Lane Change Manoeuvres for Automated Motorway Driving Applications

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ABSTRACT

To develop automated systems that can execute acceptable and comfortable lane changes on the motorway, it is useful to understand how lane changes are performed by human drivers, what factors influence the lane changes, and how they can be described parametrically. More specifically, it is important to understand the acceptable thresholds for parameters which are associated with the manoeuvre execution from a driver's perspective. Furthermore, the cognitive process of the intention and decision for a lane change needs to be addressed to provide a well-accepted automated lane change decision and timing. This work aims at gaining first qualitative insights into these aspects. Two small-scale on-road studies were conducted to initially collect data on the process of human lane change behaviour in different driving scenarios. Objective data has been collected by equipping a measurement vehicle with a broad sensor set. Qualitative subjective data was gathered through different survey methods. In the first study, both the driver and a co-driver were included by means of questionnaires. In the second study, the 'thinking aloud' method was utilised to gain a deeper insight into the driver's cognitive process. Based on the analysis of the objective data a parametric description of the lane change profile has been established. They can be used to generate automated lane change trajectories based on parameters from real data. For the evaluation of such automated lane change profiles, the implementation of driving studies in a high-dynamic driving simulator is useful and has been initially tested in an expert pilot study.

Keywords: Lane Change Manoeuvres, Automated Driving, Naturalistic Driving Studies, Driving Simulator.

1 INTRODUCTION

Automated motorway driving is a possible scenario for the introduction of automated driving features. Lane centring and adaptive cruise control systems combined already provide a basis for this use case. Adding automated lane changes would enable handling of most of the normal motorway driving situations. This paper describes some of the investigations aimed to identify automated lane change manoeuvre profiles for motorway driving that meet user requirements and expectations.

An important part of existing literature analyses lane changes is based on statistical investigations of naturalistic driving data (Fastenmeier, Hinderer, Lehning, & Gstalter, 2001; Hetrick, 1997). Many sources deal with mathematical modelling in order to recreate human lane change behaviour in traffic or driving simulations (e.g. Ehmanns, 2002; Kesting, Treiber, & Helbing, 2007). Others describe the use of these mathematical descriptions in automated driving functions (e.g. During & Pascheka, 2014). The data sources, level of detail and precision of the utilised measurement methods varied widely in these studies (Gipps, 1986; Hidas, 2002; Zheng, 2014).

For this work the lane change process has been structured into two phases (see Figure 1). The first is the decision phase that describes the cognitive process which leads to the decision to perform or not perform a lane change including all necessary assessments of the traffic situation and rough planning of the possible actions. The second is the execution phase, in which the actual lane change with all preparation actions is performed.

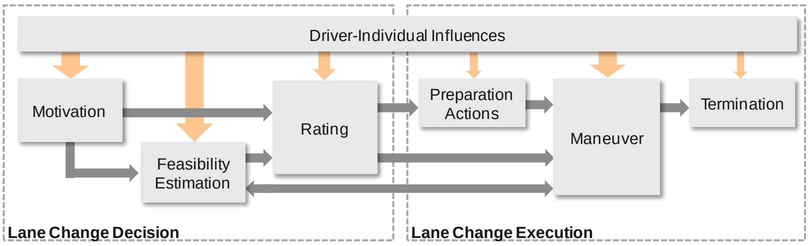

Figure 1: Defined structure of the lane change process

2 ON-ROAD STUDIES

As literature and available data sets did not cover the linkage between comprehensive and detailed sensor data and subjective information, two on-road studies have been conducted to generate a data base of manually performed lane changes, including a qualitative subjective and objective data collection describing the manoeuvres.

2.1 First On-Road Study

Besides the generation of a first set of detailed objective data, the goal of the first study was to gain a first insight into the subjective decision process as well as comfort and acceptance rating of lane change executions. Also, possible differences in subjective ratings between the driver and the co-driver should be revealed.

2.1.1 Participants and Apparatus

In total, $N = 10$ subjects ($n = 5$ female) participated in the study. Half of them were drivers (mean age of 33 years; mean annual mileage ≥ 15,000 km), the others were co-drivers (mean age of 24 years; mean annual mileage < 5,000 km) that did not drive during the whole study. Co-drivers were included to capture the perspective of passengers, because in automated vehicles their perspective on lane change appropriateness is relevant for customer acceptance. Each drive a driver and a co-driver were matched together resulting into five pairs. The study was performed in unsupported driving mode in a VW Passat CC, since natural driving behaviour needed to be captured, where the driver is responsible for accelerating, steering and braking. The vehicle was equipped with a sensor setup to monitor and log the vehicle environment as well as ego-vehicle variables. Two mid-/long-range RADAR sensors were used to log the positions of the surrounding traffic in front and behind the ego-vehicle. The bigger angular aperture of the sensor´s mid-range detection area guaranteed sufficient coverage of close vehicles in the neighbouring lanes. The vehicle´s motion state and global position was measured with a high-precision inertial measurement unit in combination with a differential positioning system. Furthermore, the access to the vehicle’s CAN bus of the vehicle allowed for acquisition of signals which described the driver vehicle interaction, e.g. steering angle, turn signal usage and accelerator and brake pedal values.

Questionnaires were used to evaluate the qualitative subjective input regarding the decision for/against and the execution of lane changes during the test drive. The drivers answered questions about (a) the arguments and intention for/against a lane change decision; (b) aspects to which they paid special attention; (c) the decisive reason to (or not to) perform the lane change. Co-drivers were asked about their agreement with as well as a reasons for/against a lane change decision. Furthermore, they answered questions about the execution of an occurred lane change (e.g. overall acceptability, sportiness, cooperation, and safety).

2.1.2 Procedure

The route had an overall distance of 134 km (about 30 km on Dutch motorway, remaining part on the German motorway) with an estimated driving time of 1.5 hours. If existing, the speed limit varied between 80 and 130 km/h. To increase the number of routing-based lane changes, drivers were requested by the experimenter to take exits and entrances along the course. The test drives were carried out at a low traffic density outside rush hours.

After a short introduction, the driver (driver's seat), co-driver (front passenger's seat) and experimenter (back seat) entered the vehicle. As soon as the driver entered the motorway, the experimenter announced the first lane change situation to be evaluated and asked the driver to memorise the central elements that influenced the driver's decision for/against a lane change decision (ego-vehicle position, environment etc.). In the meantime, the co-driver was asked to complete the questionnaire. Afterwards, the experimenter started to interview the driver. The next relevant situation was specified subsequently.

2.1.3 Subjective Results

Overall, N = 107 lane changes were subjectively rated and qualitatively evaluated. Regarding the decision process, Table 1 contains the main categories of reasons for a lane change decision as well as examples of the sub-categories mentioned by drivers and/or co-drivers. While each sub-category of the six main categories was named at least once by the drivers, co-drivers mainly focussed on reasons originating from speed regulation. That is, co-drivers did not identify environmental factors (e.g. cooperation, traffic rules, overview etc.) in their decision for a lane change. This result suggests that, in order to make an automated driving system comprehensible for a passenger, it may be advisable to inform passengers about relevant other environmental information they might otherwise miss.

Table 1 - Reasons for a lane change

Main category	# of sub-categories	Examples of sub-categories
Speed regulation	6	Maintaining velocity; Relative speed to other vehicles
Cooperation/Interaction	6	Faster vehicles approaching from behind; Go with flow of traffic
Traffic rules	4	Speed limit; Obligation to drive on the right
Strategy	7	Choice of route; Choosing faster lane
Space	1	Free target lane/sufficient space
Safety/Timing	6	Avoid hectic/risky manoeuvres; Good overview

2.2 SECOND ON-ROAD STUDY

The focus of the second on-road study was to gain further insight into the relevant aspects in the decision process.

Furthermore, an estimation for the overall timings of the cognitive process should be established. As a first approximation, this was again performed on a qualitative data level.

2.2.1 Participants and Apparatus

In total, *N* = 7 subject drivers (*n* = 2 female) with a mean age of 33 years and a mean annual mileage of 10,000-15,000 km participated in the study. The same test vehicle with the identical sensor setup was used as in the first on-road study.

2.2.2 Procedure

A 120 km route on a German motorway was chosen to focus on higher relative speeds on German motorways. If existing, the speed limit varied between 100 and 130 km/h. Time slots for the test drives were shifted at 8 AM or 3 PM to get to get into denser traffic conditions. Again, random exits were chosen by the experimenter in order to add routing considerations.

In contrast to the first study, this study was conducted with only the driver and an experimenter on board. In order to gain insights into the driver's cognitive process, the "thinking aloud" method was used. The drivers were encouraged to comment on all aspects which were relevant for their positive or negative lane change decision. They were asked to try to denote the point in time, where they feel, that a lane change will be necessary, to understand the time horizon of the lane change intention. The participants were asked to verbalise all their thoughts and considerations on their strategic and tactical actions with regard to their lane change or lane keeping behaviour using the categories of reasons for/against lane changes identified from the first study (see **Erreur ! Source du renvoi introuvable.**).

2.2.3 Subjective Results

In total *N=506* situational events have been analysed in this second study. The subjective results were mainly qualitative insights into the cognitive process and influencing aspects from the traffic environment. One main result was that the drivers could not precisely specify the point in time, when the intention for a lane change arises in their mind. This supports the assumption that the motivation for or against a lane change is a continuous monitoring process with a comparative weighting of the subjective advantages of the different lanes. In addition to that, the drivers mostly mentioned more than one category of reasons for/against lane changes for their decision. However, the most frequent aspect for their intention and decision was the keeping of their desired velocity (Category "Speed Regulation/Overtaking"), especially for lane changes to the left. For lane changes to the right, the reasons in most cases referred to the sufficient space on the target lane combined with the obligation to drive on the right on German multi-lane roads.

The drivers´ verbalisation of their consideration underlined the complexity of this cognitive process, especially with regard to the number of different aspects which are monitored, interpreted, and partially predicted. Some new aspects for the formation of an intention could be revealed. E.g., it could be observed that the drivers preview distance can be very high (~300-500 m) in traffic scenarios with low complexity. Especially for trucks, which have a known (lower) velocity, the estimation of their influence is based on the vehicle type. Near ramps, the intention for lane changes to the right was prioritised lower, because there is an increased probability of slower or decelerating traffic before exit ramps. The influence of routing considerations is subject to high interpersonal and intrapersonal variances (e.g. cautious drivers change lanes earlier than more dynamic, experienced drivers). In summary, the “thinking aloud” method allowed for a driver’s conscious motivation to be revealed. This would not have been possible with naturalistic driving data in general.

3 OBJECTIVE DATA ANALYSIS

The two on-road studies provided an extensive objective data base of measurement data for further analysis of the objective characteristics of human lane change behaviour. Objective data of 1073 lane changes and 1442 km motorway driving by 12 experienced drivers has been collected from both studies and has been pre-processed for further analysis. Below some of the analysis results and the derived model-based process for trajectory generation are presented.

3.1 Driving Data Analysis

Definitions of the general time course of a lane change were established to prepare the data analysis of the lane change execution process. The most important period is the time of the main movement into the target lane. Its start is defined as the last time, when the vehicle is aligned within the original lane before crossing the lane marking (i.e., when the ego-vehicle’s heading angle is (close to) zero). The end is set to the first alignment point in the target lane (i.e. when the ego-vehicle´s heading angle reaches zero again). This led to a well-defined lane change duration, which allows good comparability. It can be observed that 85% of the manoeuvres are between 5.5 and 8 s (based on the definition above). There was no dependency of this duration from the longitudinal driving speed of the vehicle.

As basis for the implementation of a technical representation of human lane change execution, an assumption of a two-part process was proposed. In the first portion of the steering action the driver’s main goal is to leave the original lane with a certain maximum lateral velocity. Therefore, a higher lateral acceleration and quicker change in the movement away from the original lane is adjusted. The goal of the second part, after crossing the lane marking, is to align the vehicle at a certain lateral displacement in the target lane with zero steering angle. As this set of boundary conditions needs to be met, drivers tend to adjust lower change rates and lateral acceleration, which also leads to a slightly higher duration of this portion.

3.2 Reproduction of Lane Change Profiles

The necessary input parameters for the first portion of the execution is the distance to the lane marking at the start of the lane change manoeuvre and the time at which this point shall be reached. The second portion can then be parameterised by the intended overall displacement. Based on these parameters and conditions, the necessary steering angle of the trajectory can be optimised by using a model-representation of the vehicle´s lateral dynamics. Within the optimisation, maximum values of the lateral acceleration and jerk can be considered to account for the driver´s comfort requirements. Comparisons of generated trajectories with measurement data reveal good matching, especially in terms of the course of the lateral velocity and the lateral acceleration.

4 GENERAL DISCUSSION

The presented work strived to identify user-centred automated lane change manoeuvre profiles based on objective and qualitative subjective data from non-automated on-road studies. The on-road studies helped to gain first insights into the structure and parameters of the lane change process. The studies also showed that the decision process for or against a lane change manoeuvre is manifold. Drivers seem to consider a lot of factors in their decision, while passengers do not always take all of them into account. However, these studies were based on small samples and were mainly analysed on a qualitative level. Therefore, further studies with larger and balanced samples are needed to receive robust results on a quantitative data level.

The current analysis of the objective results allows for a technical representation and reproduction of human lane change execution. These outputs can be used to create first synthetic lane change trajectories for the assessment of automated lane change manoeuvres based on parameters from real data. For a controlled and reproducible evaluation of such automated lane change trajectories, the implementation of high-dynamic driving simulator studies seems advisable. A pilot study in the high-dynamic driving simulator of the Institute for Automotive Engineering, RWTH Aachen University with $N = 5$ experts already revealed that the visualisation and the dynamics (unscaled simulation of actual dynamics) of the high-dynamic driving simulator are appropriate for future investigations of automated lane change profiles. The experts reported a realistic driving experience and that – based on their impression – drivers will probably prefer that the automated lane change is softer than a manual driven lane change. Further research will be conducted to verify and expand upon these preliminary findings.

REFERENCES

During, M. & Pascheka, P. (2014). Cooperative decentralized decision making for conflict resolution among autonomous agents. In IEEE International Symposium on Innovations in Intelligent Systems and Applications (INISTA) (pp. 154–161). https://doi.org/10.1109/INISTA.2014.6873612

Ehmanns, D. (2002). Modellierung des taktischen Fahrerverhaltens bei Spurwechselvorgängen (Dissertation). RWTH Aachen, Aachen.

Fastenmeier, W., Hinderer, J., Lehning, U., & Gstalter, H. (2001). Analyse von Spurwechselvorgängen im Verkehr (Vol. 327): GRIN Verlag.

Gipps, P. G. (1986). A model for the structure of lane-changing decisions.

Hetrick, S. (1997). Examination of driver lane change behavior and the potential effectiveness of warning onset rules for lane change or "Side" Crash Avoidance Systems. [Blacksburg, Va: University Libraries, Virginia Polytechnic Institute and State University.

Hidas, P. (2002). Modelling lane changing and merging in microscopic traffic simulation. Transportation Research Part C: Emerging Technologies, 10(5-6), 351–371. https://doi.org/10.1016/S0968-090X(02)00026-8

Kesting, A., Treiber, M., & Helbing, D. (2007). General lane-changing model MOBIL for car-following models. Transportation Research Record.

Zheng, Z. (2014). Recent developments and research needs in modeling lane changing. Transportation Research Part B: Methodological, 60, 16–32.