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Longitudinal Model Predictive Control with Comfortable Speed Planner

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Abstract—Guaranteeing simplicity and safety is a real challenge of Advanced Driver Assistance Systems (ADAS), being these aspects necessary for the development of decision and control stages in highly automated vehicles. Considering that a human-centered design is generally pursued, exploring comfort boundaries in passenger vehicles has a significant importance. This work aims to implement a simple Model Predictive Control (MPC) for longitudinal maneuvers, considering a bare speed planner based on the curvature of a predefined geometrical path. The speed profiles are constrained with a maximum value at any time, in such way that total accelerations are lower than specified constraint limits. A double proportional with curvature bias control was employed as a simple algorithm for lateral maneuvers. The tests were performed within a realistic simulation environment with a virtual vehicle model based on a multi-body formulation. The results of this investigation permits to determine the capabilities of simplified control algorithms in real scenarios, and comprehend how to improve them to be more efficient.

Index Terms—Model Predictive Control, Simulation Environment, Automated Driving.

I. INTRODUCTION

In the path of automated driving an efficient mobility is a clear purpose of the intelligent transportation industry, optimizing the use of vehicles and infrastructure to provide safety and comfort within the driving experience. It has been determined that passenger perception of comfort is very subjective and vary due several factors, being the users driving style pointed as the most important aspect [1]. The magnitude of comfort is inversely propotional to vehicle's acceleration and its relative change (jerk), hence the higher these values are, the more uncomfortable should be the driving [2].

One of the typical requirements in vehicles automation is the capability to follow specified routes being time effective, comfortable and considering limits for traveling velocities. The implementation of a speed planner that consider smoothness in acceleration and jerk transition in curve paths is a very useful way to improve comfort. Some strategies have been employed as Jerk Limitation Method [3] or Quintic Bezier Curve Method [4]. However these procedures mean additional efforts that could be avoided using alternative strategies in longitudinal control algorithms.

Model Predictive Control (MPC) is a concept based on optimal control theory, where future behaviors of a test platform can be predicted from its model. A reduced design

model with this technique permits to obtain acceptable results, having the versatility to specify constraints as acceleration and jerk responses [5]. The present work aims to use a MPC for longitudinal maneuvers, in order to take advance of its prediction capacity without complex speed planner calculation.

This paper is organized as follows: Section II present the control algorithm used for longitudinal control and its relationship with the speed planner proposed. Section III describes the simulation environment where tests are developed considering the virtual vehicle used as test platform. Section IV shows the obtained results followed by a proper discussion. Finally the Section V summarizes the most important ideas.

II. CONTROL ALGORITHM

The design of control algorithms for path tracking applications based on passenger comfort is a very useful technique on intelligent transportation systems. In this section, a novel approach based on a speed planner, with special attetion in standarization [2], and the proposed longitudinal MPC control approach is presented.

Both algorithms are developed under a general automated framework [6], a six block architecture which includes the following modules: acquisition, perception, communication, decision, control and actuation. This framework has been previously used for different automated vehicle applications such as path tracking lateral [7], validation of longitudinal controllers [8] and overtaking maneuvers [9]. This architecture is suitable for implementing a path tracking controller module taking into account the passenger comfort.

A. Speed Planner

The speed planner is based in offline and online modules as shown in Figure 1. Offline module comprises the local map and static speed planner. The local map stage used in this work is part of a decision module, where Bezier curves have been used to generate a soft path along a route including straight lines, turns and a lane change (Figure 2) [10]. Additionally, the local map stage calculates the curvature (k) of each segment of the road as parametric curves [11] delivering this information along with n local map points (x, y) to static speed planner.

The objective of the proposed approach is to assure passenger comfort during autonomous driving. The comfort parameter is obtained through a combination of longitudinal (a_x),

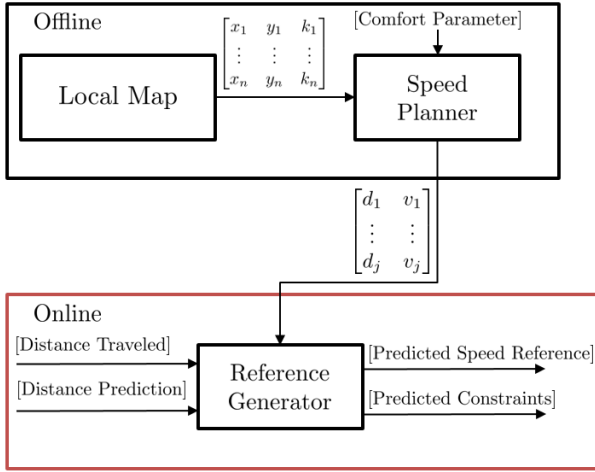


Fig. 1. Speed Planner Framework

lateral (a_y) and vertical (a_z) accelerations, considering certain weights ($n = n_x = n_y = 1.4$) [2]:

$$a_w = \sqrt{n_x \cdot a_x^2 + n_y \cdot a_y^2 + a_z^2} \quad (1)$$

Numerical values have been assigned to a_w indicating several levels of umcomfortability: 0.315m/s² (Not), 0.63m/s² (a little), 1.0m/s² (fairly), 1.6m/s² (uncomfortable) and 2.5m/s² (very). The comfort parameter and maximum speed are related using the curvature of each road segment defined as k :

$$V_{max} = \sqrt{\frac{a_w}{n \cdot k}} \quad (2)$$

According to Equation 2, the speed reference is calculated based on the curvature of the road limiting the speed to 15 km/h. The speed profile is generated as a function of the distance traveled d_t from a starting point (x_0, y_0) . Figure 2 shows the curvature profile of the test scenario. From that information a speed profile is generated using the Equation 2.

Once the speed profile is obtained (as a 2D vector relating distance traveled (d) against speed (v)), it is sent to the online reference generator, which supply the MPC with the longitudinal speed references (see Section 2.B). While the vehicle is moving it calculates the value of d_t by integrating the current speed, this value is passed to the reference generator along with the prediction of the longitudinal displacement calculated by the controller. This allows to calculate the appropriate speed reference according to the vehicle position and its future predictions based on distance traveled instead of time.

B. Model Predictive Control

Model Predictive Control approaches are based on the use of a mathematical representation of the model to predict the future behavior of a system in a finite time horizon. The control action is obtained by minimizing a cost function which can include constraints. The approach depends on a precise characterization of the system in order to work correctly.

However, real-time implementation is possible, updating the current state and solving the problem each sample time, thus allowing the use of an approximated model. With this in mind, a brief explanation of the control problem is presented.

A real-time implementation allows to work with a triple-integrator model based on the speed (v_l), acceleration (a_l) and jerk (j_l) of the vehicle seen as a particle in longitudinal displacement (d_l). The representation of the system in the classical state-space description is shown in Equation 3.

$$\begin{bmatrix} \dot{d}_l \\ \dot{v}_l \\ \dot{a}_l \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} d_l \\ v_l \\ a_l \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} j_l \quad (3)$$

In this model the jerk acts as the control variable, however interest is over the predicted states of the longitudinal acceleration which will be the input to the vehicle. Following classical state space MPC formulation [12], the control law can be calculated from the minimization of the following cost function.

$$J = \sum_{s=1}^{N_h} \|v_l(t+s|t) - v_{ref}(t+s|t)\|^2 \quad (4)$$

Where t is the current time, s is the sample index starting from time t , N_h is the number of samples of the prediction, $v_l(t+s|t)$ represents s^{th} longitudinal speed prediction calculated at time t , while v_{ref} is the reference speed including its prediction delivered by the speed planner. Finally the vector solution \bar{a}_l is found and the command selector choose to accelerate or decelerate depending on the sign; it also choose the prediction index to use as control action to the simulated vehicle. Future speed references of the online module of the speed planner are calculated based on the past prediction of the MPC as it can be shown in Figure 3 where the controller general framework and speed profile generator are detailed.

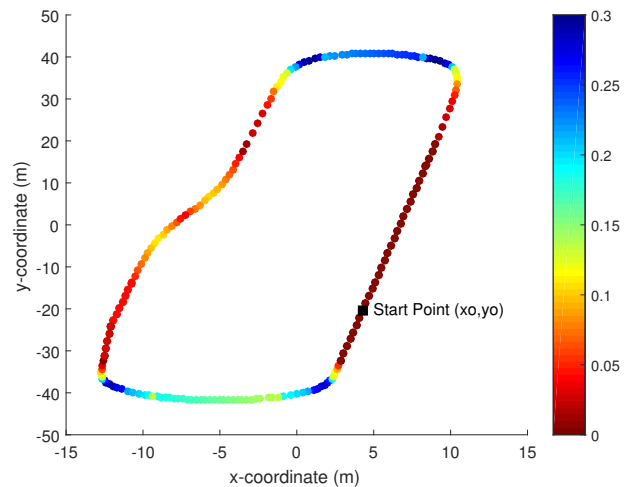


Fig. 2. Curvatures in predefined circuit

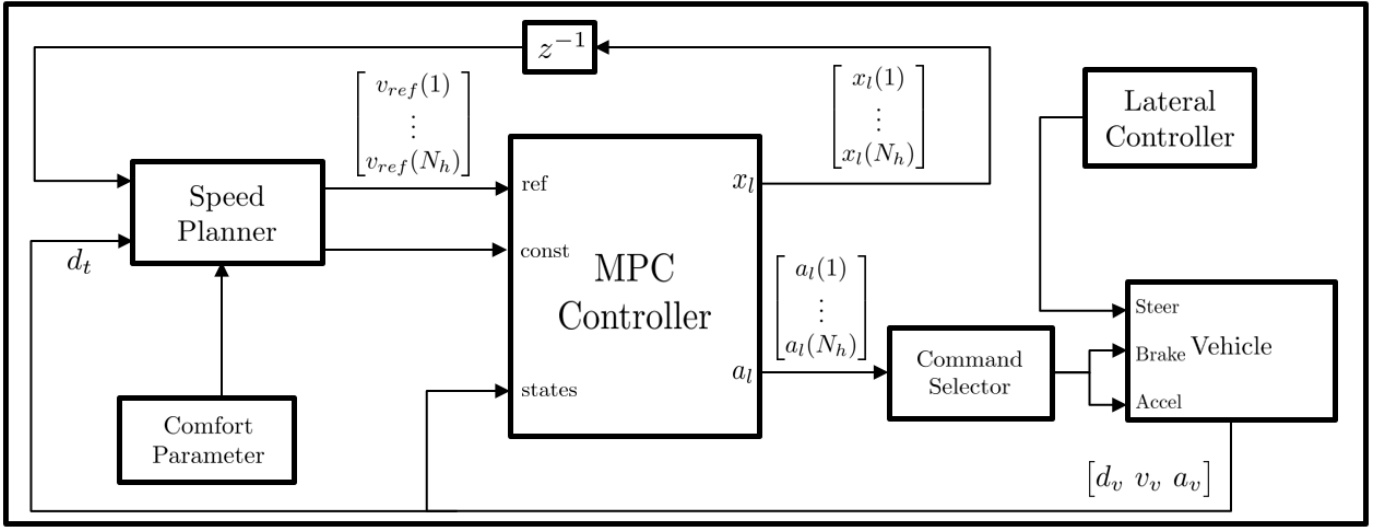


Fig. 3. Model Predictive Control Framework integrated with Speed Planner

Lastly, constraints values of the controllers are fixed for acceleration and jerk, however the speed constraints are based on the speed planner predictions. L represents an error allowed for the solution of the speed vector.

$$\begin{aligned} v_{ref}(t+s) - L &\leq v_l(t+s|t) \leq v_{ref}(t+s) + L \\ a_{min} &\leq a_l(t+s|t) \leq a_{max} \\ j_{min} &\leq j_l(t+s|t) \leq j_{max} \end{aligned} \quad (5)$$

For solving previous constrained optimization problem, the MPC solver ACADO toolkit [13] is used. It is a self-contained library based on C++ designed to solve linear and non-linear models under multi-objective optimization functions.

III. SIMULATION ENVIRONMENT

The developed approach is tested in Dynacar simulation environment [14]. Dynacar features a vehicle physical model based on multi-body formulation with a framework integrated in Matlab-Simulink. The motion of the chassis and wheels are considered into a model of fourteen degrees of freedom, being possible for the chassis to translate and rotate in any cartesian axis, and for each wheel to move in vertical direction and rotate around its own axis. The suspension system degrees of freedom are considered as macro-joints and their behavior is modelled through look-up tables. The position and orientation of wheels are important to calculate the suspension response, therefore the values within the tables strongly depend on the steering input and the roll angle [15].

The vehicle physical model has been designed to provide each wheel with steering angle, and traction or braking torque, being this an versatile to users due the possibility to test control algorithms fitted to a model within a realistic environment. The physical behavior of tire-ground contact was obtained through the Magic Formula Tire Model [16].

In the following subsections the powertrain and brake models implemented will be briefly detailed. The parameters

TABLE I
VIRTUAL VEHICLE PARAMETERS

Mass (kg)	611.500
CG location x, y, z (m)	-0.928, 0.000, 0.488
Wheelbase (m)	1.686
Trackwidth (m)	1.094
Inertia I_x, I_y, I_z (kg-m ²)	243.175, 430.166, 430.166
Front wheel radius (m)	0.265
Rear wheel radius (m)	0.281

of the virtual vehicle used as simulation testbed in this work are depicted in Table I.

A. Powertrain model

Fig. 7 shows the simplified powertrain model employed. A synchronous electric motor, a gearbox and a mechanical differential are the only elements involved. The drivetrain type is rear-wheel-drive of locked axle. The model behavior is linearly dependent of the throttle pedal position (u_t) which goes from 0 to 1.

The selected electric motor can develop 57N-m of constant traction torque (T_e) before surpassing a speed of 220rad/sec, providing a decreasing torque as the motor speed (ω_e) increases up to 785rad/sec. A regenerative braking torque (T_b) is considered into the model, which delivers 8N-m constantly

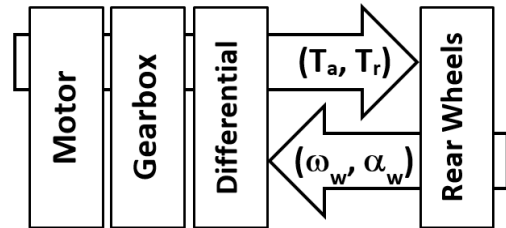


Fig. 4. Powertrain model

if the motor speed is higher than 50rad/sec and u_t is zero. This estimation was obtained from movement tests at several speeds. Both traction and regenerative braking characteristics are typical in this kind of motor [17], [18].

The automatic gearbox has a reduction of 1:9.23 permitting reverse, neutral and drive positions. The differential changes the power flow direction in 90 degrees to the rear wheels with a 1:1 transmission ratio. Compact equations for traction (T_a) and regenerative braking (T_r) torques are shown in Eqs. 6-7.

$$T_a = T_e \eta_{gd} N_{gd} \text{sign}(u_t) - ((I_e + I_g) N_{gd}^2 + I_d N_d^2) \alpha_w \quad (6)$$

$$T_r = T_b \eta_{gd} N_{gd} \quad (7)$$

Where η_{gd} is the combined efficiency of the driveline, N_d , N_d and N_{gd} are the gearbox, differential and combined transmission ratio of the driveline, and I_e , I_g and I_d are the inertias of engine, gearbox and differential. The angular acceleration of the rear wheels (α_w) is necessary to calculate the loss of tractive force due to the inertia of driveline components [19].

B. Brake model

The braking behavior is related with brake pedal position (u_b) that goes from 0 to 1. The model consists of a reduced single-circuit [20] where the braking torque depends of the pressure over the braking disc exerted by the wheel cylinder (P_w) as shown in Fig. 5. As the dynamic of a typical brake line considers a lag associated to the hydraulic system (τ_b), the pressure can be modeled as a discrete transfer function with a defined time span (t_s) as depicted in Eq. 8.

$$P_w(z) = (K_c t_s u_b) / (\tau_b z + (t_s - \tau_b)) \quad (8)$$

Control valves in brake systems are generally used to adjust pressure in rear brakes and prevents tires lock. This behavior is introduced keeping a brake gain ($K_b i$) constant for rear wheels when its value exceeds a selected limit. An hyperbolic tangent function is used to control the orientation of the braking torque, being this calculation dependent of the wheel speed (ω_w) as can be seen in Eq. 9

$$T_b = P_w K_b \tanh(\omega_w) \quad (9)$$

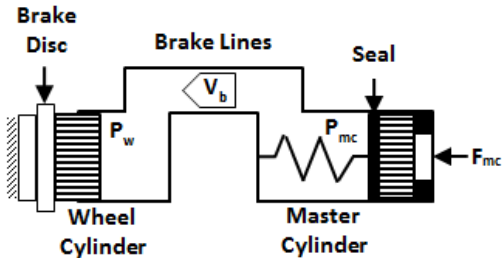


Fig. 5. Brake model

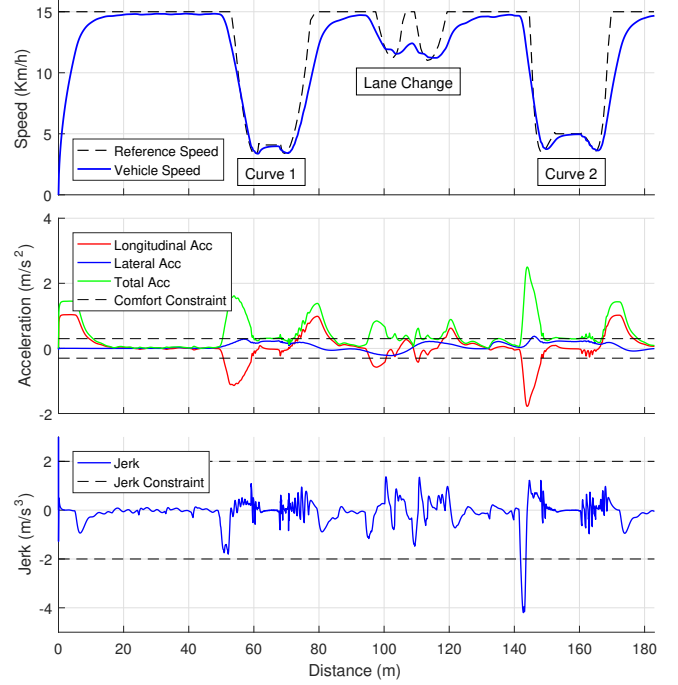


Fig. 6. Not uncomfortable Accelerations (0.3m/s^2)

IV. TEST AND RESULTS

In this section the proposed approach will be tested in several scenarios, considering the test circuit depicted in Figure 3. This circuit is suitable to evaluate the performance of the proposed approach in different urban conditions, such as straight lines, turns with different radii and lane change.

For the developed tests, the speed profiles are calculated in such way that total accelerations are lower than specified constraint limits, going from not uncomfortable (0.315m/s^2) to very uncomfortable (2.5m/s^2) level. A permissible speed error band of 0.1km/h around the speed profile depicted as L in Equation 5, accelerations limits of -4m/s^2 and 1m/s^2 , and jerk boundaries of -2m/s^3 and 2m/s^3 were considered as constraints within the MPC. The optimization problem was solved with a sample time of 1s and 10 total samples.

Two tests were performed in the environment detailed in Section II for evaluating the performance of the MPC speed tracker with a speed planner. Test responses for comfort parameters levels of Not Uncomfortable ($a_w = 0.3\text{m/s}^2$) and Very Uncomfortable ($a_w = 2.5\text{m/s}^2$) are detailed as follows.

In both cases the speed of the vehicle follows the reference. The MPC anticipates future changes at the entrance and exit of turns and lane change situation. For Very Uncomfortable level the lane change does not appears due higher accelerations are permitted. Some inconsistencies are observed during curve paths (close to $d = 50\text{m}$ and $d = 140\text{m}$), and is because the vehicle faces turns at high velocity and violent transitions are needed to follow the speed reference.

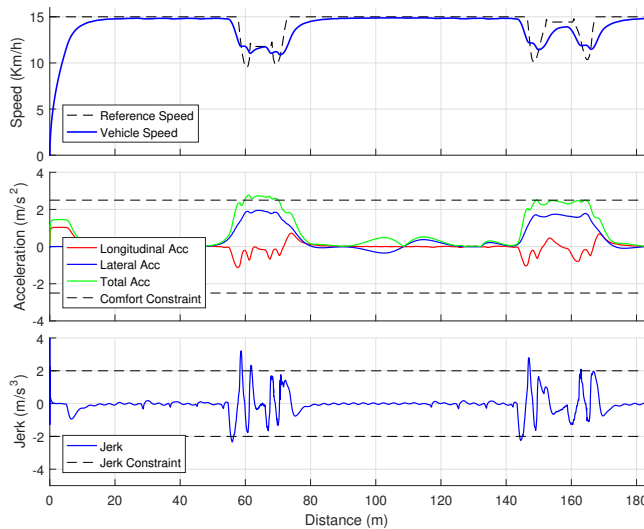


Fig. 7. Very Uncomfortable Accelerations (2.5m/s^2)

The acceleration component which comprises longitudinal and lateral values succeeded while the vehicle circulates through curve paths. For Not Uncomfortable level, some peaks appear in longitudinal accelerations in order to follow the speed planner before entrance and after exit of curves, having this an impact in the level of comfort in total acceleration value. However, the study is focused to achieve a desirable comfort level exclusively during turns to adapt the safety user perception under this circumstance. Peaks of acceleration are not observed in Very Uncomfortable level because speed does not need a violent transitions from curves to straight paths.

Jerk values are generally within limits in both comfort level cases. The solver surpasses jerk constraint in order to achieve reference speed under very short periods of time, where greater priority is given to the MPC optimization function.

V. CONCLUSIONS

The results of this investigation permits to determine the capabilities of simplified control algorithms in real scenarios, and comprehend how to improve them to be more efficient. An MPC speed tracker was evaluated and showed a good performance while working together with an speed planner based on curvature and comfort of passengers. At different comfort levels the controller behaves properly and total acceleration in curves were kept close to the reference limit. In future investigations this simplified MPC will be evaluated and configured on real test platforms.

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