Explicit MPC design and performance evaluation of an ACC Stop-&-Go

Gerrit Naus, Roel van den Bleek, Jeroen Ploeg, Bart Scheepers, René van de Molengraft, Maarten Steinbuch

Abstract— **This paper presents the synthesis, the implementation and the performance evaluation of an Adaptive Cruise Control (ACC) Stop-&-Go (S&G) design. A Model Predictive Control (MPC) framework is adopted, enabling hybrid control synthesis. Performance of the controller is evaluated, distinguishing between comfort of the resulting longitudinal vehicle behavior and the behavior due to traffic requirements. Comfort is related to vestibularly detectable variables, whereas required behaviour is related to visually and auditorily detectable variables. Metrics are determined to enable objective performance evaluation of an ACC (S&G) system in a qualitative manner.**

I. INTRODUCTION

Adaptive Cruise Control (ACC) originates from Cruise Control (CC), which today is a widespread functionality in modern vehicles. CC controls the vehicle speed steering the throttle only, via tracking of a speed v_{CC} that is set by the driver. ACC automatically adapts the vehicle's speed depending on a predecessor's behavior, steering the throttle as well as the brake system. Typically, the control objective amount to following of a predecessor at a desired distance, see Fig. 1.

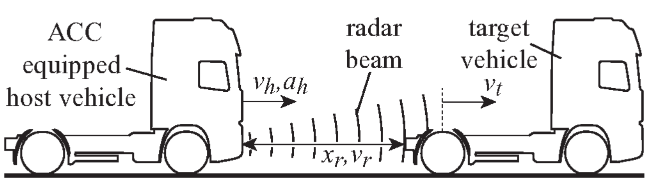

Fig. 1. Example of the ACC working principle; the host vehicle is equipped with an ACC system, which assures automatic following of the preceding target vehicle at a distance $x_r = x_{r,d}$. The corresponding radar measures the relative distance x_r and relative velocity v_r between the two vehicles.

Starting in the late 1990s with luxury passenger cars, ACC functionality is available in a number of commercially available passenger cars as well as trucks today. Focusing on passenger cars, ACC is intended as a comfort system primarily. Secondarily, ACC might also enable increased safety, fuel economy and traffic efficiency [25]. Current research focuses on the implementation of new ACC functionality like Stop-&-Go (S&G), which enables low-speed ACC in urban traffic and traffic jams, and appropriate tuning of ACC.

G.J.L. Naus, R.A.P.M. v.d. Bleek, M.J.G. v.d. Molengraft and M. Steinbuch are with the Department of Mechanical Engineering, Control Systems Technology group, Technische Universiteit Eindhoven, Eindhoven, The Netherlands g.j.l.naus@tue.nl, m.j.g.v.d.molengraft@tue.nl, m.steinbuch@tue.nl, r.a.p.m.v.d.bleek@student.tue.nl J. Ploeg and B. Scheepers are with the Business Unit Automotive, Department of Integrated Safety, TNO Helmond, The Netherlands jeroen.ploeg@tno.nl, bart.scheepers@tno.nl

As ACC takes over control from the driver, it should resemble driver behavior to some extent. A driver however, exhibits nonlinear, i.e. situation-dependent behavior. Furthermore, every driver exhibits different behavior. Determination of objective control goals and corresponding performance evaluation metrics that are valid for a complete envelope of working conditions thus is difficult [4], [5]. As a result, subjective, trial-and-error based techniques are commonly adopted in the design and specifically the tuning of ACC.

The contribution of this paper is two-fold. Firstly, metrics to enable objective performance evaluation of an ACC S&G in a qualitative manner are specified, distinguishing between comfort of the resulting longitudinal vehicle behavior and the behavior due to traffic requirements. Secondly, a structured ACC S&G design is proposed, incorporating these performance metrics.

In Section II, an overview of performance evaluation of ACC systems in literature is presented. The design of the ACC S&G is discussed in Section III. The implementation and performance evaluation are discussed in Section IV.

II. ACC PERFORMANCE EVALUATION IN LITERATURE

Generally, ACC behavior is compared to human driver behavior to validate the proper working as well as to evaluate performance of the system. Focusing on ACC as a comfort system, performance is often related to the comfort of longitudinal vehicle motion. However, both comfort of the vehicle behavior as well as the behavior due to traffic requirements have to be considered.

A. Driver modeling

Human driver modeling to validate and evaluate an ACC system can be divided into modeling from an engineering point of view [5] and modeling from a psychological point of view [26], [4]. In modeling from an engineering point of view, human perception is not considered. Typically, peak acceleration values in combination with the relative distance are taken as a performance metric [15]. As the ACC system output in general represents an acceleration profile, this forms a convenient basis for controller design and hence is widely adopted in industry. In modeling from a psychological point of view, additional criteria to define driver comfort are incorporated [11], [19]. It is assumed that human driver behavior from a psychological point of view requires the use of neural networks [4]. The subsequent controller design and tuning is rather complex as a result of the corresponding variety in performance metrics. This is thus scarcely employed in practice.

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B. Longitudinal vehicle motion

Regarding control of longitudinal motion of a vehicle in general, the terms comfort, driveability, ride or driving comfort and quality are used confusedly in literature. In the first place, longitudinal comfort is often related to the amount, size and frequency of vibrations or oscillations in the longitudinal acceleration of the vehicle due to e.g. external disturbances, engine torque peaks, driveline characteristics, etc. [21], [8]. Damping of such vibrations forms an obvious control objective and is often presented as control of longitudinal comfort [20], [9]. In the second place, comfort or driveability is often related to the handling of a vehicle. Focusing on longitudinal aspects, this comprises amongst other things a vehicle's character, pedal response, brake control and in case the vehicle is equipped with an ACC system, the corresponding ACC behavior. Many different aspects can be accounted for [17]. Analogous to the modeling of human driver behavior from a psychological point of view (II-A), it is assumed that neural networks are required for appropriate modeling of vehicle handling [23], [22].

C. Comfortable and required behavior

Besides the differences, both modeling approaches discussed in Section II-A distinguish separate evaluation variables for comfortable and required driving behavior. Vestibularly, i.e. somatosensorily detectable variables such as acceleration are indicated as comfort metrics, whereas required behavior of a driving action is related to visually and auditorily detectable variables; substantial braking may be required in case of a vehicle cut-in at a small distance, while the corresponding levels of deceleration may not be comfortable. Hence, comfortable and required driving behaviour have to be considered separately.

Typically, acceleration peak values are related to comfort (II-A, II-B). Regarding jerk peak values as a comfort metric for ACC (S&G) behavior, little is reported in literature. [19] state that jerk is the best metric to reflect human's comfort criteria. In designing trains and elevators for example, the jerk is typically limited to $2.0\,\mathrm{m\,s^{-3}}$. Yet, [14] state that no objective statements can be made regarding passenger acceptability of any specific acceleration or jerk profile in a given transportation system.

Required ACC (S&G) behavior is typically rendered into control objectives that are based on a desired relative distance and equal speed of the host and the target vehicle. Besides the relative distance, the so-called Time-To-Collision $TTC = x_r/v_r$ may be used to evaluate driver behavior. When approaching a target vehicle, a minimum TTC_{min} is attained. The moment braking is initiated, is indicated by TTC_{br}. In literature, these variables are often pointed out to form objective metrics to determine required driving behavior [7], [26], [11]. However, in general only one specific situation is considered and research focuses on Collision Avoidance (CA) situations rather than 'normal' ACC (S&G) situations.

The distinction between performance criteria related to comfortable and required vehicle behavior will be validated and evaluated on the basis of simulations and experiments.

III. Explicit MPC applied to ACC Stop-&-Go

In general, ACC systems are divided into a generic, vehicle independent part and a vehicle-specific part, i.e. an outer control and an inner control loop respectively (see Fig. 2). The generic part determines the behavior of the system by prescribing a desired acceleration profile $a_{h,d}$ for the vehicle. The vehicle-specific part assures tracking of this profile via actuation of the throttle and brake system. This paper focuses on the generic part. A model of two following vehicles, the control objectives and the corresponding constraints are presented after which the design of an explicit Model Predictive Controller (MPC) is discussed.

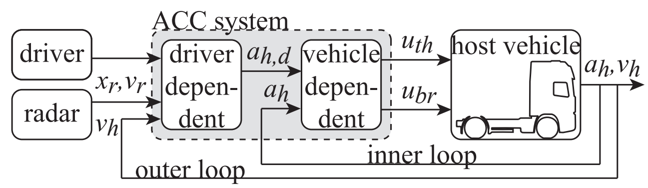


Fig. 2. Schematic representation of the ACC S&G control loop. The ACC S&G system is divided into a generic, outer control loop determining the desired acceleration $a_{h,d}$ and a vehicle specific, inner control loop determining the actual throttle and brake control signals u_{th}, u_{br} respectively.

A. Modeling, control objectives and constraints

The dynamics of two following vehicles are considered for modeling (see Fig. 1). For simplicity, vehicle models are not taken into account. A discrete time model is used, adopting a zero-order hold discretization with sample time T_s, i.e. $t = kT_s$ with $k \geq 0$ representing the discrete time steps. A radar detects the relative distance x_r and relative velocity v_r between the two vehicles (see Fig. 2). The host vehicle speed v_h is assumed to be known. The state vector $x(k) = (x_r(k), v_r(k), v_h(k))^T$ contains these variables, yielding the following discrete time model

$$\mathcal{M} : \begin{cases} x(k+1) = Ax(k) + Bu(k) \\ y(k) = x(k) \end{cases} \qquad k \geq 0 \tag{1}$$

with input $u(k) = a_h(k)$ and full state feedback. As the acceleration of the target vehicle $a_t(k)$ is unknown, it is regarded as a disturbance. For now as a nominal case, $a_t(k)$ is assumed to be zero, yielding

$$A = \begin{pmatrix} 1 & T_s & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}, \quad B = \begin{pmatrix} -\frac{1}{2}T_s^2 \\ -T_s \\ T_s \end{pmatrix} \tag{2}$$

The primary control objective amounts to following a target vehicle at a desired distance $x_r(k) = x_{r,d}(k)$. Typically, the desired distance is determined based on the so-called desired time-headway $t_{hw,d}$. The time-headway t_{hw} is the time it would take for the host vehicle to reach the current position of the target vehicle if continuing to drive with current speed. This yields

$$\mathcal{O}_1 : x_{r,d}(k) = x_{r,0} + v_h(k)t_{hw,d} \tag{3}$$

where $x_{r,0}$ a constant representing the desired distance at standstill. The driver is enabled to vary $t_{hw,d}$ in between 1.0 to 2.5 s, thus influencing $x_{r,d}(k)$. The corresponding tracking error is defined as $e(k) = x_{r,d}(k) - x_r(k)$.

Besides the primary objective $\mathcal{O}_1$, several secondary control objectives are defined. Regarding the comfort of a driving action, the peak values of the host acceleration $a_h(k)$ should be minimized. This holds as well for the jerk $j_h(k)$, however this is not taken into account to this point. To obtain required driving behavior, the relative speed $v_r(k)$ should be minimized. This yields the following secondary control objectives $\mathcal{O}_2$

$$\mathcal{O}_2 : \begin{cases} \min\limits_{k\to\infty} v_r(k) \\ \min\limits_{k\to\infty} |a_h(k)| \end{cases} \tag{4}$$

To guarantee safe operation with respect to erroneously detected objects, the host vehicle minimum acceleration is constrained at $a_{h,min} = u_{min} = -3.0\,\mathrm{m\,s^{-2}}$ [1]. Out of comfort reasons, the maximum acceleration $a_{h,max} = u_{max}$ of the host vehicle and the absolute value of the jerk $j_h(k)$ are constrained as well. For the same reason, the constraint on the maximum acceleration is (linearly) dependent on the host speed, i.e. $u_{max} = u_{max}(v_h(k))$, with decreasing u_{max} for increasing $v_h(k)$. Furthermore, the relative distance should always be positive in order to avoid a collision, i.e. $x_r(k) > 0$. The constraints thus are

$$\mathcal{C} : \begin{cases} 0 < x_r(k) \\ u_{min} \le u(k) \le u_{max}(v_h(k)) \\ |j(k)| \le j_{max} \end{cases} \tag{5}$$

B. Model Predictive Control

Model Predictive Control (MPC) is widely adopted in industry as an effective means to deal with multivariable constrained control problems. MPC in a receding horizon fashion performs an optimization in every time-step, yielding state or situation dependent control [12]. Besides the multivariable, constrained model derived in the previous section, situation dependent control is required to enable mimicking of human driver behavior to some extent. Application of MPC to a linear system yields a hybrid system [2]. Due to the equivalence of MPC and other subclasses of hybrid systems, analysis and synthesis tools of these subclasses may be adopted [13]. Hence, MPC in a receding horizon fashion is chosen as an appropriate framework to design the ACC S&G system (see e.g. [6]).

The state vector $x(k)$ is extended with the previously implemented control value $x_e(k) = (x^T(k), u(k-1))^T$ and $\delta u(k) = u(k) - u(k-1)$ becomes the new control output. The output vector is extended accordingly, $y_e(k) = x_e(k)$. The original Input-Output model thus converts to an Incremental Input-Output (IIO) model, thus assuring zero steady-state error [18]. Furthermore, the variation in the control output $\delta u(k)$ is used as a measure for the jerk $j_h(k)$.

MPC is based on the minimization of a cost criterion J over a prediction horizon. Assuming steady-state behavior of the target vehicle, the future system states are predicted using the model $\mathcal{M}$ and the current states $x_e(k)$. This yields the predicted states $x_e(k+n|k)$ and the predicted tracking error $e(k+n|k)$, at $n \ge 0$ time steps in future, starting at discrete time step k. The quadratic cost criterion becomes

$$J(\delta U(k), x_e(k)) = \sum_{n=1}^{N_y} \left[\xi^T(k+n|k)\, Q\, \xi(k+n|k)\right] + ...$$
$$... \sum_{n=0}^{N_u-1} \left[\delta u^T(k+n)\, R\, \delta u(k+n)\right] \tag{6}$$

where $\delta U(k) \triangleq (\delta u(k), \ldots, \delta u(k+N_u-1))^T$ and $\xi(k+n|k) \triangleq (e(k+n|k), v_r(k+n|k), a_h(k+n|k))^T$ column vectors, $k+n|k$, $n \ge 0$ predictions replacing the states and output at time $k+n$, Q, R the weights on the tracking error, the secondary control objectives and the derivative of the control output respectively, and N_y, N_u the output and the control horizon, with $N_u \le N_y$. For $N_u \le n < N_y$ the control signal is kept constant, i.e. $\delta u(k+n) = 0$. Furthermore, $x_e(k|k) = x_e(k)$ and $u(k+n) = u(k+n-1) + \delta u(k+n)$, for $n \ge 1$.

Assume that a measurement of the state $x_e(k)$ of the model $\mathcal{M}$ is available at the current time k. The MPC optimization problem is then formulated as

$$\min_{\delta U(k)} \{J(\delta U(k), x_e(k))\} \tag{7}$$

which is subject to the model $\mathcal{M}$ and the constraints $\mathcal{C}$. Every time step k, the computed optimal $\delta u^*(k)$ is used to compute the new control output $u(k) = u(k-1) + \delta u^*(k)$. This $u(k)$ is applied to the system, after which the optimization (7) is performed again. Stability of the resulting controller has been proven afterwards via an appropriate common quadratic Lyapunov function. This is out of the scope of this paper and will not be discussed further at this point.

C. Explicit MPC

The optimization (7) requires significant computational power. Consequently, direct online implementation is prohibited. Solving (7) as a multi-parametric quadratic program (mpQP) with parameter vector x_e enables an explicit definition of the problem by offline optimization. The resulting explicit controller inherits all stability and performance properties of the original controller. A disadvantage is the need to tune the controller offline after which a re-computation of the explicit controller is necessary [3].

Solving a mpQP, the state-space $X \in \mathbb{R}^{n_x}$ with $n_x = \dim\{x_e\}$ is divided into R polyhedral regions $R_i(x_e)$, $i = 1, \ldots, R$. For each region R_i, an optimal control law is computed. The result, a state dependent and a constant part, $F(R_i, x_e(t)) \in \mathbb{R}^{R \times n_x}$ and $g(R_i) \in \mathbb{R}^R$, $i = 1, \ldots, R$ respectively, is stored in a look-up table. This yields a state feedback solution, which is continuous and piecewise affine

$$u(t, R_i) \quad = \quad F_i\, x_e(t) + g_i, \quad i = 1, \ldots, R \tag{8}$$

In every time step t, a function evaluation instead of the original optimization problem remains. To constrain the solution space of the mpQP, system boundaries $\mathcal{B}$ are defined

$$\mathcal{B} : \begin{cases} 0 < x_r(t) \le x_{rr} \\ 0 \le v_h(t) \le v_{h,max} \\ 0 \le v_t(t) \le v_{t,max} \\ -v_h \le v_r(t) \le v_{t,max} \end{cases} \tag{9}$$

where x_{rr} the radarrange, $v_{h,max}$ the maximum host vehicle velocity and $v_{t,max}$ the maximum target vehicle velocity. The bounds on $v_h(t)$ and $v_t(t)$ in fact yield the bound on $v_r(t) = v_t(t) - v_h(t)$. In Fig. 3 a crosscut of the state-space at constant $u(k-1)$ is shown, including the bounds $\mathcal{B}$.

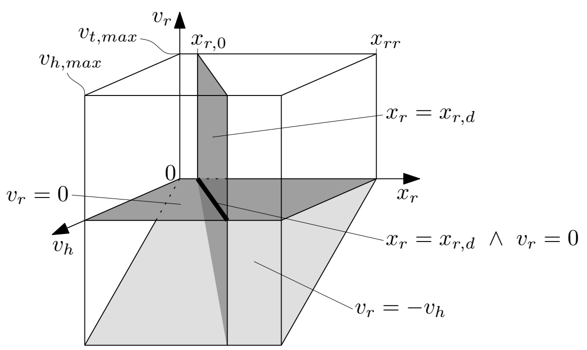


Fig. 3. Visualization of a 3D crosscut of the state-space $x_e(t)$ at constant $x_{e,4} = u(k-1)$. The state-space is bounded by $\mathcal{B}$.

The total controller design is implemented using the Multi Parametric Toolbox (MPT) [16]. The result is a 4D solution space comprising a continuous, piecewise affine state feedback control law, which is dependent on the 4D state vector $x_e(t)$. In Fig. 4, three 2D crosscuts of this solution space are shown. The grey surfaces represent regions with a constant control law. The three crosscuts are made at constant x_r and show the variation in regions as a function of $x_{e,4} = u(k-1)$. As Fig. 4 shows, the number and size of the regions R_i changes. Furthermore, the solution space decreases as a result of the speed dependency of the constraint $u(t) \leq u_{max}(v_h)$.

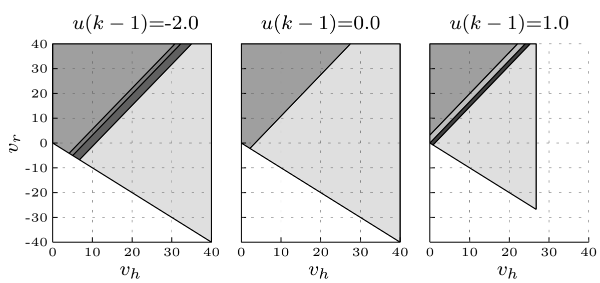


Fig. 4. Three 2D crosscuts of the solution space at constant $x_r = 10\,\mathrm{m}$ with varying $x_{e,4} = u(k-1) \in \{-2.0, 0.0, 1.0\}\,\mathrm{m\,s^{-2}}$.

IV. Implementation and performance evaluation

To enable actual implementation and corresponding performance evaluation, some additional functionality is required for the controller designed in Section III. Simulations exploring the complete envelope of working conditions have validated the functionality of the resulting controller. Final implementation on a vehicle has enabled actual performance evaluation of the controller. Both comfortable and required driving behavior are discussed.

A. Additional functionality

The ACC S&G system should incorporate ACC functionality as well as CC functionality. Furthermore, to prevent chattering between actuation of the throttle and the brake system, u_{th} respectively u_{br}, a hysteresis is incorporated at the corresponding transitions. This is achieved by a subdivision of the control output $a_{h,d}$ into separate control signals $a_{h,th,d}$ and $a_{h,br,d}$ for the acceleration respectively the deceleration part. The difference between $a_{h,th,d}$ and $a_{h,br,d}$ is established via different time-headway values. Nor the throttle, nor the brake system is actuated during a transition. As a result, the vehicle gradually decelerates due to friction and resistance forces. This is comparable to human driver behavior.

To incorporate CC functionality, a 'virtual target vehicle' is designed. This vehicle virtually drives with a speed equal to the CC setspeed v_{CC} at the desired distance $x_r = x_{r,d}(v_h(t))$ with respect to the host vehicle. In this way, the same controller as designed in Section III can be used, requiring only appropriate switching between the actual and the virtual target vehicle radar output. The switching is based on the control output $a_{h,d}$; the control output in CC-mode $a_{h,CC,d}$ is compared to the output in ACC-mode $a_{h,ACC,d}$. The smallest of the two determines which vehicle is used as a target assuring smooth switching between CC and ACC-mode.

B. Simulations

In order to evaluate the functionality of the controller, a set of 7 distinct situations encompassing the total envelope of working conditions is determined, see Table I. Based on this set of situations, a test program with different driving scenarios is set-up. All test scenarios have first been simulated and evaluated. For the simulations, Matlab / Simulink is used in combination with PreScan, which provides a visual simulation environment [24]. In Fig. 5(a) a screenshot of such an environment is shown. Different control settings have been evaluated, showing proper and safe operation of the ACC S&G system for the complete envelope of working conditions.

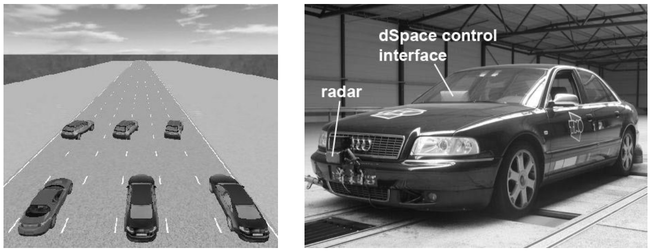
C. Experimental setup

To validate the simulation results and to enable performance evaluation, the controller has been implemented on an Audi S8 using a dSpace AutoBox (Fig. 5(b)). A test program again encompassing the complete envelope of

TABLE I

Envelope of working conditions

1) Steady following of a target vehicle with varying speed under various conditions; e.g. traffic jam, highway and urban traffic
2) Approach of a standstill or stationary driving vehicle yielding a CC to ACC switch
3) A negative and positive cut-in, i.e. $x_r < x_{r,d}$ for $v_r < 0$ and $v_r > 0$ respectively
4) A cut-out, yielding an ACC to CC switch
5) Following of a decelerating vehicle to standstill
6) Driving away at a traffic light and following of an accelerating vehicle yielding an ACC to CC switch
7) Accelerating and decelerating to v_{CC}



(a) (b)

Fig. 5. (a): Screenshot of a PreScan simulation environment. Three ACC S&G-equipped host vehicles and three target vehicles causing corresponding cut-in situations are shown. The ACC S&G systems of the host vehicles are tuned distinctively for comparison. (b): The Audi S8 in which the ACC S&G is implemented. The functionality of the controller was first tested in the TNO VEHIL test facility [24] before the tests in actual traffic have been performed.

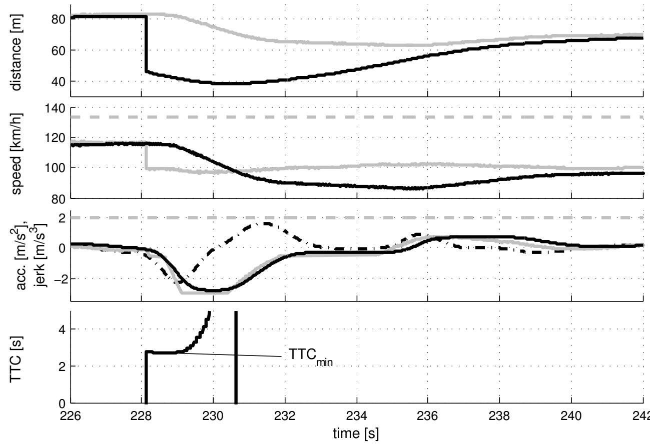


Fig. 7. Experimental results of a cut-in situation (at about 228 s). See Fig. 6 for explanation of the plots.

working conditions, is set up. While performing the tests, an indication of the comfort of the driving behavior and the actual required driving behavior is given.

Fig. 6 and 7 show example results corresponding to the approach of a standstill vehicle respectively a negative cut-in situation (situations 2 and 3 of Table I). In both cases, acceleration is limited to $-3.0 \leq a_h \leq 2.0\,\mathrm{m\,s^{-2}}$, which explains the saturation of $a_{h,ACC,d}$ and $a_{h,CC,d}$. Fig. 6 shows switching between CC and ACC mode at about 22.5 s; Initially, $a_{h,d}$ equals $a_{h,CC,d}$. With decreasing x_r, $a_{h,ACC,d}$ decreases, crossing $a_{h,CC,d}$ at about 22.5 s. This yields a switch from CC to ACC mode. In Fig. 7, a transient between braking and throttle at about 232 to 235 s is shown; The vehicle gradually decelerates, yet x_r increases (see IV-A).

D. Comfortable behavior

Evaluating measurements solely on the basis of acceleration peak values is not decisive regarding comfort of a driving action. The corresponding jerk peak values have to be taken into account as well. Driving actions with relatively high deceleration peak values do not automatically imply uncomfortable driving when these peak values are reached gradually, i.e. with small jerk peak values, and vice versa. For example the results shown in Fig. 6 show a relatively high acceleration peak value. Yet the corresponding driving action was experienced as comfortable, which may be related to the relatively low jerk peak values. In general, it is difficult to accurately distinguish whether uncomfortable behavior is related to acceleration or jerk peak values.

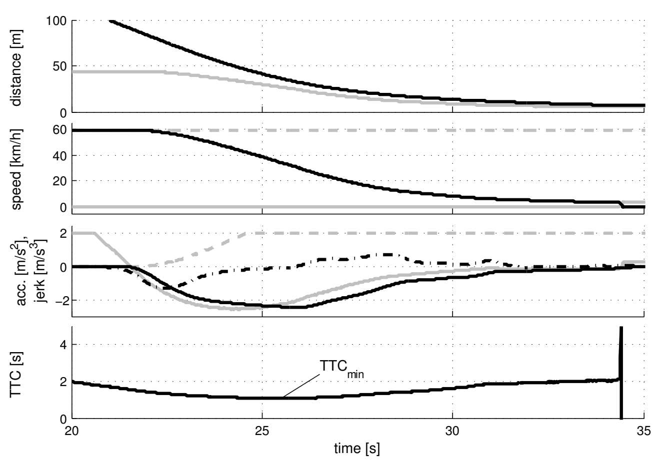


Fig. 6. Experimental results of the approach of a standstill vehicle. The solid black plots represent x_r, v_h, a_h and TTC. The solid grey plots represent $x_{r,d}$, v_t and the corresponding $a_{h,d} = a_{h,ACC,d}$. The dashed grey plots represent v_{CC} and the corresponding $a_{h,d} = a_{h,CC,d}$. The jerk is shown in dash-dotted black on the same scale as the acceleration.

Furthermore, comfortable acceleration and jerk peak values are proportional to the host-speed; the higher the host-speed, the lower the peak values that are still experienced as comfortable. 'Normal' acceleration and deceleration peak values for passenger cars are bounded by $-3.3 \leq a \leq 1.2\,\mathrm{m\,s^{-2}}$, whereas typical values for traffic jam or congestion behavior are bounded by $-0.75 \leq a \leq 3.7\,\mathrm{m\,s^{-2}}$ [10]. Actual values are clearly subjective, yet the experimental results show about the same values for comfort limiting acceleration values. Besides that, these values support the perceived host-speed dependency of comfortable acceleration levels. Regarding comfort limiting jerk peaks, the experimental results indicate values of about the same order as the values for the comfort limiting acceleration peaks.

E. Required behavior

Typically, ACC S&G behavior due to traffic requirements is rendered into control objectives that are based on a desired time-headway and zero relative speed (Eq. (3), (4)). These objectives, or more specific the corresponding tuning however, are not valid for the complete envelope of working conditions. Braking when $v_r \approx 0$ to compensate for $x_r < x_{r,d}$ (e.g. a cut-in), is not regarded as required behavior. Braking when $x_r \approx x_{r,d}$ to compensate for $v_r < 0$ (e.g. a negative cut-in), indeed is regarded as required. In a cut-in situation with $v_r < 0$, a large negative speed difference is less desirable than a small distance x_r. This result indicates that negative speed differences demand speed control, whereas positive speed differences demand position control without braking.

In accordance with literature (II-C), the experimental results show the relation between the value of TTC_{min} and the corresponding required driving action. As these values are subjective, they are not reported here. Firstly however, per situation different values correspond to the same required behavior; they differ from values that are comparable to literature for braking to standstill, up to two times higher values for cut-in situations (Fig. 6, 7) and even three times higher values for braking behind a stationary driving vehicle. Secondly, the moment TTC_{min} is reached differs; for cut-in situations, this minimum coincides with the jerk peak value, whereas for the other situations, this minimum coincides with the maximum deceleration value, see Fig. 6, 7.

V. CONCLUSIONS

The explicit MPC framework has shown to be very suitable for the design and online implementation of an ACC S&G system. Simulation as well as experimental results have shown the proper functioning of the resulting controller for a complete envelope of working conditions.

Both comfortable driving behavior and driving behavior due to traffic requirements have to be considered when evaluating the performance of an ACC (S&G) system. Comfort is mainly related to vestibularly detectable variables, whereas required behavior is mainly related to visually and auditorily detectable variables. Regarding comfort of an ACC (S&G) system, acceleration and jerk peak values enable objective performance evaluation. Regarding required behavior, $t_{hw}(v_h)$, v_r and $TTC_{min}(x_r, v_r)$ are the most promising metrics enabling objective performance evaluation, yet some situation dependency seems inevitable.

VI. RECOMMENDATIONS AND FUTURE WORK

The distinctness of cut-in situations regarding corresponding required driving behavior demands further research. Future work will focus on the tuning of the controller regarding comfort as well as required behavior, based on the corresponding metrics.

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NOMENCLATURE

Roman letters

a	acceleration	$(\mathrm{m\,s^{-2}})$
e	error vector	
j	jerk	$(\mathrm{m\,s^{-3}})$
k	discrete time	$(-)$
r	reference vector	
t	continuous time	(s)
t_{hw}	time-headway	(s)
T_s	sample time	(s)
TTC	Time-To-Collision ($= x_r/v_r$)	(s)
u	control output	
v	speed	$(\mathrm{m\,s^{-1}})$
v_{CC}	CC setspeed	$(\mathrm{m\,s^{-1}})$
x	position	(m)
	system state vector	
x_{rr}	radarrange	(m)
y	system output vector	

Super and subscripts

br	brake	max	maximum value
d	desired	min	minimum value
e	extended state, i.e. 4D instead of 3D	r	relative, i.e. $x_r = x_t - x_h$
		t	target vehicle
h	host vehicle	th	throttle