffic conditions of the road. Heavy good vehicles (HGV) have a speed limit of 80 km/h, while Dutch HGVs are physically limited to 89 km/h. There are no speed checks on the stretch. Usually, the speedometers indicate a speed which is several km/h higher than the real speed. For automated tickets (speed cameras), a 3% correction is deducted from the measured speed. Fines are only issued at corrected speeds of 104 km/h and higher. Police patrol officers are usually less strict, and will only fine speeds which are more than typically 15 km/h over the speed limit. The average speed on the road is 90 km/h, including trucks.

On average, there is an on-ramp every 4–5 km in the Netherlands (Autosnelwegen, 2014). Between the entry and exit locations of the road there are no other connections. However, there are entrances and exits for the fuel station. The merging lane of the southbound on-ramp changes into a merging lane for the traffic to the fuel station (total length: 560 m). Downstream of the fuel station, there is a 300 m merging lane parallel to the right lane. In the northbound direction, a fuel station is located at the same position. Upstream of this fuel station, there is a merging lane of 300 m (right side of the peak-hour

[1] For interpretation of color in Fig. 2, the reader is referred to the web version of this article.

Fig. 1. The view of the rear facing camera.



(a)

(b)

Fig. 2. Opened peak hour lane (a); closed peak hour lane (b).

lane). Downstream of the fuel station, the merging lane for traffic from the fuel station is the same as the merging lane for the traffic toward Delft exit. The total length of this weaving lane is 560 m (see Fig. 4 for schematic details).

2.1.3. Interviews

The videos recorded during the test-drive (i.e., the rear and the front view) were shown to each participant. Firstly, they were questioned to which extent their driving behavior was the same as their normal driving behavior, and then specific points in their trip were discussed. Three different groups of questions were provided and asked. The first part includes some background questions such as age, profession, years of holding a driving license, annual driving in kilometres, accident records on motorway and self-speed-wise rating. The second part contained some general driving behavior questions not

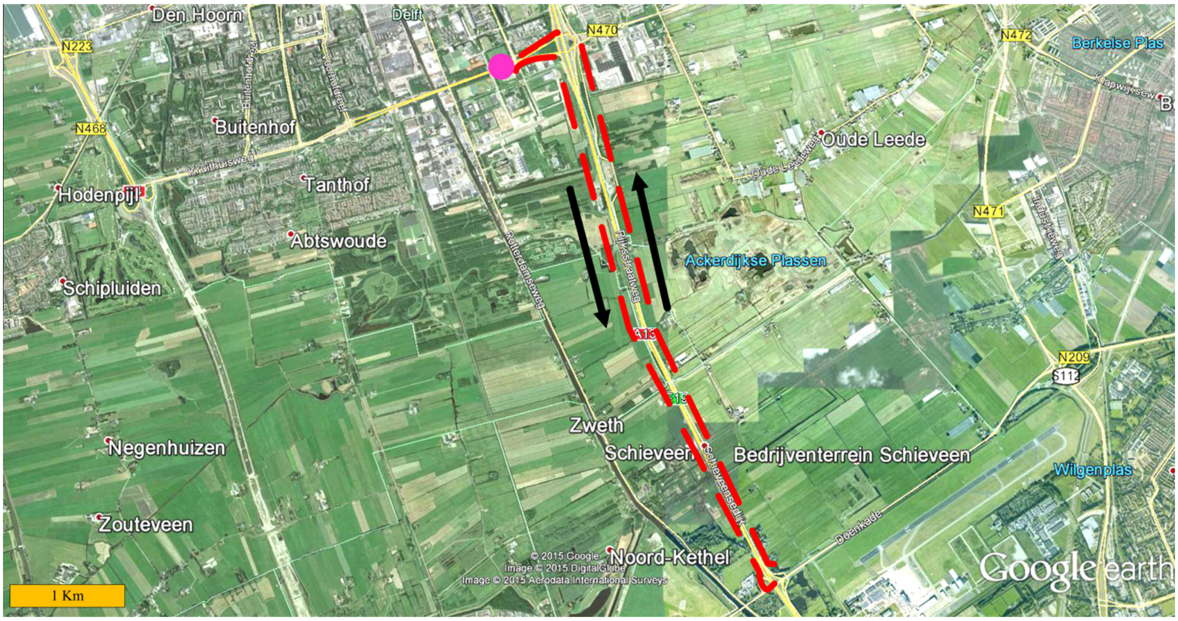


Fig. 3. Satellite view of A13 freeway stretch (Delft-Rotterdam, the Netherlands; indicated by the dashed red line); starting-ending point and travel direction shown by the pink circle and black arrows, respectively). [Image © 2015 DigitalGlobe, © 2015 Google]. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

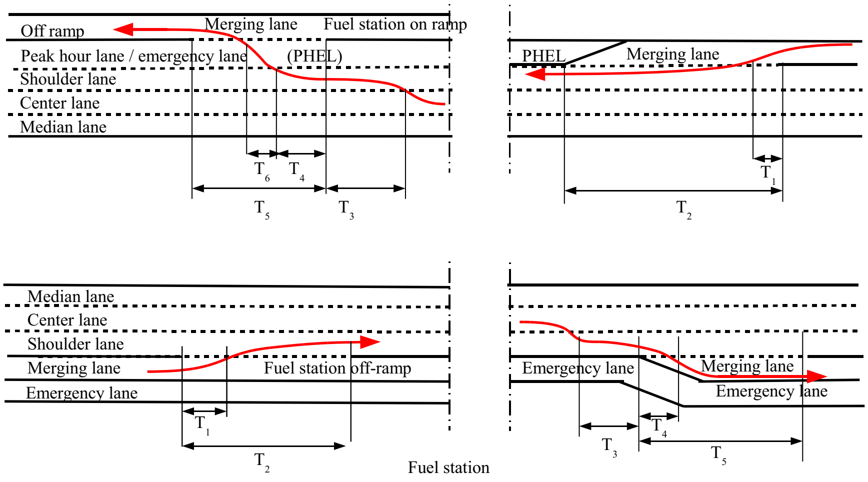


Fig. 4. The figure on the top shows the northbound and the lower figure is the southbound. The road stretch is longer in between the open areas in the middle (figure is not to scale); T_1 to T_6 are defined in Table 2. The red arrows indicate merging (right top and bottom left) and diverging (left top and bottom right) maneuvers. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

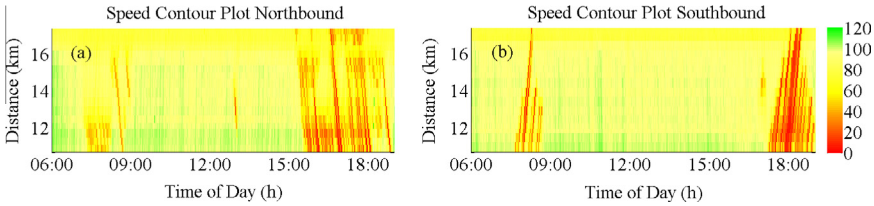


Fig. 5. Speed contour plot of the northbound (a) and the southbound traffic (b) (speed in km/h).

directly related to the test-drive experience. The participant was asked about the frequency of his/her lane changes in a stretch of 10 km of motorway, the reasons for accelerating or decelerating on a freeway, main situations for deciding to change lanes, considerations during a lane changing action (including merging) and the fraction of lane changes for reaching the destination or improving the driving conditions. The third group of questions were about the test-drive experience of the test-person. A mixture of pre-specified and open questions related to driving behavior was asked during the interview.

2.1.4. Data analysis

In addition to the interviews, the videos have been watched by the authors to analyze the behavior for performing discretionary lane changes and the mandatory lane changes (i.e., the lane change from the merging lane into the main lanes of the freeway as well as merging from the main lane into the merging lane at the off ramp).

By means of GPS device, we had the longitudinal position of the test-car. For the lateral position (including lane change maneuvers), the GPS data was not accurate enough to be applied. Hence, by a thorough monitoring of the front view video, we indicated the exact time and position where the merging and diverging lane change process begins. In addition, using the in-view head-up display appearing in the recorded video, the speed at the moment of merging and diverging has been observed. Moreover, the time which they changed lanes compared to the time they took to drive the distance of the complete merging lane has been analyzed. This is converted to a distance without taking the speed differences into account. Speeds generally increase when merging onto the main road and decrease when merging out of the main road. This might lead to some errors in the general case. The error is zero at exactly the beginning or the end of the merging lane (because those moments are known precisely). Calculations show that for changing speed profiles the error never exceeds 10 m or 3% of the length of the merging lane. Therefore, this measure is still considered to be relatively accurate. For the off-ramp, it is also indicated how long before the start of the off-ramp drivers are in the right lane, and what is the speed at the end of the off-ramp. Since the speed is not constant but will be generally increasing, it will give a bias. The measure is accurate for the beginning and end of the merging lane, but in between the estimation of the merging location will be further upstream than the real location. This error can be quantified. For instance, the calculated position error for a speed profile increasing from 75 km/h to 95 km/h over 90% of the distance of the merging lane is 10 m in the worst case, which is at a speed of 30 m/s 1/3 of a second. Note that we read the time in seconds, thus the error due to speed changes might be neglected.

2.2. Interviews without test-drive

To enlarge the number of participants, we set up further interviews in which we questioned drivers without showing them the results of the found strategies in the study with the test-drive. This complementary study has been carried out by interviewing 11 additional individuals with driving experience in the Netherlands. The participants were recruited in the (private) network of the authors. These participants were aware of the nature of the questionnaire (traffic-related study), but not the exact purpose of the research, the hypotheses and the results of the first phase (i.e. based on the 10 interviews including the test-drive). In the entire interviews, the principal focus was on realistic driving behavior. It was also emphasised that the interview was not about criticizing their driving behavior or finding incompliance with the driving regulations. Some hypothetical situations were described to the interviewee to clearly define their driving actions (e.g. lane choice, speed choice, merging behavior, etc.). In that case, the drivers were asked to consider driving on a three-lane freeway with a 100 km/h speed limit with no average speed check, i.e. the situation like the A13 motorway in the real life experiment. A hypothetical situation would always be in line with the participant's behavior. The interview for the 11 people started with the question ''Can you describe your way of driving on the freeway?''. This question was generally asked but we mainly focused on the lane change rather than the car-following behavior. In some cases, the participant clearly described the essence of a strategy right from the beginning and in other cases, the participant was more descriptive which conceptually could fit into one of the derived strategies. Based on the answers, follow-up questions were posed. The drivers are also asked what they would have done in different situations. The interview also discussed to which extent the participants actually know their driving behavior. In total, each interview took approximately 10–15 min. The interviews has shown that the findings of our study cover a wide range of drivers' strategies on freeways (see Sections 3 and 4 for a detailed description of the derived strategies).

2.3. Additional feedback from the presentation

Preliminary results of the test-drive have been presented at several scientific meetings at the University of California at Berkeley, California Polytechnic State University (CalPoly), Swiss Federal Institute of Technology in Zurich (ETH Zurich), Delft University of Technology and Transportation Research Board (TRB) 2015 (Knoop et al., 2015). The audience of these meetings (in total around 150 people) have been mainly working in the field of traffic engineering and operations. In all the aforementioned sessions, the audience were invited to participate actively in the discussions and comment on the presented strategies. Their comments confirmed the strategies found earlier, and no additional strategies have been presented. It did provide a very comprehensive overview of the drivers motivations for following a specific strategy. As a result, we were able to formulate more precisely the strategies and further details regarding the drivers' incentives have been revealed (see Section 5).

3. Findings: strategies on the freeway (discretionary lane changes)

The interviews with the test-drivers revealed four different strategies (i.e. *Speed Leading*, *Speed Leading with Overtaking*, *Lane Leading* and *Traffic Leading*) for the discretionary lane changes. This variety of strategies is not described in the literature yet.

A substantial finding was that all drivers considered the driving strategy of the other drivers similar to the one they showed, whereas the strategies were in fact completely different. At the beginning of the interview, the participants stated that they drove the stretch normally and "the same way as the other drivers do". But after asking more questions regarding the decisions in the test-drive and also in general cases, it was revealed that their presumption of having the same strategy as the other does not hold. The four strategies were also assessed and agreed upon by the interviewed people, with additional argumentations on why a certain strategy was chosen. Additional reasoning for a certain strategy is confirmed by the attendees during the presentations of this work.

Most drivers have one or two general strategies, which is shown in Table 1. For instance, in the interview without test-drive, one driver has expressed, while merging into the mainstream, he would change to the left lane as fast as possible and try to maintain his speed as high as the speed limit. This is obviously an example of a lane leading strategy combined with a desired speed. In this section the four derived strategies on freeways: speed leading, speed leading with overtaking, lane leading and traffic leading are discussed.

3.1. Speed leading

The drivers who follow this strategy choose a desired speed and try to keep it. Although the car is equipped with an adaptive cruise control, none of the drivers utilized it. In this strategy the drivers change lanes such that they can drive their desired speed. Most of the drivers adapted this strategy. The desired speed that drivers showed in free flow conditions differed between around 90 km/h to well over 120 km/h (see also the other strategies).

Drivers choose their speed based on their driving style and preference. Some drivers indicated that they wanted to drive faster but due to the possibility of getting fined they did not do so. Sometimes drivers might have speed leading strategies with different speeds depending on the location of the speed control cameras (fast in between the cameras, and then strongly braking if the speed is being checked). Drivers using cruise control are usually speed leading. One driver addressed that he will not speed up and uses the cruise control due to the risk of a fine. Other reasons for using the cruise control were its comfort and the fuel economy.

3.2. Speed leading with overtaking

Another strategy is to choose a speed and stay at the rightmost lane which is possible with that speed. When the speed in that lane decreases, i.e. when there is a driver with a lower speed limiting the continuation of that speed, this driver will change lanes. Contrary to the driver applying the "speed leading" strategy, the class of drivers applying this strategy will consider this as overtaking and increase the speed while being in the more left lane. The motivation for increasing the speed is "overtaking maneuver takes less time". This type of drivers seems to take the progress of other drivers more into account. However, note that none of the drivers commented explicitly on the driver following them. In the interviews of the non-test-drive participants, most participants mentioned that they did not want to hinder other traffic too much. Additionally, in other interviews, possible tailgating was mentioned as a reason. According to a recent study, tailgating is the top irritation for the Dutch drivers ([Dutch] public prosecutor, 2010).

3.3. Lane leading

Most drivers have an idea of their perceived driving speed. In other words, every driver has a sort of self-perception of his/her driving speed. As addressed in Section 2, based on a group of pre-specified question we tried to attain some general information about the driving behavior of the interviewee. Every individual was asked to rate him/herself speed-wise. Some indicated themselves as fast and some as slow driver. The strategy based on this ranking is that drivers choose a lane based on their perceived relative driving speed. On a strategic level perhaps the speed is leading to determine which lane would match the current "urgency" of the driver. For tactical decisions to change lanes, this is fixed. So at a tactical level, the decision is made such that the speed (almost) completely follows the others in the same lane.

For instance, one of the test persons commented that he always chose the center lane, and adapted his speed accordingly. For a 100 km/h speed limit in uncongested conditions he accepts speeds between 85 and 120 km/h (seen in video and explored in interview). He would not change lanes. He considered changing speeds as less tiresome than changing lanes. Note that this strategy implies an offence of the Keep Right Unless Overtaking rule in case there are gaps, large enough, to merge into the right lane.

The interviews and comments of the non-participants shed light on other motivations. One driver mentioned safety as argument to take the middle lane (possible escape to both sides), whereas another argued that one of the lanes at the side was more safe (only one direction where people can come in). Some drivers preferred not to be in the lane with trucks due to

Table 1
The different strategies applied by the drivers participated in the test-drive.

ID	Speed leading	Speed leading with overtaking	Lane leading	Traffic leading
1	•			•
2	•			
3		•		
4	•		•	•
5	•			•
6			•	
7		•		
8	•			
9	•		•	
10			•	

safety and sight, whereas others choose the lane with truck because that moves generally smoother (trucks accelerate less, and have a better overview in busy traffic). A last reason mentioned was that in congestion, one can also choose a lane based on the expected speed in the lane. For instance, if one knows the jam is due to merging traffic from the right, the driver would choose the left lane, and if the congestion is due to a drop of the left lane, the driver would choose the right lane.

3.4. Traffic leading

Several drivers indicated that they followed the speed of other drivers on the road. It is very important to note that this does not mean that all drivers who claim so, drive similarly. We will discuss two extremes of this strategy here. First, there was a driver who had little experience on the Dutch roads (“around 30 km”, gained over one year living in the Netherlands), but much experience in Asian countries. In the interview he told us that he was unaware of the speed limit, and adapted his speed to the other vehicles. The practical consequence for this driver in the driving experiment was that he took the center lane and chose a speed between 75 and 90 km/h. That was approximately the speed of the HGVs at the right lane, and he overtook not a single passenger car. It was also much lower than the normal speed in that lane at around 95–100 km/h. However, the vehicles behind him, queuing, drove the same speed.

The other extreme was a participant who was a professional private driver. He commented that he would “go with the flow”. For him, that meant taking the speed of the fastest vehicles on the road except perhaps for the most extreme and aggressive (high acceleration and deceleration) drivers. His motivation was that he wanted to be quick because his employer would usually be in a hurry, but he should still drive in such a way that the employer could work in the car. In the interview, the driver indicated that his free-flow speed could be *lower* than the speed he shows with traffic. Namely, his speed would go up if there are faster vehicles around. This is similar to a finding by Tracz and Gaca (2009), which showed that speeds go up if the density increases. This driver would be most in the left lane, because that is the overtaking lane, but he still changes to the center lane if there are possibilities. On this two aspects (the increased desired speed with more traffic and the lane changes), this strategy differs from the previous strategy. Note that in this strategy, speed choice and desired lane changes cannot be separated from a behavioral point of view.

None of the people interviewed without test drive gave this strategy. This might be due to the fact that in the interview without test drive, people were forced to give a reasoning.

3.5. Use of peak hour lane

Two test-drives were carried out with the peak-hour lane opened. Not all drivers were familiar with the peak-hour lane. One driver merged at the end of the driving lane, and did not see the signs of the opened peak-hour lane until he merged into one of the remaining lanes. Another participant performed an overtaking maneuver. Afterwards, he decided not to change back onto the peak-hour lane because of the uninterrupted marking at the right hand side. That means that the drivers, especially the drivers which are not familiar with the peak-hour lanes, are not using it, and will not comply to the Keep Right Unless Overtaking rule. Moreover, this might be a reason why the lane is underutilized. In the interviews without test-drive, some participants used the peak hour lane, and some did not. One interviewee indicated he used the peak hour lane as much as possible, not only for the speed but also “to educate the others”.

4. Findings: strategies for merging (mandatory lane changes)

In this test-drive, there were mandatory lane changes at the on-ramps and off-ramps. Twice, the drivers needed to merge into the main road, and twice they needed to exit from the freeway. This section describes the decisions related to those maneuvers.

4.1. Use of the on-ramp and merging lane

All drivers were asked about the process of gap selection for merging. They addressed that they started with the process of speed selection and gap selection "as early as possible". However, there were large differences in the moment when drivers actively started considering traffic conditions. Some drivers started analyzing the traffic as soon as they could see the traffic. For most drivers that meant they would actively be involved in the merging process around 150 m upstream of the starting point of the merging lane. Some drivers were already considering the speed of the traffic much more upstream, when they could not yet see the gaps next to them, but mainly the speed of the flow. One driver did not realize he had to merge into the stream until the merging lane ended, and he had to use the emergency lane to merge onto the driving lanes.

The gap selection was for most drivers an easy task because the merging was done at higher speeds than the mainstream. That means after speeding up to approximately their desired speed, or the speed of traffic, the number of suitable gaps reduced mostly to one. Table 2 also presents the details of the merging actions for all drivers as well as the median values (see Fig. 4 for schematic illustration of T_1 to T_6). Note that, for driver #4, the T_1 for the southbound merging segment is 29 s which is significantly higher than the other participants. This participant stayed on the acceleration lane even after it changed into the emergency lane (therefore also 107%). The median speed of merging is 89 km/h in the southbound direction and 86 km/h in the northbound direction. This difference, although not significant, may be due to the layout and geometric characteristics of the on-ramp. In the southbound direction the on-ramp is long and open, whereas in the northbound direction it is curved with road works.

4.2. Use of the off-ramp

Table 2 displays the details of the use of the off-ramp. The table shows how long the drivers are in the right lane before they reach the start of the exit lane. This differs for the southbound and northbound direction, with median values of 52 and 15 s respectively (equaling approximately 3000 m and 500 m). Perhaps the minimum value is more appropriate to indicate when drivers do not want to change any more (it is a so-called censored observation, where all values can be observed which are larger than the minimum). That also shows differences, with 38 s in the southbound direction and 9 s in the northbound direction. This difference might be due to the road geometry. In the southbound direction, the exit is after a corner and therefore not visible from a long distance, and drivers might take extra care. For the southbound direction, all commented that they could have gone later, but in order to be sure, they wanted to be in the right lane in advance. On average drivers preferred to be in the right lane approximately 1 km before the 300 m long merging lane started. It should be noted that generally there are signs 1200, 900, 600, 300 and 0 m upstream of the start of the merging lane. Some drivers commented that they were already in the right lane at or before that point and because of a HGV in front of them, they could not see whether there were other opportunities to take over these HGVs and change back to the shoulder lane. Consequently, they decided to remain in the right lane. For one driver, at 3000 m before the start of the merging lane, the distance was too short to be in another lane rather than the right lane.

Note that for the northbound direction, the off-ramp is located right of the peak-hour lane. If that is not in use, the drivers have to cross that lane as well. The time they take to cross that lane is also indicated in Table 2. Most drivers slowed down on the merging lane. The speed at the shoulder lane is usually lower than in the other driving lanes, so this way drivers prepare for the lower speed. One driver *increased* his speed on the deceleration lane. He commented that he likes to speed up and tries to overtake at least another car. Also in the interviews without test-drive, people were asked to comment on the moment they start using the right lane. Most values were in-line with the values for the northbound off ramp. They mostly commented that if they know the situation are familiar with the road, they allow for shorter distance. Two interviewees even indicated that they are willing to go to the right lane even after the merging lane has started.

5. Discussion

One of the strong aspects of this study is the fact that it does not rely only on the data derived from the interviews combined with the test-drive. The two additional phases (i.e. interview without test-drive and feedbacks from the presentations) implied that the four revealed strategies cover most frequently driving strategies applied by different drivers on freeways. Moreover, as mentioned earlier, the complementary studies provided a very good overview of the drivers' incentives for following a strategy. For instance, a lane leading strategy was adopted for comfort, but also for safety. However, different people choose different lanes for safety reasons. As an example, one interviewee addressed that he does not feel safe while driving behind a truck on the right lane. On the contrary, another driver mentioned that in congestion she prefers to drive behind the truck because she feels safer (the accelerations and decelerations are smoother). The same argument was also valid for the middle and the most left lane. A driver argued that the safest lane is the left lane, since you may avoid the merging area and dangerous maneuvers in the weaving zone. Another participant had an opposite opinion and mentioned that the middle lane is the safest lane because the driver is neither on the fast lane nor on the right lane with merging maneuvers. Some drivers choose a lane based on their information regarding downstream of the road. In case of a left lane drop, they choose the right lane and in case merging cause problem they choose the left lane. All the aforementioned cases describe the lane leading

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Table 2
Empirical data on the mandatory lane changes for the 10 drivers participated in the test-drive.

	1	2	3	4	5	6	7	8	9	10	Median
Merging											
Southbound											
Speed at merge (s)	96	84	87	77	97	91	87	110	85	94	89
Time on merging lane, T_1 (s)	5	1	2	29	5	2	3	2	3	4	3
Total time to pass merging area, T_2 (s)	21	24	22	27	23	28	23	20	30	22	23
Percentage (%)	24	4	9	107	22	7	13	10	10	18	12
Northbound											
Speed at merge (km/h)	84	81	99	86	85	95	91	94	82	85	86
Time on merging lane, T_1 (s)	5	8	4	12	6	5	3	3	3	3	5
Total time to pass merging area, T_2 (s)	14	16	11	15	15	14	15	13	15	15	15
Percentage (%)	36	50	36	80	40	36	20	23	20	20	36
Diverging											
Southbound											
Speed at merge (km/h)	96	80	80	81	83	92	85	77	74	71	81
Time at right lane before merging lane, T_3 (s)	38	51	97	34	53	43	69	41	184	175	52
Time on right lane next to merging lane, T_4 (s)	4	5	4	6	4	5	6	5	4	4	5
Total time to pass merging area, T_5 (s)	11	11	12	12	12	11	12	12	13	13	12
Percentage (%)	36	45	33	50	33	45	50	42	31	31	39
Northbound											
Speed at merge (km/h)	99	89	102	85	99	110	95	99	93	99	99
Time at right lane before merging lane, T_3 (s)	42	10	9	15	80	14	18	13	14	57	15
Time on right lane next to merging lane, T_4 (s)	5	9	4	5	6	4	4	6	6	12	6
Time on closed peak hour lane to cross merging, T_5 (s)	–	–	4	4	4	3	3	4	–	–	4
Total time to pass merging area, T_6 (s)	24	27	17	23	20	15	18	16	26	25	21
Percentage (%)	21	33	24	22	30	27	22	38	23	48	25

strategy, but with different motivations. Similarly, comfort could lead to a speed leading strategy (using a cruise control, only need to consider lane changing, and no speeds) or a lane leading strategy (only need to consider the speed of the predecessor, and no lane changes).

For the diverging mandatory lane changes, the strategy "do not miss the exit" can be implemented in a driving simulation package right away. This is already present in several packages. This study showed that drivers are hesitant to overtake from 1500 m before the start of the merging lane and like to be in the right lane from at least 500 m upstream of the starting point of the ramp, but for some ramps that might be considerably more.

The next research steps are to find which fraction of drivers uses which strategy (e.g. "30% of the drivers have a lane leading strategy"). This is not a straightforward task. Currently, we are testing the developed model in a micro-simulation environment by considering different penetration rates for the four revealed strategies. Calibrating the model is a future research direction. Big data (microscopic data) could be a solution, but perhaps different collective traffic patterns emerge for different fractions. Afterwards, the different elements of the driving strategy need quantification (e.g. "the lowest speed for which drivers in the lane leading strategy do not change lane is stochastic with normal distribution of 90 km/h and at standard deviation of 5 km/h"). This is ongoing work.

6. Conclusion

In this study, drivers were asked to participate in a test drive which was recorded on video. Afterwards, interviews with these drivers were held. Moreover, another group of participants was questioned without test drive. This lead to a categorization of lane change strategies. The following four strategies were identified: (1) speed leading, (2) speed leading with overtaking, (3) lane leading, (4) traffic leading. Presentation of these categories to over 150 people, drivers and traffic engineers, did not reveal additions to these four categories. It did provide more insight for the motivations to follow a particular strategy.

The revealed strategies in this study might be implemented in driving simulation packages. Generally there are different classes of drivers, which can not only be characterized by a different parameter set in the same driver models. We found distinct strategies regarding speed and lane choice. Especially, the relation between speed and lanes is currently not in most models. We found that there is not a single desired speed, but this changes with the lane and with traffic conditions. These findings are relevant for the modeling of multi-lane traffic control, and especially if control measures are being applied. A lane change ban might influence the desired speed, or strict speed check might influence the lane change behavior, but possibly in a completely different way than if predicted by the regular software packages, where longitudinal and lateral behavior are disconnected.

There is limited number of test-drivers that drove with an opened peak hour lane. Lane flow distribution plots show that the lane is underutilized. The test-drives showed that drivers are not aware of the opened lane, and do not know that the solid line can be crossed. The drivers did not notice the opened peak-hour lane on the merging lane in time so they changed toward the mainline. The road authority could hence improve the use of the peak hour lane by improving communication on its usage. In the interviews without the test-drive, no one indicated that he was unaware of the regulations regarding the peak-hour lane.

The sample size is too small to perform statistically relevant tests. For larger samples, it would be interesting to check whether there is a correlation between the merge location and the driver, i.e. whether the same drivers always merge early. Also relations between speed and merging location would be interesting. The results of these strategies on an aggregated level are unknown. Only if implemented in a traffic simulation program one can find the effects. On-going research is investigating the impact of the forenamed driving strategies on freeway traffic operations in a microscopic simulation environment.

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References

Aghabayk, K., Moridpour, S., Young, W., Sarvi, M., Wang, Y., 2011. Comparing heavy vehicle and passenger car lane changing maneuvers on arterial roads and freeways. Transp. Res. Rec.: J. Transp. Res. Board 2260, 94–101.

Ahn, S., Cassidy, M., 2007. Freeway traffic oscillations and vehicle lane change manoeuvres. In: Allsop, R.E., Bell, M.G.H., Heydecker, B.G. (Eds.), Proceedings of the International Symposium of Transportation and Traffic Theory. Elsevier, Amsterdam, pp. 691–710.

Cassidy, M., Rudjanakanoknad, J., 2005. Increasing the capacity of an isolated merge by metering its on-ramp. Transp. Res. Part B 39 (10), 896–913.

Daamen, W., Loot, M., Hoogendoorn, S.P., 2010. Empirical analysis of merging behavior at freeway on-ramp. Transp. Res. Rec.: J. Transp. Res. Board 2188 (1), 108–118.

Dutch Public Prosecutor, 2010. <https://www.om.nl/actueel/nieuwsberichten/@83914/nieuwe-ergernis-top/>.

Gipps, G.P., 1986. A model for the structure of lane changing decisions. Transp. Res. Part B: Methodol. 20, 403–414.

Hidas, P., Wagner, P., 2004. Review of data collection methods for microscopic traffic simulation. In: Proceedings of World Conference on Transport Research, Istanbul, Turkey.

Hidas, P., 2005. Modelling vehicle interactions in microscopic simulation of merging and weaving. Transp. Res. Part C 13 (1), 37–62.

Kerner, B., Rehborn, H., 1996. Experimental features and characteristics of traffic jams. Phys. Rev. E 53 (2), 1297–1300.

Kesting, A., Treiber, M., Helbing, D., 2007. General lane changing model MOBIL for car-following models. Transp. Res. Rec.: J. Transp. Res. Board, 86–94, No. 1999.

Kita, H., Fukuyama, K., 1999. A merging-giveaway behavior model considering interactions at expressway on-ramps. In: Proceedings 14th International Symposium on Transportation and Traffic Theory, pp. 173–187.

Knoop, V.L., Hoogendoorn, S.P., Yasuhiro, S., Buisson, C., 2012. Quantifying the number of lane changes in traffic: empirical analysis. Transp. Res. Rec. J. Transp. Res. Board 2278, 31–41.

Knoop, V.L., Keyvan-Ekbatani, M., Daamen, W., 2015. Hidden Strategies of Driving Behavior on Freeways. In: Transportation Research Board 94th Annual Meeting (No. 15-4074).

Kondyli, A., Elefteriadou, L., 2009. Driver behavior at freeway-ramp merging areas: focus group findings. Transp. Res. Rec.: J. Transp. Res. Board 2124 (1), 157–166.

Kondyli, A., Elefteriadou, L., 2011. Modeling driver behavior at freeway-ramp merges. Transp. Res. Rec.: J. Transp. Res. Board 2249 (1), 29–37.

Laval, J.A., Daganzo, C.F., 2006. Lane changing in traffic streams. Transp. Res. Part B: Methodol. 40 (3), 251–264. http://dx.doi.org/10.1016/j.trb.2005.04.003.

Marczak, F., Daamen, W., Buisson, C., 2013. Merging behaviour: empirical comparison between two sites and new theory development. Transp. Res. Part C: Emerg. Technol. 36, 530–546.

Mauch, M., Cassidy, M.J., 2002. Freeway traffic oscillations: observations and predictions. In: Taylor, M.A.P. (Ed.), Proceedings of the15th International Symposium on Transportation and Traffic Theory. Pergamon-Elsevier, Oxford, UK, pp. 653–674.

Moridpour, S., Mazloumi, E., Sarvi, M., Rose, G., 2012. Enhanced evaluation of heavy vehicle lane restriction strategies in microscopic traffic simulation. J. Transp. Eng. 138, 236–242.

Ossen, S., Hoogendoorn, S.P., Gorte, B.G.H., 2006. Interdriver differences in car-following: a vehicle trajectory-based study. Transp. Res. Rec.: J. Transp. Res. Board, 121–129, No. 1965.

Prevedouros, P.D., Wang, Y., 1999. Simulation of large freeway and arterial network with CORSIM, INTEGRATION, and WATSim. In: Proceedings of 78th Annual Meeting, Transportation Research Board, Washington, DC.

Sen, B., Smith, J.D., Najm, W.G., 2003. Analysis of Lane Change Crashes. In: John, A. (Ed.), Volpe National Transportation Systems Center, Cambridge, MA. DOT-VNTSCNHTSA-02-03.

Schakel, W.J., Van Arem, B., Knoop, V.L., 2012. LMRS: an integrated lane change model with relaxation and synchronization. In: Proceedings of the 91st Annual Meeting of the Transportation Research Board.

Sun, D.J., Elefteriadou, L., 2011. Lane changing behavior on urban streets: a focus group-based study. Appl. Ergonom. 42 (5), 682–691.

Toledo, T., Koutsopoulos, H.N., Ben-Akiva, M.E., 2003. Modeling integrated lane changing behavior. Transp. Res. Rec. J. Transp. Res. Board 1857, 30–38.

Toledo, T., Koutsopoulos, H.N., Ahmed, K.I., 2007. Estimation of vehicle trajectories with locally weighted regression. In: Proceedings of the 86th Annual Meeting of the Transportation Research Board, Washington D.C.

Tracz, M., Gaca, S., 2009. Influence of various restrictions on speed-flow models. Transp. Res. Rec.: J. Transp. Res. Board 2124 (1), 167–177.

Treiber, M., Hennecke, A., Helbing, D., 2000. Congested traffic states in empirical observations and microscopic simulations. Phys. Rev. E 62, 1805.

Zheng, Z., 2014. Recent developments and research needs in modeling lane changing. Transp. Res. Part B: Methodol. 60, 16–32.

Zheng, Z., Ahn, S., Monsere, C.M., 2010. Impact of traffic oscillations on freeway crash occurrences. Accident Anal. Prev. 42, 626–636.

Zheng, Z., Ahn, S., Chen, D., Laval, J., 2013. The effects of lane-changing on the immediate follower: Anticipation, relaxation, and change in driver characteristics. Transp. Res. Part C 26, 367–379.

www.autosnelwegen.net, 2014.