Lane Change Strategies on Freeways: A Microscopic Simulation Study

Mehdi Keyvan-Ekbatani, Victor Knoop, Vincent Grébert and Winnie Daamen

Abstract Understanding the influence of lane changing manoeuvres on the capacity, stability, and breakdown of traffic flows is a crucial issue. In a recent study, four distinct lane change strategies on freeways have been found: (1) Speed Leading; (2) Speed Leading with Overtaking; (3) Lane Leading; (4) Traffic Leading. To the best of our knowledge, combining speed choice and lane preference is not currently considered in most driving behaviour models. The principal aim of this paper is to investigate the impact of the forenamed lane change strategies on freeway traffic operations. The developed strategy-based lane change model has been implemented in a microscopic simulation environment. The study revealed that different lane change strategies may have various impact on the lane flow distribution and consequently on the freeway capacity. It has been seen that an unbalanced distribution of flow on a multi-lane freeway may lead to reduction of capacity. In addition, it has been found that the lane change rate variates under different lane change strategies. The highest traffic stability has been observed under speed leading and speed leading with overtaking strategies.

1 Introduction

Microscopic simulation tools might be applied in various traffic and transportation studies. They can be utilised for analysing traffic incidents or providing a virtual environment to evaluate new traffic management policies and evaluating their impacts.

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Modelling of the movement of vehicles on freeways is mimicked by a combination of a longitudinal (car-following) and a lateral (lane change (LC)) model. The validity of the aforementioned microscopic sub-models is currently a challenging issue. Comprehending the influential factors of the driver's lane change behaviour and the corresponding decisions seems to be an essential issue for developing realistic and accurate models.

Knoop et al. [3] addressed that there are large discrepancies between the principles modelled and the observations for discretionary lane changes (DLC). Empirical studies have revealed that drivers show different driving behaviour in practice (see [2] for lane changing and [7] for car-following behaviour).

Without asking people, the motive and stimulus behind the lane change decision process cannot be known. Thus, Kondyli and Elefteriadou [5] applied interview techniques for a study on driving behaviour in merging areas. Later, the same authors conducted a test-drive with an instrumented vehicle [6]. Keyvan-Ekbatani et al. [2] combined an interview-based study with a test-drive (using an instrumented car). The test-persons were requested to drive on a freeway sketch in a camera-equipped vehicle. Immediately after the drive, the participants were interviewed and questioned regarding their decisions (i.e. for changing lane or not) during the test. The study led to a categorisation of lane change decision process (i.e. strategies). Four distinct lane change strategies for DLC behaviour were unveiled based on the aforementioned study: (1) *Speed Leading*; (2) *Speed Leading with Overtaking*; (3) *Lane Leading*; (4) *Traffic Leading*.

The research objective is to study the impact of the forenamed strategies on the traffic flow characteristics. The four lane change strategies have been implemented in the microscopic simulation tool MOTUS [1]. A three-lane freeway stretch without considering any on- and off-ramps has been applied as a test-bed. It should be noted that this paper only focuses on the simulation part of the strategy-based lane change model and does not discuss the modelling and implementation details.

The remainder of the paper is organised as follows. The methodological details (i.e. brief introduction of the four lane change strategies and simulation set-up) are addressed in Sect. 2. The simulation results are presented in Sect. 3. Finally, a brief summary and conclusion are included in the last section.

2 Methodology

In this section, the four lane change strategies found in [2] are introduced briefly. Then, the defined simulation scenarios along with some technical details of the simulation set-up are discussed.

2.1 Lane Change Strategies

The four lane change strategies found in [2] (i.e. *Speed Leading*, *Speed Leading with Overtaking*, *Lane Leading* and *Traffic Leading*) are defined as follows:

Speed Leading: The drivers who follow this strategy choose a desired speed and try to keep it. They change lanes such that they can drive with their desired speed. Drivers choose their speed based on their driving style and preference. Drivers using cruise control are usually speed leading.

Speed Leading with Overtaking: Drivers driving with this strategy choose a speed and stay at the rightmost lane possible with that speed. In case the speed on that lane decreases (i.e. presence of a vehicle with a lower speed), the driver will change lanes. In other words, the drivers applying this strategy consider this action as an overtaking and increase their speed while being in the more left lane. The motivation for increasing the speed is that ‘an overtaking manoeuvre takes less time’.

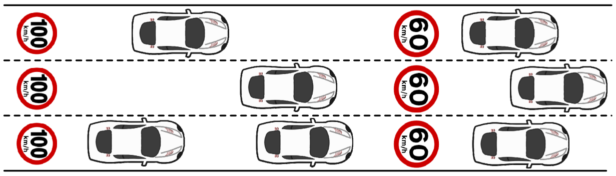
Lane Leading: In this strategy drivers choose a lane based on their perceived relative driving speed. In other words, drivers settle for a lane and adapt their speed to that of vehicles in that lane. The combination of speed and lane choice is the incentive in this strategy.

Traffic Leading: Drivers follow the speed of the other drivers in a stream. There is no desired speed or lane in this strategy. Drivers may join faster vehicles or slower ones. Faster drivers might drive faster in busier conditions, since there is a higher probability of existence of a driver with higher desired speed.

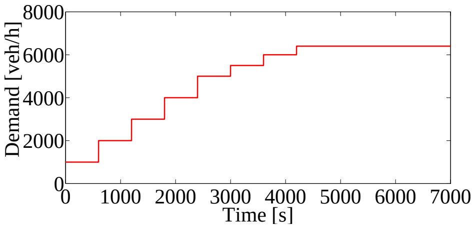
2.2 Simulation Set-up

The main goal of this paper is to investigate the impact of the different lane change strategies on the traffic flow characteristics. To this end, the strategy-based lane change model has been implemented in a microscopic simulator. More specifically, lane flow distribution, lane change rate, creation of stop-and-go wave and the road capacity under each lane change strategy have been investigated. Four different simulation scenarios have been defined. In scenarios (1)-(3), 100% of drivers drive with the strategies *Speed Leading*, *Speed Leading with Overtaking* and *Lane Leading*, respectively. Scenario (4) includes 50% of the drivers driving with *Traffic Leading* and 50% with *Speed Leading* strategy. Drivers with *traffic leading* adapt their speed to other drivers. However, if all drivers are traffic leading, no reference speed is available. This implies that a flow composition cannot only consist of *traffic leading* vehicles. We therefore choose a traffic composition of 50-50. A longitudinal neighbourhood of 100 m from the front and 50 m from the back of the vehicle linearly distance-weighted (highest weight for the closest vehicle) has been considered. For the lateral neighbourhood, the vehicles on the same lane, adjacent lane and next to the adjacent lane have the weights 1, 0.8 and 0.6. If the vehicle drives on the middle lane, the left and the right lanes are equally weighted (i.e. 0.8). Trucks are not considered in these scenarios.

MOTUS is an open-source microscopic traffic simulation package which is developed in java. MOTUS is stochastic, thus different simulation runs (replications) with different random seeds may lead to different results. For this reason, 10 different replications have been utilised for each investigated scenario and then the average value of the 10 runs for each simulation result has been calculated. As shown in Fig. 1a, a three-lane freeway stretch (7 km) without any off- and on-ramp has been modelled in the microscopic simulation MOTUS. To create a bottleneck (for reproducing a part of the congested branch of the fundamental diagram), a speed limit has been imposed on the last 2 km of the modelled road layout. A step-wise demand increase has been implemented for the two-hour simulation (see Fig. 1b). The car following model utilised for this simulation is IDM+ [8]. In scenarios (1), (2) and (4) a speed limit of 100 km/h for the first 5 km and for scenario (3) different speed limits (i.e. 100 km/h, 85 km/h and 70 km/h for the left, middle and right lanes, respectively) have been set. The speed limit in the last 2 km of the freeway is 60 km/h in all scenarios. The desired speed of the drivers are produced based on a Gaussian distribution function with an average value of 100 km/h and a standard deviation of 10% (or 10 km/h).

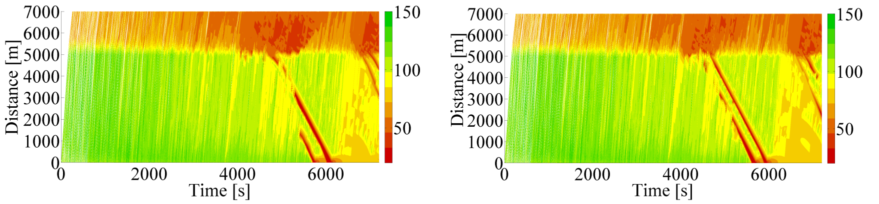


(a) Three-lane freeway stretch applied as test-bed

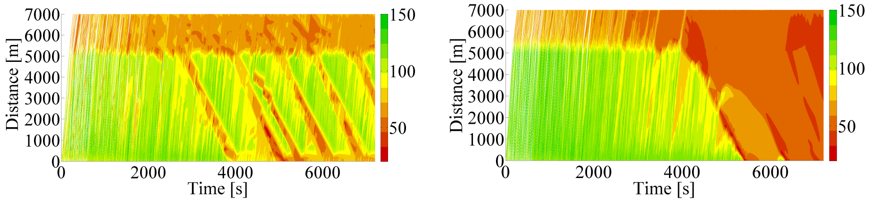


(b) Two-hour demand profile

Fig. 1 Simulation set-up



(a) Speed leading (b) Speed leading with overtaking



(c) Lane leading (d) Speed leading + traffic leading

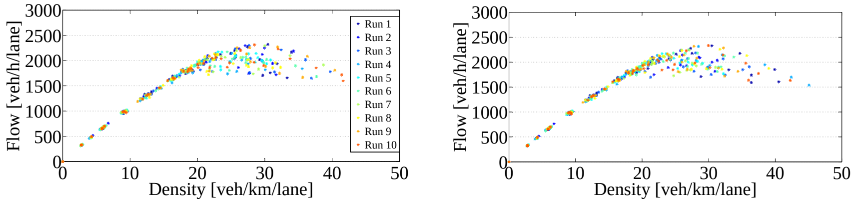
Fig. 2 Speed contour plots for the four simulation scenarios

3 Simulation Results

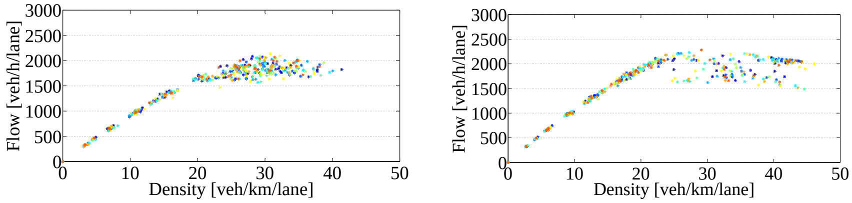
In this section, we describe the simulation results for the previously introduced scenarios. First, we discuss the speed contour plots (for one replication), followed by the fundamental diagram, the lane flow distribution and the lane change rates. The trajectory data of a section of 1000-5000 m has been considered for derivation of the last three plots.

Figure 2a-d display the speed contour plots for scenarios (1) to (4), respectively. In all scenarios, congestion starts at the bottleneck (after 5 km) and propagates upstream. As it is realised from Fig. 2a and b, the instabilities (stop-and-go waves) are similar for the first two scenarios. For scenario (3), a different pattern of stop-and-go waves can be seen. The traffic conditions showed more unstable under this lane change strategy (more waves are visible) compared to two previous scenarios. The most congested traffic condition can be seen in scenario (4). After 4000 s the entire freeway stretch is affected by the congestion created upstream of the bottleneck. This might be due to the speed adaptation concept of this scenario. The drivers adapt their speed to the speed of the vehicles in their neighbourhood, thus reduction of speeds at the bottleneck might affect the drivers upstream more and faster.

The fundamental diagrams for the different simulation scenarios are found in Fig. 3a-d, (10 different replications shown by different colours). A rough estimation of the capacity might be determined by taking the maximum value in the fundamental diagrams. The highest observed flows of the *speed leading*, *speed leading with overtaking* and *traffic leading* strategies appear to be larger than the *lane leading* strategy. All scenarios except scenario (3) reach a flow value of around 2500 veh/h/lane. The flow in scenario (3) does not exceed 2000 veh/h/lane (see Fig. 3c).



(a) Speed leading (b) Speed leading with overtaking



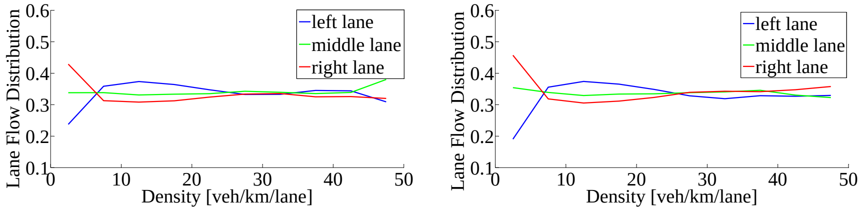
(c) Lane leading (d) Speed leading + traffic leading

Fig. 3 Fundamental diagrams for the four simulation scenarios

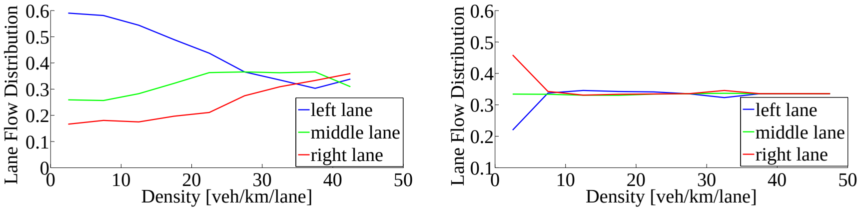
This might be due to the suboptimal distribution of flow over lanes and consequently congestion occurrence on specific lanes. In the cases of *speed leading* strategies, drivers will merge into the faster lane if needed and also merge back to the right, and high flows will be obtained in all lanes.

For the *traffic leading* strategy, much more noise and scatter have been found in the fundamental diagram after the onset of congestion (around the density of 30-40 veh/km/lane) compared to the other three strategies. Apparently, drivers accept different speeds at the same densities. This is in line with the fact that drivers adapt the speed in this strategy.

Figure 4 displays the lane flow distribution on different lanes vs. density in the four introduced simulation scenarios, averaged over 10 different runs. As it can be realised from Fig. 4a and b, under *speed leading* and *speed leading with overtaking* strategies, most of the traffic is on the right and the middle lane in the low-flow conditions. In higher densities, gradually, traffic utilises the middle lane and the median lane more. A similar pattern has been found in empirical data for Dutch freeways [4]. In the study with real data [4], it was found that near capacity, the left lane has an excess load, because drivers do want the ‘spots in the overtaking lane’. This is partially found in the simulation data: indeed, there is the high flow in the left lane, but this at densities which are slightly lower than capacity. In *speed leading with overtaking*, the reduction of right lane usage is less sharp than in speed leading. In the *lane leading* strategy, the flow distribution is not as balanced as in the other scenarios. This might be one of the reasons of the lower capacity compared to the other scenarios (see Fig. 3). In *traffic leading* strategy, drivers distribute quite well over the lanes. This could be a reason of the high capacity despite of the more congested traffic state.



(a) Speed leading (b) Speed leading with overtaking



(c) Lane leading (d) Speed leading + traffic leading

Fig. 4 Lane flow distribution for the four simulation scenarios (averaged over 10 runs)

Figure 5 shows the lane change rate vs. density for each of the scenarios. For the *speed leading* strategy, the number of lane changes depends strongly on the density. For lower densities, drivers change lanes often (approximately 0.5 lane change per km). As the densities increase, drivers keep their lane for a longer time. This can be explained by the fact that the speeds in all lanes become similar, taking away the necessity of a lane change. A similar pattern is visible for the *speed leading with overtaking strategy*. As anticipated, the number of lane changes for the *lane leading* strategy is very low. Note that the number of lane changes increases with an increasing density. This can be explained by the fact that if there are no other vehicles, the *lane leading* drivers will follow the lane. The most remarkable pattern is found for the *traffic leading* strategy. In cases of low density, drivers tend to follow other drivers, which might have a different speed. Hence, the lane changes are relatively high. For higher densities, the number of lane changes decreases to the lowest values found for all strategies (they even stop changing lane). *Traffic leading* drivers will simply follow the traffic, and if there are drivers in front, driving at a reasonable speed, they have no incentive to leave the lane and change lane, since there is neither a desired lane where they should head to, nor a desired speed.

4 Conclusions

In this paper, the recently found lane change strategies are implemented in a microscopic simulation environment. The impact of each strategy on the freeway traffic operations has been investigated. In particular, it has been realised that under dif-

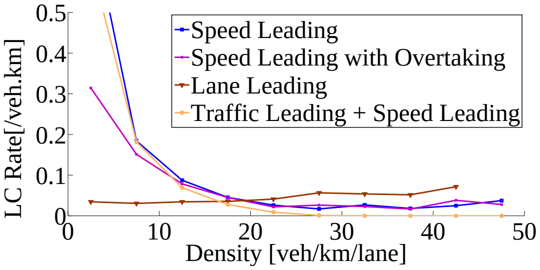


Fig. 5 Lane change rate for the four simulation scenarios (averaged over 10 runs)

ferent lane change strategies, various stop-and-go waves can occur. Under *speed leading* and *speed leading with overtaking* strategies the highest stability has been observed. In addition, for higher densities, the number of lane changes decreases to the lowest values in all strategies. Various lane flow distributions have been found under different lane change strategies. It has been seen that an unbalanced distribution of flow on a multi-lane freeway may lead to reduction of capacity.

Future research directions in this area include investigating the traffic operations under different combinations of lane change strategies, sensitivity analysis of the model parameters, validation and calibration of the model.

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