

The geometrical parameters include the wheelbase l and the distance b between points R and G. The vehicle mass is denoted by m , while J_G is the yaw moment of inertia about the center of mass and J_F denotes the mass moment of inertia of the steering system.

Deriving the equations of motion of the vehicle model using the Appell-Gibbs method (see [13] for details) leads to

$$\dot{x}_R = V \frac{\cos \psi}{\cos \gamma} - \sigma \frac{\sin(\psi+\gamma)}{\cos \gamma} - l\omega \cos \psi \tan \gamma, \quad (1)$$

$$\dot{y}_R = V \frac{\cos \psi}{\cos \gamma} + \sigma \frac{\cos(\psi+\gamma)}{\cos \gamma} - l\omega \sin \psi \tan \gamma, \quad (2)$$

$$\dot{\psi} = \omega, \quad (3)$$

$$\dot{\gamma} = \Omega, \quad (4)$$

and

$$\begin{bmatrix} m_{11} & m_{12} & 0 \\ m_{21} & m_{22} & J_F \\ 0 & J_F & J_F \end{bmatrix} \begin{bmatrix} \dot{\sigma} \\ \dot{\omega} \\ \dot{\Omega} \end{bmatrix} = \begin{bmatrix} f_1 \\ f_2 \\ f_3 \end{bmatrix}, \quad (5)$$

where σ is the lateral velocity of point R, ω is the yaw rate of the vehicle, and Ω is the steering rate. The generalized mass matrix includes the elements

$$m_{11} = \frac{m}{\cos^2 \gamma}, \quad (6)$$

$$m_{12} = m_{21} = m(b + l \tan^2 \gamma), \quad (7)$$

$$m_{22} = J_G + J_F + m(b^2 + l^2 \tan^2 \gamma). \quad (8)$$

The right-hand side of Eq. (5) consists of

$$f_1 = \frac{F_F}{\cos \gamma} + F_R - \frac{m}{\cos \gamma} (V - (l - b)\omega \sin \gamma)\omega + \frac{m \sin \gamma}{\cos^3 \gamma} (V \sin \gamma - \sigma - l\omega)\Omega, \quad (9)$$

$$f_2 = \frac{F_{Fl}}{\cos \gamma} - \frac{m}{\cos \gamma} (bV + (l - b)\sigma \sin \gamma)\omega + \frac{ml \sin \gamma}{\cos^3 \gamma} (V \sin \gamma - \sigma - l\omega)\Omega + M_F + M_R, \quad (10)$$

$$f_3 = M_F + M_S. \quad (11)$$

The lateral tire forces F_F and F_R , as well as the self-aligning moments M_F and M_R are considered as functions of the side-slip angles

$$\tan \alpha_F = -\frac{\sigma + l\omega}{V \cos \gamma} + \tan \gamma, \quad (12)$$

$$\tan \alpha_R = \frac{V \cos \gamma}{-V + (\sigma + l\omega) \sin \gamma} \quad (13)$$

using the nonlinear brush tire model, as detailed in [13].

In order to ensure stable path following, a higher-level controller is designed in this paper to follow the straight-line reference path along the x axis. Thus, the desired steering angle γ_{des} is calculated using the feedback of the lateral position y_R and the course angle θ of the rear axle center point:

$$\gamma_{des} = -k_y y_R(t - \tau) - k_\theta \sin(\theta(t - \tau)), \quad (14)$$

where τ is the feedback delay, which includes sensor and communication delays, data processing time and

actuation delay. The course angle is calculated as $\theta = \psi - \alpha_R$, and k_y and k_θ are the control gains. The tracking performance of this simple controller can be improved in case of varying path curvature by adding a feedforward term, as in e.g. [14].

In order to realize the desired steering angle, the steering torque M_S is generated according to the lower-level PID controller

$$M_S = -k_p(\gamma - \gamma_{des}) - k_d \dot{\gamma} - k_i z, \quad (15)$$

where k_p , k_d and k_i are the lower-level control gains and

$$\dot{z} = \gamma - \gamma_{des}. \quad (16)$$

It has been shown in [15] that as long as the time delay in the lower-level controller is below a critical value of ~ 1 ms, it has negligible effects on the stability of the system, therefore it will not be considered in our analysis.

3. NONLINEAR ANALYSIS

The resulting system of delay differential equations (1-16) of the controlled vehicle is analyzed with the help of the DDE-Biftool software package [16,17]. Subcritical Hopf bifurcations are detected along the stability boundaries in the plane of the control gains k_y and k_θ . The periodic orbits emerging from these bifurcation points are followed using numerical continuation within the entire linearly stable parameter domain of the control gains.

The bifurcation diagrams in Fig. 2 (a) and (b) show the limit cycle amplitudes in terms of the lateral position y_R as a function of the control gain k_θ for the vehicle parameters listed in Table 1. It can be seen that the linearly stable range of k_θ is bounded by Hopf bifurcation points on both sides which are connected by an unstable periodic orbit. As shown in the bifurcation diagrams, for larger control gains, the amplitude of the unstable limit cycle is smaller, suggesting a smaller basin of attraction for stable path following. This means that if the vehicle is sufficiently perturbed, the controller will not be able to steer the vehicle back towards the reference path, even if the closed-loop system is stable in the linear sense.

The color coding in Fig. 2 (c) shows how the unstable limit cycle amplitudes change inside the linearly stable parameter domain of both control gains, up to 2 meters in terms of the lateral position y_R . Points where the limit cycle amplitudes are above 2 meters are considered safe, since in these cases the controller can handle larger perturbations too. The corresponding safe zone of control gains is shaded in gray in Fig. 2 (c).

Observe that a large part of the linearly stable parameter domain falls outside of this safe zone. This means that the system can leave the basin of attraction of the stable solution in these cases for sufficiently large perturbations, which is a severe safety issue in practice.

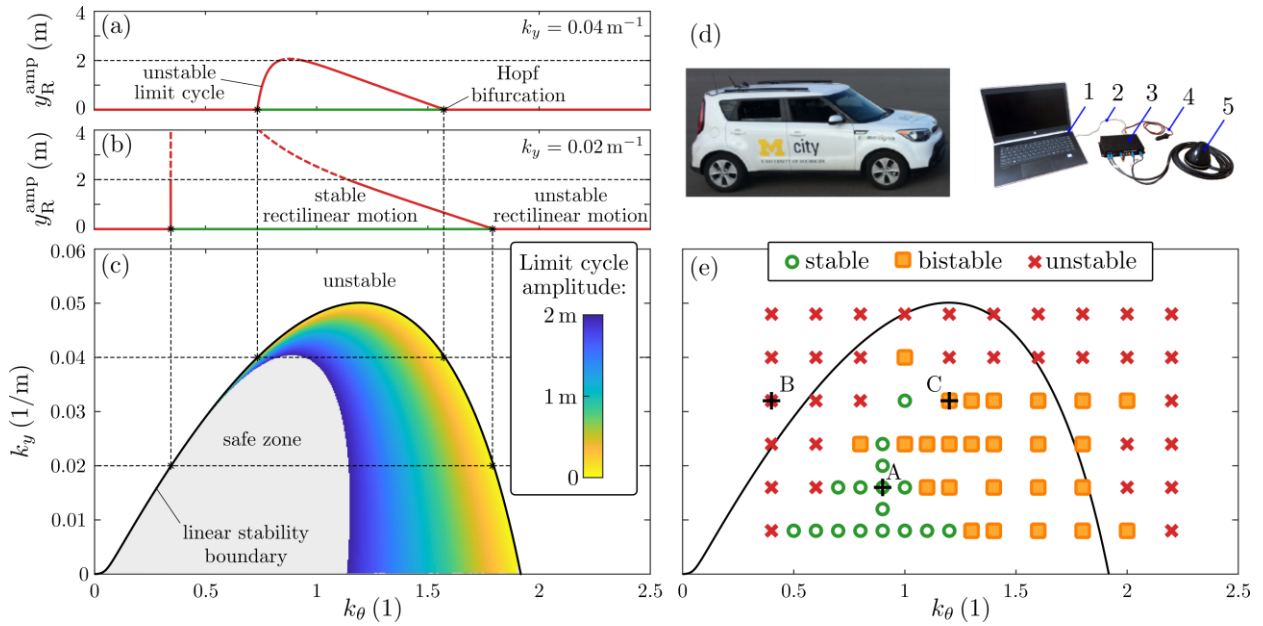


Fig. 2 (a)-(b) Bifurcation diagrams of the controlled vehicle. (c) Unstable limit cycles around the linearly stable domain of control gains. The coloring refers to the unstable limit cycle amplitudes. (d) The vehicle and the V2X measurement setup used in the experiments - 1: host computer, 2: network cable, 3: electronic control unit, 4: power cable, 5: antennae. (e) Experimental results.

Table 1 Vehicle Parameters

| | | |
|--|---------|-----------------------|
| wheelbase | l | 2.57 m |
| distance between rear axle and center of gravity | b | 1.54 m |
| vehicle mass | m | 1770 kg |
| yaw moment of inertia | J_G | 1343 kgm ² |
| steering system moment of inertia | J_F | 0.25 kgm ² |
| lower-level steering control proportional gain | k_p | 640 Nm |
| lower-level derivative gain | k_d | 8 Nms |
| lower-level integral gain | k_i | 40 Nm/s |
| tire contact patch half-length | a | 0.1 m |
| tire cornering stiffness | C | 40 kN |
| sliding friction coefficient | μ | 0.6 - |
| rolling friction coefficient | μ_0 | 0.9 - |
| longitudinal velocity | V | 15 m/s |
| feedback delay | τ | 0.7 s |

4. EXPERIMENTAL VALIDATION

In order to validate the results of the theoretical analysis, a series of real vehicle experiments were performed at the Mcity test track of the University of Michigan. The test vehicle (shown in panel (d) of Fig. 2) was equipped with a GPS device mounted at the rear axle center point. The experiments were aimed at demonstrating the feasibility of motion control relying on vehicle-to-everything (V2X) communication only, in cases when the onboard sensors fail [13]. This means that the applied control algorithms must be able to handle less frequent data transfer and less accurate sensor data. In

case of the GPS device used in the experiments, the satellite data was upgraded only every 1 sec (with state estimations in-between) with an accuracy of approximately 0.7 m.

The experiments were performed for different combinations of the higher-level control gains, where the vehicle aimed to follow the lane centerline of a straight multi-lane segment of the test track, relying on GPS data. For each control gain combination in Fig. 2 (e), three different measurements were carried out. Depending on the behavior of the vehicle, the individual measurement points were labelled as either stable (green circles in Fig. 2 (e)), bistable (orange squares) or unstable (red crosses). For the gain combinations labelled as stable, the lane-keeping controller was working as intended in all three test runs, with decaying oscillations. In the measurement points labelled as bistable, solutions with increasing and decreasing lateral oscillations were both observed presumably due to the non-uniform initial conditions and measurement noise. Finally, in the points labelled as unstable, the vehicle was not able to successfully follow the lane centerline in any of the test runs.

Figure 3 shows some representative time series data of the lateral position of the vehicle in the measurement points marked in Fig. 2 (e). Figure 3 (a) shows a stable measurement (using the gains at point A), where the vehicle tended towards the reference path even from a relatively large initial condition. In panel (b), the control gains were selected from the theoretically unstable region (point B), which resulted in an oscillatory stability loss even when the vehicle was started close to the reference path. Panel (c) shows an example of the bistable behavior observed during the measurements (point C): for a small initial perturbation, the vehicle safely follows the reference path, but a slightly larger initial error leads to stability loss.

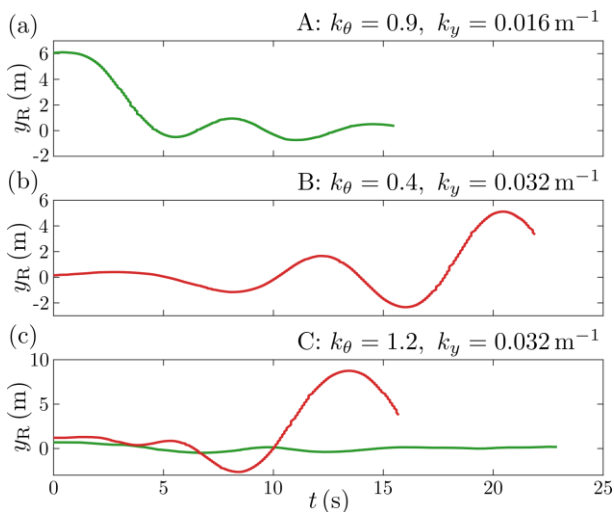


Fig. 3 Measured time series of the vehicle lateral position y_R for the experiments corresponding to points A, B and C in Fig. 2 (e).

5. CONCLUSION

The bifurcation analysis of the lane-keeping control of automated vehicles was performed in this paper. Using numerical continuation, unstable limit cycles have been identified along the linearly stable domain of control gains. The oscillation amplitude of these periodic orbits around the equilibrium of stable path following can be used as an indicator of the robustness of the controller against perturbations. Based on the results of the nonlinear analysis, a safe zone of control gains has been identified, where the controlled vehicle is able to safely handle larger perturbations.

The results have been verified using a series of real vehicle experiments on a test track. The measurement results confirm the importance of taking into account the time delay as well as the nonlinear effects in the control design. Consistently stable measurements were only achieved in the region of the stable domain where the amplitude of the unstable limit cycle was sufficiently large. Stable operation can still be achieved outside of this region, but the system was demonstrated to be more susceptible to perturbations and noise, which may lead to serious safety hazards in practice.

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