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Measuring and Modeling Driver Steering Behavior: From Compensatory Tracking to Curve Driving

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Introduction

Today, driving is still a manual control task that requires continuous attention and control from the human driver. Drivers manipulate the gas pedal, brakes, and gears to change the vehicle's forward velocity (longitudinal control), and they use the steering wheel to negotiate curves, change lanes, and supress disturbances like wind gusts (lateral control). To effectively design *individualized* systems for autonomous driving or driver assistance, as currently pursued [Abb11, Sal13, Gor15], it is essential to understand driver control behavior. However, humans exhibit an extremely versatile set of control skills, and it is safe to say that, today, many aspects of driver control behavior are still poorly understood. Even for lateral steering control in isolation (i.e., at constant forward velocity), a wide variety of plausible theories exist about drivers' use of preview, motion feedback, and path prediction. This is reflected by the fundamental differences in available control-theoretic models of driver steering behavior [McR77, Mac81, Hes90, Sal13, Boe16].

The goal of our research project is to obtain the much needed fundamental insight into driver steering behavior, by developing a novel driver model for curve driving tasks. As a starting point we take the widely accepted, and applied, crossover model for compensatory tracking tasks (see Fig. 1) by McRuer *et al.* [McR67]. In this model, the human's control dynamics are represented by a *linear* transfer function $H_{o_e}(j\omega)$ that relates the human's sensory input (the visual error E) to the human's steering action U, in the frequency domain:

$$H_{o_e}(j\omega) = \frac{U(j\omega)}{E(j\omega)} = K_e \frac{1 + T_{L,e} j\omega}{1 + T_{l,e} j\omega} e^{-j\omega\tau_e}. \quad (1)$$

This model is extremely useful, as the human's control gain K_e, lead $(T_{L,e})$ and lag $(T_{l,e})$ equalization time constants, and the effective input-output time delay τ_e can be intuitively adapted, or explicitly estimated from experimental data, to *predict* human behavior in new situations, to *design* human-machine interfaces, to *quantify* human skill, and to *explain* observed behavior. Unfortunately, the crossover model is only applicable to the extremely limited single-axis, visual compensatory tracking task (error-minimization).

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We identified four main differences between compensatory tracking and curve driving tasks: 1) pursuit and preview, 2) perspective viewing, 3) multiple feedback cues, and 4) boundary-avoidance behavior due to available lane width, see Fig. 1. In our research project we will stepwise introduce these elements into the compensatory tracking task.

First, opposed to compensatory tracking tasks, drivers that negotiate curves perceive cues that contain information about the desired trajectory f_t and the vehicle states x. Drivers can direct respond to all the available signals, which is often referred to as *pursuit* control. Moreover, drivers can typically *preview* the road for some part ahead, yielding information about the future desired trajectory $f_t([t, t+\tau_p])$, up to a certain preview time τ_p. In **Step 1** of our research project, we investigate pursuit and preview control behavior in a single-axis tracking tasks with a plan-view display that closely resembles McRuer's *et al.*'s compensatory tracking task [McR67] (see Fig. 1).

Second, the viewing perspective in normal driving tasks differs markedly from this plan-view preview tracking task. Due to linear perspective, the previewed trajectory in driving tasks appears smaller with increasing distance ahead. Tracking errors close ahead are thereby visually emphasized. In contrast, the plan-view display has a uniform scaling, or "gain", such that previewed trajectory's appearance is not affected by distance ahead. In **Step 2** of our research project, we investigate how linear perspective affects human use of preview information (see Fig. 1).

Third, the single-axis tasks from the first two steps involve only a single feedback signal (e.g., lateral position), while curve driving tasks provide the driver with a wealth of cues. Drivers can integrate visual, vestibular, proprioceptive, and auditory information to estimate the vehicle's lateral position, heading, and path (angle and rate) relative to the road. In **Step 3** of our research project, we investigate various control tasks that involve multiple feedback cues, most importantly: 1) a lateral position, plan-view preview tracking task (**Step 1**), but with additional physical motion feedback, and 2) a visual tracking task with a "camera" position (and rotations) that correspond to the driver's natural view, yielding visual cues for lateral position, heading and path (see Fig. 1, **Step 3**).

Finally, in the *tracking* tasks of the first three steps,

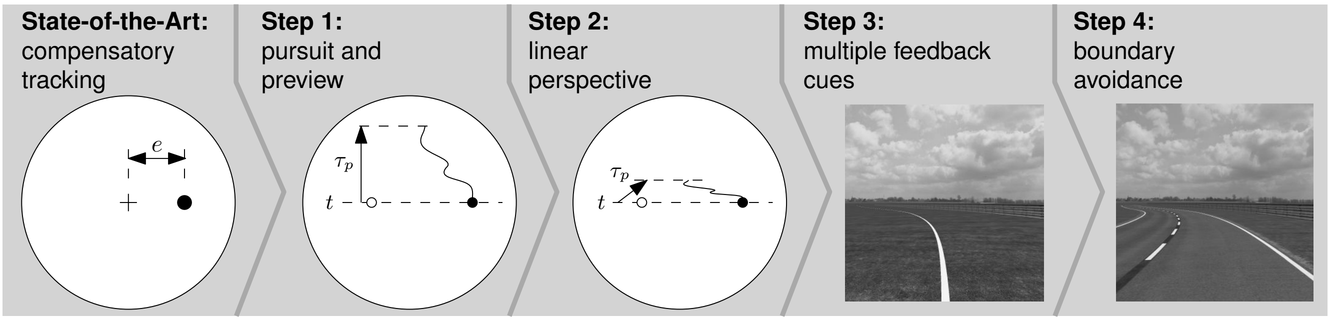

Figure 1: Stepwise introduction of elements from a curve driving task (far right) into a compensatory tracking task (far left).

the human follows a well-defined signal. Drivers do not typically aim to continuously keep their vehicle on the lane's center-line, but instead steer only when the vehicle laterally approaches the road's edges [Boe16]. This *boundary-avoidance* behavior is known to result in less aggressive and even intermittent (or "satisficing") driver steering [McR77, Boe16]. In **Step 4** of our research project we will extend the visual tracking task from **Step 3** to a boundary-avoidance, curve driving task (see Fig. 1).

From **Step 1** onwards, humans can respond to multiple signals, instead of the single error signal in compensatory tracking. To separately estimate humans' responses to each of the available inputs (i.e., the frequency response function from each input to the human's steering action U), we will use a multiloop system identification technique, based on Fourier coefficients [Paa98]. Then, a novel model can be formulated that strongly resembles the observed dynamics in the multiple, disentangled human responses.

Results and Conclusions

In a first human-in-the-loop experiment, which' results were recently published in [El16], we performed the preview tracking task from **Step 1**. Based on the multiloop system identification results, we found that McRuer *et al.*'s model for compensatory tracking tasks [McR67] can be extended to preview tracking tasks by including two additional responses to two viewpoints on the previewed trajectory ahead. The model's additional preview parameters appear to have a unique physical interpretation, similar as the compensatory model's parameters in Eq. 1, and these parameters can be explicitly estimated from experimental data. As such, it was found that humans adapt their viewpoints positions to the vehicle dynamics, with a near viewpoint between 0.1 and 0.9 s and a far viewpoint between 0.6 and 2 s ahead [El17].

To further verify our approach, we performed two more experiments in a fixed-based driving simulator: the same preview tracking task from **Step 1**, and the curve driving task from **Step 4**. In both experiments we varied the preview time, effectively restricting the length of the road that is visible ahead. Multiloop system identification results reveal a substantial control adaptation between these two tasks. This justifies our proposed stepwise introduction of a different viewing perspective, additional feedback cues, and lane width, to learn exactly which steps evoke certain human adaptations. Nonetheless, changing the preview time was found to evoke highly similar adaptations of the human's control dynamics in preview tracking and curve driving tasks. This strong correspondence support the feasibility of our proposed approach to develop a novel driver model based on McRuer *et al.*'s model for compensatory tracking tasks. Because this new model will strongly resemble drivers' actual control dynamics, the model parameters will have unique and direct physically interpretation, which can provide unmatched insights into between-driver steering variations, and facilitate the systematic design of novel individualized driver support systems.

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