Impact of automated driving regulations on traffic flow: The case of Automated Lane-Changing

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SHORT SUMMARY

International regulations on automated driving systems (ADS) are now being introduced, representing an important milestone in the deployment of connected, cooperative, and automated mobility systems. Those regulations focus on safety, and only marginally on traffic efficiency. Yet, they introduce restrictions on the operation of those systems, inevitably influencing traffic flow. An example is the UN Regulation 157 on lane changing, setting a critical distance from an approaching vehicle in the target lane.

Analysis based on naturalistic data shows that human drivers often perform lane-changing maneuvers that do not fulfill these regulation requirements. The percentage of those aggressive lane-change maneuvers is increased in situations of traffic flow breakdown. A simulation framework is introduced to investigate further the impacts of the regulatory provision. The main results show that the progressive introduction of automated driving systems benefits the traffic flow and increases the average traveling speed of vehicles in congested conditions.

Keywords: Automated and connected driving, Lane-changing, Traffic flow theory.

1. INTRODUCTION

The introduction of connected and automated vehicles (CAVs) can directly impact the traffic flow (Makridis et al., 2020). Several studies have so far tried to anticipate the effects of introducing CAVs on traffic. Very few of them have instead tried to understand the effects on traffic flow of regulatory requirements currently being developed (Mattas et al., 2021), and mainly focus on safety. An obvious example is provisions regarding lane changing, that can impact traffic flow and safety (Rahman et al., 2013). While lane-changes can have obvious benefits in harmonizing the flow, and in allowing vehicles to choose the lane that better accommodates their speed preferences, they have been found to bring also negative impacts on the flow (Laval & Daganzo, 2006).

Recently, the first international regulations regarding automated driving systems have been introduced. Among them, the UN Regulation 157 regarding SAE level 3 (SAE, 2021) automated highway systems is already adopted and vehicles with such systems are currently being type-approved (*UN*, 2021). The regulation regards systems with a very strict Operational Design Domain (ODD), only being allowed to be activated on highways. In the first version of the regulation, automated lane-changing maneuvers were prohibited, and the speed was limited to 60 km/h. The term used to describe the systems is Automated Lane Keeping Systems (ALKS). However, in the first amendment of the regulation, in 2022 (*UN*, 2022), the speed limit was lifted to 130 km/h, and the possibility for automated lane changes was introduced. In particular, the Regulation introduces a specific set of requirements regarding lane changes. One of them concerns the distance to the new follower vehicle must be larger than a specific critical distance threshold. The requirement has been motivated by safety concerns, to avoid automated systems that can carry out reckless cut-in maneuvers. Nevertheless, such restrictions directly impact traffic dynamics, especially for higher penetration rates of ALKS systems. The same restriction exists on regulations on level 2 systems, such as UN Regulation 79 (UN, 2018).

In the present work, we investigate the possible implications of this specific requirement through naturalistic data and simulation. First, the critical safety distance is compared with what is considered acceptable by human drivers. The highD dataset (Krajewski et al., 2018), a collection of vehicle trajectory data collected on German highways, is used to analyze the behavior of human drivers on highways and understand the potential differences between human drivers and ALKS systems in lane-changing. To further investigate the potential impacts of the introduction of ALKS, and since those systems are not yet widely available in the market, a simulation framework has been developed for assessment purposes in generalized scenarios with penetration rates of ALKS. The results show that enforcement of the restriction policy can improve traffic conditions, even for small market penetration rates. The density is decreasing and the average speed in congested conditions is increasing when keeping a constant arrival rate. Moreover, the average number of lane changes does not change significantly, showing evidence that the improvement of traffic conditions makes safer lane changes easier.

2. METHODOLOGY

ALKS required distance

For an ALKS system to follow through a lane change maneuver, the net distance between the ALKS system and the follower in the adjacent lane has to be larger than a critical distance s_{crit}, according to **eq.1**:

$$s_{crit} = (u_{rear} - u_{ALKS})t_{reaction} + \frac{(u_{rear} - u_{ALKS})^2}{2a_{rear}} + u_{ALKS} * t_G$$

where u_{rear} and u_{ALKS} the speeds of the rear vehicle and the ALKS vehicle, $t_{reaction}$ the time for the other vehicle to react, set to be 0.4 s as long as the ALKS vehicle had turned on the turn indicators for sufficient time, a_{rear} the deceleration of the rear vehicle is set to 3 m/s^2, and t_G the safe time gap of 1 s.

Simulation framework

The proposed simulation framework in this work allows for the simulation of road sections of multiple lanes, using different car-following and lane-changing models. Vehicles of different types can coexist in each simulation run, accommodating the simulation of both cars and trucks. Each vehicle is a different agent, with the possibility to have different characteristics from others. The simulation step for each simulation is 0.1 s. A random seed parameter is also included, so different replications can be run, to account for the stochasticity in the experiment.

The IDM model has been used with the standard parameters according to Treiber et al. (Treiber et al., 2000). The desired speed is different for each vehicle, coming from a normal distribution with a mean value of 30 m/s and 23 m/s, with a standard deviation of 6 m/s and 2 m/s, for cars and trucks respectively. A simple lane-changing model is selected, based on the MOBIL model (Kesting et al., 2007), avoiding the cooperation terms. The acceleration benefit required to change a lane was chosen to be 0.55 m/s^2, with a bias of 0.1 m/s^2 towards the rightmost lane. Then, a lane change can be carried out if there is sufficient space in the adjacent lane. As soon as a lane change decision is made, the vehicle starts a lane-changing process that lasts 2 seconds. For 1 second, the vehicle occupies space in both lanes, affecting both the follower in the previous and the next lane. For the last second of the lane-changing maneuver, it is assumed that the vehicle is already in the new lane and adjusting its lateral position inside it, thus, the previous follower in the other lane is no longer affected. In the cases of simulating ALKS vehicles, the process is the same, with one additional restriction in the final stage. After the lane-changing decision is made, the distance to the new follower is calculated, and compared to the mandated minimum distance for ALKS vehicles. If the distance is below the regulatory threshold the decision is rejected.

Case-study

The highD dataset (Krajewski et al., 2018) has been investigated to study the lane-changing behavior of real drivers. The dataset consists of 60 vehicle trajectory files concerning German highways at six different locations near Cologne. Human lane-changing behavior is investigated based on all data. For the simulation framework, the most congested file and direction has been used, namely file 25. The length of the section in the observation is 434 m, the duration of the observation is 1178 s, and the ratio of trucks is 13.6 %. Hyperparameters of the simulation framework have been manually calibrated to fit the specific file.

The main performance metrics for the current investigation are the average flow of the section, the average density, the average speed, and the number of lane changes. The method for calculating the performance was the same both for the observation and the simulation data, as in both cases detailed vehicular trajectories are available. The flow is calculated as the number of vehicles exiting the section under investigation, divided by the duration of interest and by the number of lanes. For the density, the number of vehicles in the section is divided by the length of the section and the number of lanes, calculated for each simulation step. The average density in the network for all simulation steps is calculated. The average speed is directly calculated by the speeds of the vehicles in the section under investigation. Finally, the number of lane changes is directly counted.

In the simulations, six different scenarios are tested, with a percentage of ALKS vehicles being 0, 20, 40, 60, 80, and 100% in which all vehicles carry out lane changes only if the ALKS minimum distance restriction is satisfied. For each one, 30 different simulations are run, using different random seeds.

The current study considers only discretionary lane changes and not mandatory ones. The relevant ADS systems only operate on highways. Therefore, mandatory lane changes are carried out by human drivers, and automation takes over only the discretionary ones.

3. **RESULTS**

HighD results

We isolated 7832 lane-changing maneuvers from the highD dataset. In 43 % of the cases, the distance at the time the vehicle crossed the lane markings was smaller than what the regulation would require for the ALKS vehicle. Such maneuvers will in this paper be characterized as non-compliant, although, such restriction does not hold for human drivers.

The flow-density relationship, as derived from the naturalistic data, is depicted in **Figure 1**. Each dot refers to a specific highD file and direction. The dots are colored according to the rate of ALKS non-compliant lane-changing maneuvers. When the density is lower than 15 veh/km/lane, the flow does not seem to be affected by that rate. On the other hand, when the density in the lane increases, the lanes where the rate is higher than 0.5 (red dots) are associated with smaller values of flow compared to the lanes with smaller rates (blue dots). The clear distinction shows a potential relationship between the flow breakdown and the rate of hard lane changes. However, it is not clear from the data if it is the congested conditions that give the drivers incentive to carry out hasty lane changes, or the reckless lane changes are the source of the flow breakdown, or both.

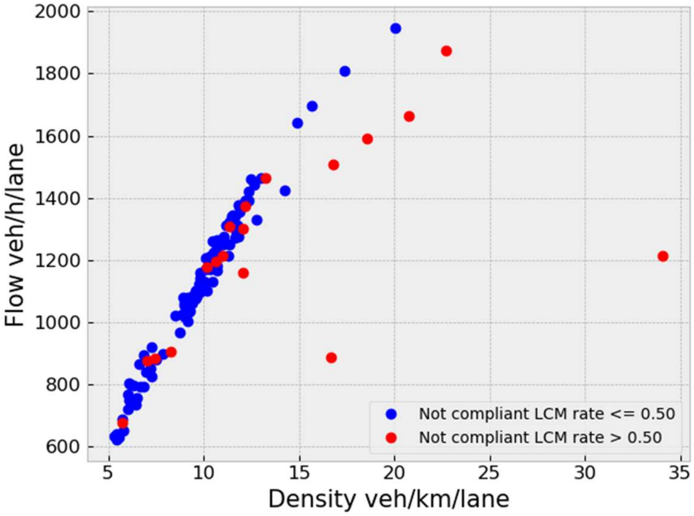

Figure 1. Flow-density diagram.

A specific case of a lane-changing maneuver creating a traffic disturbance is presented in **Figure 2**. The figure shows the space-time diagram for a specific lane. Each line represents a vehicle trajectory inside the specific lane. The vehicle trajectories in the diagram are colored based on the vehicles' speeds. A vehicle is cutting in, and its trajectory is colored black. It forces the following vehicle to decelerate. In particular, the following vehicle in the target lane starts reacting before the maneuver is complete, i.e. before the black line appears in the figure. This perturbation propagates upstream, creating a traffic wave. This figure gives an example of how a lane-changing maneuver can trigger a traffic oscillation, which in turn causes a loss in flow.

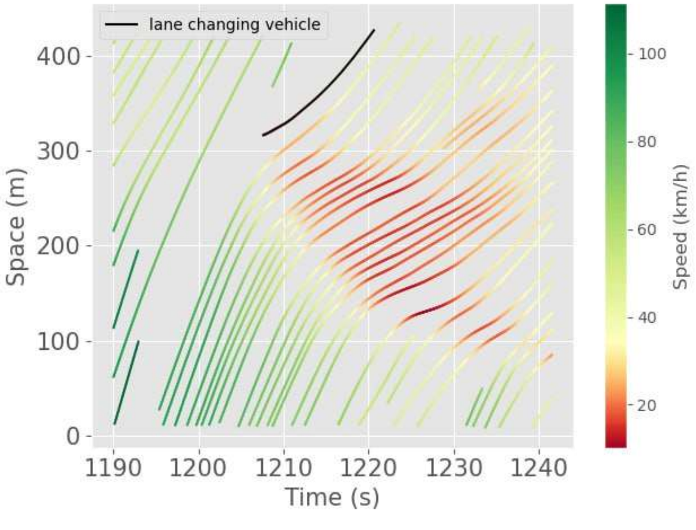

Figure 2. Space-time evolution for a group of vehicles in the same lane.

Simulation results

The results of the simulations are presented in **Figures 3** to **8**, for all performance metrics, in violin plots. In each case, the x-axis represents the percentage of ALKS vehicles, and the y-axis the value of the performance metric. For the simulations, given the 30 replications, a distribution is presented for each case. The observed values are denoted by blue dots, on the 0 % penetration rate position. The first observation is that the means of the distribution extracted for the baseline scenario are very close to the observed values.

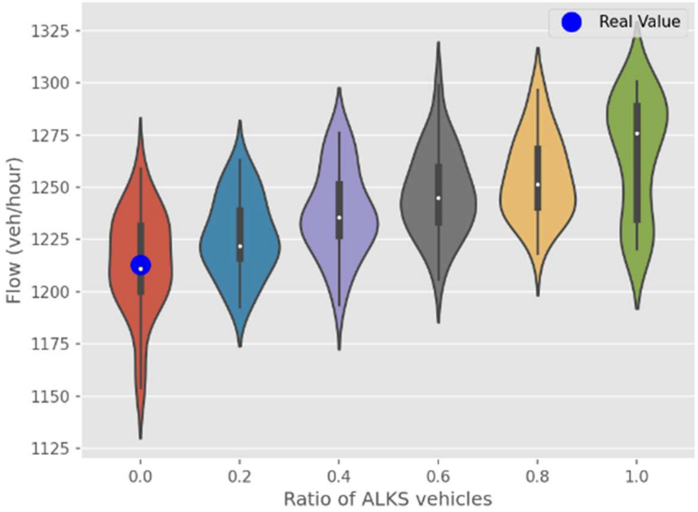

Figure 3. Distribution of traffic flow for the simulated cases compared to the real value

The traffic flow observed in the network is shown to be well reproduced, with the spread being around 150 veh/h for different random seeds in the base scenario. For increased percentages of ALKS vehicles, the flow has a mildly increasing trend. However, the flow in the simulation is limited by the arrival rate, which is set according to the observation.

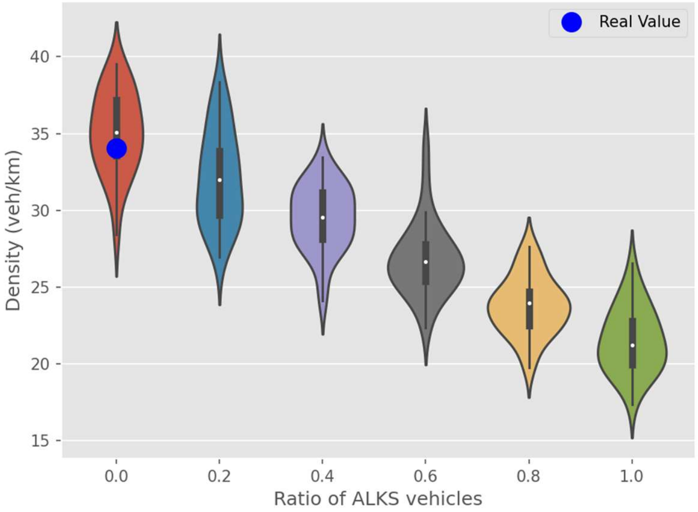

Figure 4 Distribution of average density for the simulated cases compared to the real value

The impact on density is shown in **Figure 4**. The benefit is obvious even for 20 % ALKS vehicles, which is the smaller percentage tested. The decreased density, in combination with the flow not being much affected, shows an effect on the average speed. Indeed, as shown in **Figure 5**, the average speed in the network is sharply increasing. This effect shows how with the increasing percentage of ALKS vehicles, traffic oscillations caused by lane changing were less frequent, and vehicles were able to keep higher speeds for longer periods.

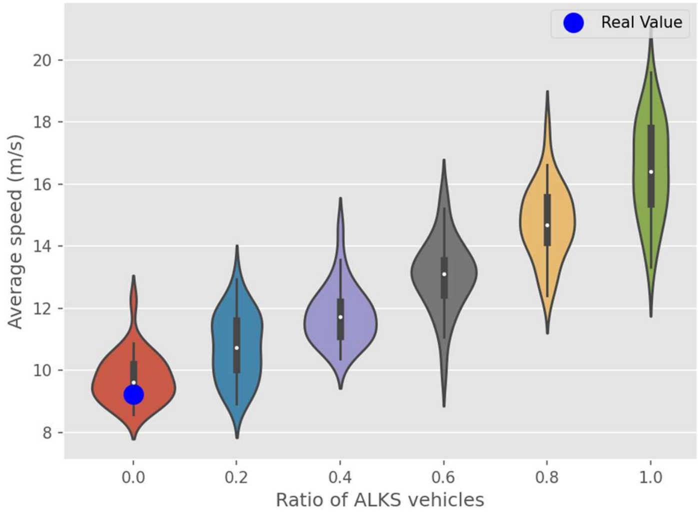

Figure 5 Distribution of average speed for the simulated cases compared to the real value

Finally, a very interesting result is presented in **Figure 6**, regarding the distributions of lane changes for the different percentages of ALKS vehicles. As mentioned, the spread in the number of lane changes for the different replications of the base scenario is very significant. This spread is decreasing with the increased percentage of ALKS vehicles in the network. However, the average number of lane changes for the different scenarios remains quite stable. Therefore, although lane changes are harder to carry out, the number of lane changes is not decreasing. This can be an effect of the decreased density in the section, so vehicles intending to change lane are able to do so because of the larger spaces between the vehicles.

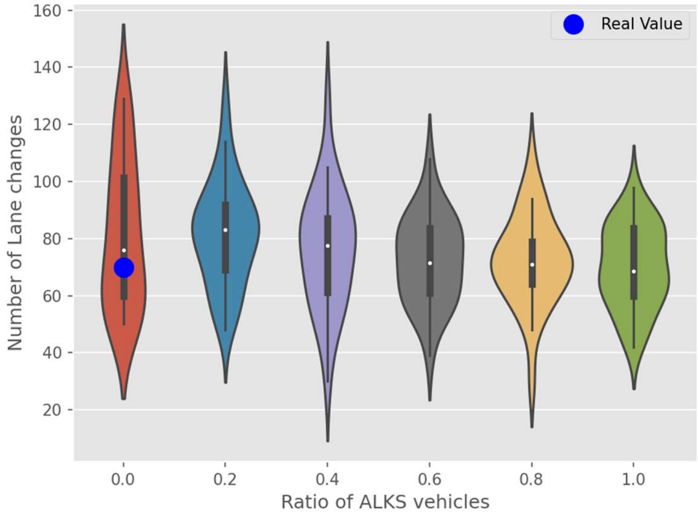

Figure 6 Distribution of the number of lane changes for the simulated cases compared to the real value

4. CONCLUSIONS

Recently, UN Regulation 157 was amended to include SAE level 3 vehicles operating on highways, defined as ALKS, able to make automated lane changes. A critical distance is defined as a regulation requirement, to ensure safe lane changing for those systems. In the present work, real data observations are used to show that human drivers regularly carry out lane change maneuvers with distances shorter than what is required for the ALKS systems. Moreover, the percentage of those lane changes that do not comply with the ALKS requirement is shown to be correlated to flow breakdown, on high densities.

A simulation is designed and used to carry out experiments, modifying only the lane-changing model, to abide or not by the Reg. 157 critical distance requirement. The scope has been to investigate the potential effect that restricting discretionary lane changes can have on the traffic flow. Results show that traffic conditions can be improved by those restrictions. The average speed for a congested section improves, even for a small penetration rate of ALKS vehicles. Moreover, keeping a constant arrival rate, and so the inflow, the average number of lane changes seems to be unchanged. Therefore, vehicles in slower lanes are still able to change lanes and choose the one more suitable for their desired speed, as larger gaps appear, due to the improvement of the traffic conditions.

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