Experimental verification of understeer compensation by four wheel braking

F2014-IVC-074

EXPERIMENTAL VERIFICATION OF UNDERSTEER COMPENSATION BY FOUR WHEEL BRAKING

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KEYWORDS – Vehicle dynamics; vehicle control; understeer; active safety; vehicle testing

ABSTRACT

This study is designed to validate a new approach to understeer mitigation chassis control, based on a particle motion reference: parabolic path reference (PPR). Considering the scenario of excess entry speed into a curve, related to run-off-road crashes, the aim is that automatic braking minimizes lateral deviation from the target path by using an optimal combination of deceleration, cornering forces and yaw moments. Previous simulation studies showed that four-wheel braking can achieve this much better than a conventional form of yaw moment control (DYC). The aim of this work is to verify this on a test track with an experimental vehicle, and to compare performance with DYC and an uncontrolled vehicle. Experiments were performed with a front-wheel-drive passenger vehicle equipped with an additional four identical brake callipers controlled via an electro-hydraulic brake (EHB) system, enabling individual brake control. Minimizing the maximum deviation from the intended curve radius is the control objective. Feedback to the controller consists of the available steering wheel angle, wheel speeds, yaw rate and lateral acceleration sensors in the vehicle. Additional to these variables, also the vehicle position was logged using a GPS system. It was found that PPR is superior to DYC in reducing the maximum deviation from the intended path, confirming the trends previously found in simulations. Furthermore, the PPR concept is found to be inherently more stable than DYC since more brake force is applied to the outer wheels than the inner wheels throughout the manoeuvre. The experiments involve a first implementation of a PPR control which is not a fully closed-loop control intervention and tuned to a step steer (transition from straight to fixed-radius curve. This is the first study to explicitly and systematically evaluate this new approach to understeer mitigation. The approach is fundamentally different from common DYC and suggests the potential for a new generation of controllers based on trajectory control via chassis actuators.

INTRODUCTION

Overspeed in curves may result in road departure and/or interference with oncoming traffic. According to two US reports on fatal single-vehicle run-of road crashes [7][8], around one third of such crashes occurred in a turn and nearly half of these crashes involved speeding. Furthermore, the reports conclude that run-of road crashes are more likely to occur in adverse weather conditions.

In vehicle dynamics, overspeed in curves often results in so-called terminal understeer, or loss of directional control. Terminal understeer is a result of the front tires being saturated, meaning that the curvature of the turn cannot be increased further.

It is commonly reported that the way modern electronic stability control compensate terminal understeer is by a turn-in yaw moment resulting from differential braking [1][3][9][12], as is done for counteracting oversteer. However, in [2], [13] and [14] it is recognized that a more effective way to increase the curvature of the vehicle trajectory is to reduce the vehicle speed. Braking, however, will reduce the lateral force capability of the vehicle further [2][5], so optimization of braking and lateral forces is necessary to minimize the maximum deviation from the intended path.

This study is designed to validate a new approach to understeer mitigation chassis control, based on a particle motion reference: parabolic path reference (PPR). The aim is that automatic braking minimizes lateral deviation from the target path using an optimal combination of deceleration, cornering forces and yaw moments. Previous simulation studies [4], [5] and [9] showed that four-wheel braking can achieve this much better than a conventional form of yaw moment control (DYC). The aim of this work is to verify this on a test track with an experimental vehicle, and to compare performance with DYC and an uncontrolled vehicle.

The experiments involve a first implementation of a PPR control which is not a fully closed-loop control intervention and tuned to a step steer (transition from straight to fixed-radius curve). Also the controller did not include any oversteer intervention or other form of sideslip control. This was found to be highly necessary for

DYC and while PPR was found to be less prone to yaw instability it certainly requires additional yaw control. Also we did not look at driver interaction in a systematic way.

EXPERIMENTS

Experiments were performed with a front-wheel-drive 2009 Saab 9-3 test-vehicle (shown in Figure 1) with a 250hp V6 engine and a six-speed manual transmission. The vehicle is equipped with an additional four identical brake callipers controlled via an electro-hydraulic brake (EHB) system, enabling individual brake control via a dSpace MicroAutobox real-time controller. The experiments were performed at the Stora Holm proving ground in Gothenburg, Sweden, attempting to negotiate outside a 30 m radius turn (see Figure 2) at initial speeds in excess of the limit speed for the curve; which on dry tarmac is about 55 km/h. Minimizing the maximum deviation from the intended curve radius is the control objective. Feedback to the controller consists of the available steering wheel angle, wheel speeds, yaw rate and lateral acceleration sensors in the vehicle. Additional to these variables, also the vehicle position was logged using a GPS system.

Figure 1: Overspeed experiments with test vehicle.

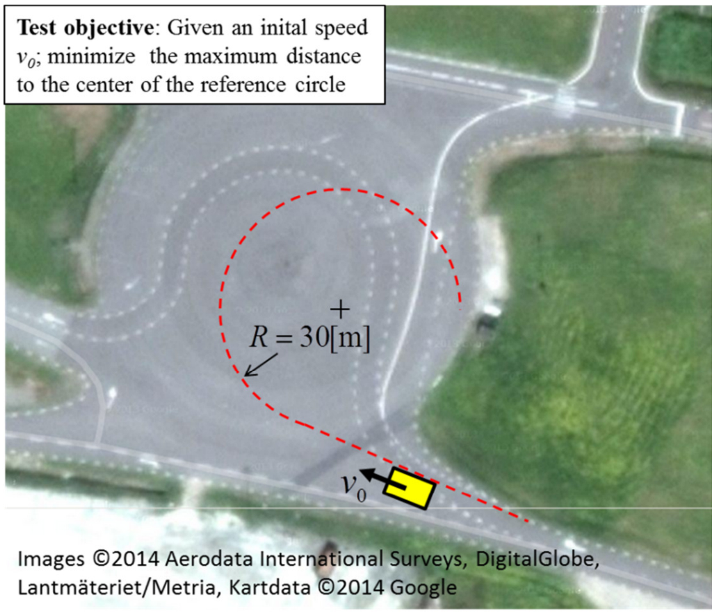

Figure 2: Experimental setup involving the test vehicle negotiating a curve of 30 m radius.

CONTROL LOGIC

As mentioned above, the control inputs are the four brake pressures and the state feedback variables are the vehicle speed v, yaw rate $\dot{\psi}$, longitudinal and lateral acceleration and steering wheel input δ_H.
Two different control strategies were compared. One is yaw moment control based on yaw-rate feedback (DYC) and the other is the speed following strategy based on PPR. Since proper PPR requires positional feedback and since this is currently not implemented, only the principle of speed reduction is evaluated. See [4] and [5] for more discussion on this topic.

The DYC yaw-rate control applies brake pressure p_i of the inner wheels proportional to the difference between the reference yaw rate $\dot{\psi}_{\mathrm{ref}}$ and the measured yaw rate as described in [1] and [4], namely

$$p_i = \gamma_i^{\mathrm{DYC}} \min\left(\left|\dot{\psi}_{\mathrm{ref}}\right| - \left|\dot{\psi}\right|, 0\right),\ i = 1,2,3,4 \tag{1}$$

where γ_i^{DYC} is the proportional gain for the i:th wheel with the odd numbers being the left front and rear wheels, respectively and the even numbers indicating the right front and rear wheels. For a left turn ($\dot{\psi}$>0), only the left wheels are braked and the right wheels for a right turn.

In this work the reference yaw rate is inferred from the steering input such that

$$\dot{\psi}_{\mathrm{ref}} = \frac{v}{L}\frac{\delta_H}{i_S} \tag{2}$$

where L is the wheel base and i_S is the steering gear ratio.

The implemented PPR speed following strategy is to apply brake pressure proportional difference between the actual speed and the maximum speed v_{lim} that can be attained with the current friction level such that

$$p_i = \gamma_i^{\mathrm{PPR}} \min(v - v_{\mathrm{lim}}, 0),\ i = 1,2,3,4 \tag{3}$$

where

$$v_{\mathrm{lim}} = \sqrt{\hat{\mu} g i_S L / \delta_H} \tag{4}$$

and where $\hat{\mu}$ is the estimated friction and g is the gravitational acceleration.

The friction is estimated based on a peak hold-and-decay strategy based on the combined lateral and longitudinal acceleration magnitude normalized by the gravitational acceleration. This strategy, described in more detail in [9], means that the maximum utilized friction is stored for a pre-defined time after which the estimation is decayed to the current utilized friction.

DATA ACQUISITION

Data was recorded separately on two data acquisition systems:

- DL1 (Race Technologies) captures GPS path, speed and acceleration (inertial sensors) and yaw rate
- Vehicle CAN data logged via dSpace MicroAutoBox controller provides steer angle, vehicle speed, accelerations and yaw rate.

Vehicle speed is used as a common signal and to align data and vehicle accelerations are used for confirmation.

EXPERIMENTAL RESULTS

Several test-runs were performed, with three levels of control applied on the vehicle: uncontrolled, with PPR and with DYC.

The trajectories from these measurements are shown in Figure 3. For all figures in this section, the left sub-plot shows PPR (blue, solid) relative to the uncontrolled vehicle (black, dashed) and the right figure shows DYC (red, solid) relative to the uncontrolled vehicle. The dashed circle indicates the reference circular path; of course at the given entry speed it is not possible to follow the path, significant off-tracking is unavoidable, as we see in the plots.

In Figure 3 there is a clear pattern of reduced off-tracking for PPR relative to the uncontrolled vehicle, whereas DYC is much more variable, with two very large deviations. There is a degree of variability throughout, due to the fact that the human driver forms part of the control loop. In spite of this, the pattern of improved performance for PPR is very clear.

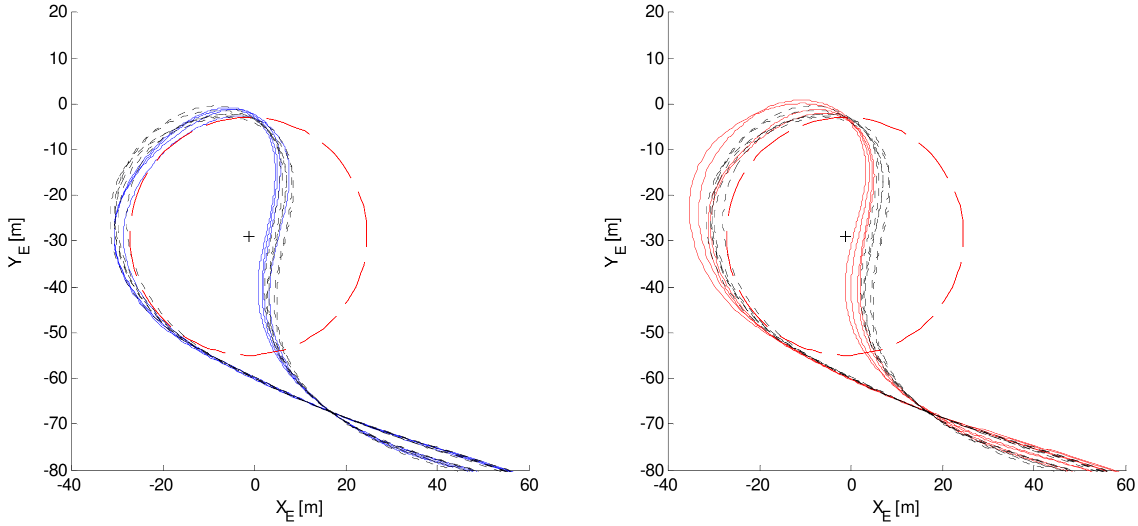

Figure 3: Vehicle trajectories in global (X_E, Y_E) coordinates showing off-tracking from the reference circle (dashed red lines) for PPR (left, solid lines) and DYC (right, solid lines) relative to the uncontrolled vehicle (dashed lines).

The acceleration *magnitude* – combined lateral and longitudinal acceleration – versus time is shown in Figure 4. Again there is some variability, but it is clear that during the event the vehicle is at the limit of adhesion, with an acceleration magnitude of around 9 m/s^2.The different test-runs are aligned such that $t = 0$ coincides with the cross-over point of the entry and return trajectories, shown in Figure 3. In Figure 4 it can be seen that the duration of the event, as defined by the time of large acceleration magnitude, is significantly shorter for PPR relative to both the uncontrolled vehicle and DYC. In the right sub-plot, for DYC, some curves exhibit a strong reduction in acceleration magnitude only to become large again; these correspond to a loss of yaw stability, where the driver counter-steers, and these cases also correspond to large off-tracking as seen in Figure 3.

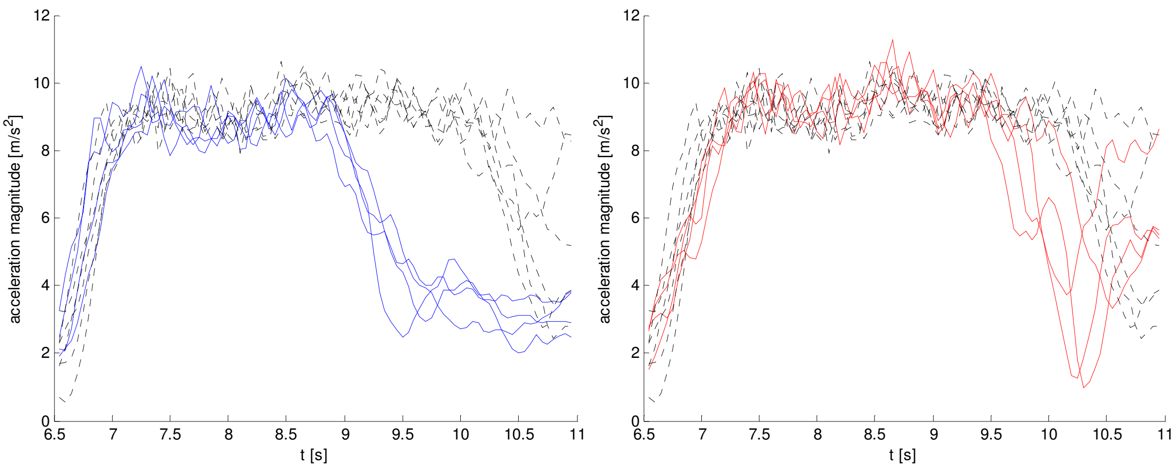

Figure 4: Acceleration magnitude versus time of PPR (left, solid blue curves) and DYC (right, solid red curves) relative to the uncontrolled vehicle (dashed lines).

As mentioned in the Introduction, PPR operates in a way that optimally combines speed reduction with path curvature, with smooth progression from greater speed reduction in the early stage of the intervention, transitioning to increased path curvature, while staying within the friction limits. Thus, for PPR, we expect more of a reduction in vehicle speed at the point of maximum off-tracking compared, as well as reduced off-tracking at this point. Both effects are clearly seen in Figure 5. And both effects are likely to have a positive influence on safety, with improved path control and with reduced speed approaching a point of a possible impact. This is not formalized in this work, but it is an important spin-off; requiring reduced off-tracking automatically leads to speed reduction as well as shorter duration of the off-tracking event.

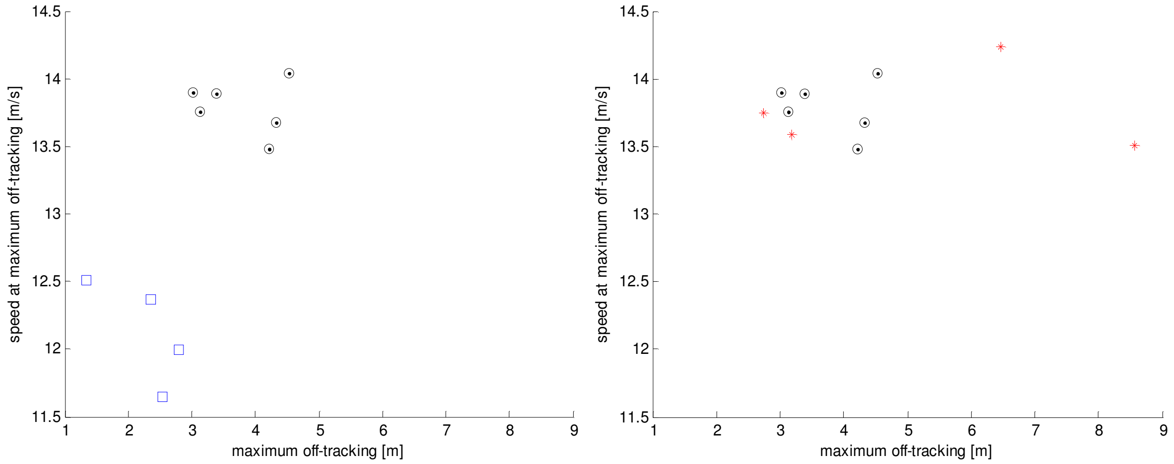

Figure 5: Speed at point maximum off-tracking versus the maximum off-tracking deviation PPR (left, blue squares) and DYC (right, red stars) relative to the uncontrolled vehicle (circles).

Note: no instructions were given to the driver to recover the circular path after the point of maximum off-tracking, but one would expect the driver to reduce the steering angle after this point is reached. For PPR this occurs at around $t = 9$ s, and in Figure 6 (left sub-plot) this is seen in the steering wheel angle time histories – and later for DYC and uncontrolled. For DYC (right sub-plot) it is also clear that the driver executes counter-steering behaviour to correct for yaw instability.

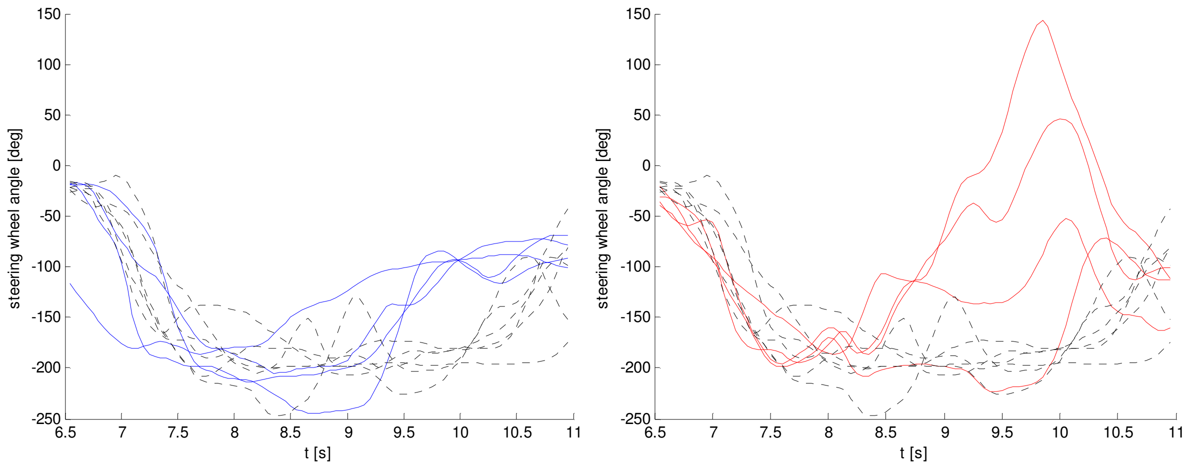

Figure 6: Steering wheel angle versus time for PPR (left, solid blue lines) and DYC (right solid red lines) relative to the uncontrolled vehicle (dashed lines).

In a commercial ESC system such a correction is normally applied via a turn-out yaw moment applied through brake actuation; and while a brake-based intervention will also help to reduce speed, we know from the PPR concept – and backed-up by the present experimental verification – that early four-wheel braking is most effective, and that no such additional intervention is required. So in spite of excluding such a secondary oversteer correction by braking for DYC, we are able to conclude that PPR is the more effective strategy for reducing off-tracking. Further, it is clear that even the very simple control algorithm, designed to approximate PPR, can be highly effective when the driver interacts with the control system, to avoid excessive off-tracking in a friction-limited manoeuvre.

CONCLUSIONS

This is the first study to explicitly and systematically evaluate a new approach to understeer mitigation. The approach is fundamentally different from common DYC and suggests the potential for a new generation of controllers based on trajectory control via chassis actuators.

The experiments involve a first implementation of a PPR control which is not a fully closed-loop control intervention but tuned to a step steer (transition from straight to fixed-radius curve). Also the controller did not include any oversteer intervention or other form of sideslip control. This was found to be highly necessary for DYC and while PPR was found to be less prone to yaw instability, for robust operation it certainly requires additional yaw control. Also, while we did not look at driver interaction in a systematic way we did establish that the advantages of PPR seen in simulation, do indeed take place in real-world conditions with a driver in the loop. Also, access to accurate positional and road information [6] is currently not used as feedback to the controller, but should be explored in future studies.

The main conclusions are that trends previously found in simulation are clearly demonstrated in this work. More specific, these are that PPR control, relative to both the uncontrolled vehicle and conventional DYC, shows:

- Reduced duration of the off-tracking event
- Less maximum off-tracking
- Lower speed at the point of maximum off-tracking

Relative to DYC it is further noted that PPR requires less steering from the driver, which is further subjectively confirmed by the driver during the experiments. Further feedback from the driver indicates that, although more braking is applied, that PPR is felt to give the driver a larger degree of directional control. Future work will refine the control algorithm and expand the range of scenarios, to include cases with non-constant curvature of the desired path.

ACKNOWLEDGMENTS

The authors would like to acknowledge the financial support of SAFER Vehicle and Traffic Safety Center (project no. A40) as well as the support of the project partners Chalmers, AB Volvo, Volvo Car Corporation, Autoliv and the first two author’s organizations Lincoln University and AAM, respectively.

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