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Speed Profile Generation based on Quintic Bézier Curves for Enhanced Passenger Comfort

David González±, Vicente Milanés±, Joshué Pérez∓ and Fawzi Nashashibi±

Abstract— **Automated ground vehicles are becoming a reality for future deployment due to their potential improvement of safety, comfort or emission reductions. However, some challenges remain unsolved such as navigation in dynamic urban environments, where safety and comfort are paramount. In this paper, a novel speed profile generator, based on quintic Bézier curves, is presented. This approach permits to improve the comfort in automated vehicles by constraining the global acceleration in the whole ride. Moreover, a comparison with a Jerk limitation algorithm for continuous acceleration profile and a smooth speed profile is performed. The quintic Bézier curves assure continuity of velocity curves and therefore a smooth Jerk and acceleration profiles. The ISO 2631-1 standard, for evaluation of human exposure to whole-body vibration, is considered in both methods for lateral and longitudinal comfort constraints. Simulations show that this approach improves comfort by smoothing the acceleration and jerk profiles, while also constraining the total acceleration perceived by the passengers.**

I. INTRODUCTION

Intelligent vehicles are reaching maturity and, with them, road security is increasing. A traffic safety report from the National Highway Traffic Safety Administration (NHTSA) shows that from 2003 to 2012 fatalities in the U.S. decreased 27% and 14% in rural and urban areas respectively [1]. This is directly linked to current developments in Advanced Driver Assistance Systems (ADAS), which are aiding drivers by reducing human errors [2].

As a matter of fact, several real road demonstrations using automated vehicles have been recently carried out: Daimler demonstrated autonomous capabilities in the Berta-Benz memorial route [3]; Audi demonstrated high speed control in a TTS model [4]; and Delphi traveled from San Francisco, CA, to New York city, NY, in 9 days[1]. These are examples of a growing list of manufacturers that, along with Google and several research centers worldwide, push for the development of this technology. However, fully automated driving still remains unsolved, with challenges related to motion and speed planning, involving collision and obstacle avoidance, safe and comfortable driving, among others.

Motion planning research on automated vehicles has been mainly focused on generating optimal paths with respect to length, curvature, its derivate, or a combination of them optimized by a cost function as in [3] or [5]. However, the planning of a proper speed profile has received little attention, as well as the consideration of lateral and longitudinal accelerations and jerk for passenger comfort [6].

Some authors have implemented spatiotemporal lattices to evaluate simultaneously path and speed planning. Ziegler et.al. [7] describe de generation of candidate piecewise trajectories considering position, velocity, acceleration and time (7 dimensions). In McNaughton et al. [8] a similar technique is implemented, arguing that the algorithm has a high computational cost and therefore implementing a graphic processing unit (GPU) to reduce this computation time. Moreover, in both approaches, the search space has to be pruned in order to arrive to a solution in time, introducing suboptimality. On the other hand, Rapidly exploring Random Tree (RRT) has also been implemented to plan simultaneously a path and a speed profile. In [9] RRT* is implemented as an on-line method, considering limit accelerations for the vehicle. This provides a solution that is somehow continuous but not smooth, making it jerky and uncomfortable.

Considerations of comfort in path and speed planning are found in [10]. Firstly, the path is determined by splines or clothoids and then the speed profile is computed following the comfort constraints in ISO 2631-1 standard [11]. The result is a continuous but not smooth speed profile that respects lateral and longitudinal acceleration constrains. Other authors prefer to separate the problem and focus in the speed profile generation as is the case of [12] and [13]. In [12], a speed profile is generated by constant jerk changes in order to have a linear acceleration and a smooth speed profile. This method will be called in the following Jerk Limitation. If a new velocity profile is needed, is possible to redefine the trajectory and follow changes in real time. In [13], the maximum velocity is set respecting lateral and longitudinal accelerations limits. However, the velocity profile is neither smooth nor comfortable.

Villagra et al. [6] achieved to obtain speed profiles that are smooth, respecting the lateral and longitudinal accelerations at the same time. This approach is based on planning smooth speed changes outside the curves with the jerk limitation method [12] and limiting target velocities to respect lateral accelerations when curves occur. Other approaches implement polynomial curves to set speed profiles as [14] and [15]. In [14], curves are chosen by a cost function similar to spatiotemporal lattices, but no reference is given on how the comfort parameter is chosen. On the other hand, in [15] cubic polynomials set time constrained speed profiles, but acceleration is always linear, with a non-continuous jerk.

This paper proposes a novel speed planner algorithm based

±Authors are with the Robotics and Intelligent Transportation Systems (RITS) Team, Inria Paris-Rocquencourt, Domaine de Voluceau, 78153 Le Chesnay, France david.gonzalez-bautista, vicente.milanes, fawzi.nashashibi@inria.fr

∓Author is with Tecnalia, Calle Geldo, Edificio 700, Parque Cientfico y Tecnolgico de Bizkaia, E-48160 Derio, Spain joshue.perez@tecnalia.com

[1]Available online at: http://www.delphi.com/delphi-drive

on quintic Bézier curves, improving the comfort in automated driving. This approach has been compared with the jerk limitation method, as in [6]. The proposed method complies with speed and acceleration limitations, while providing smooth and continuous jerk and acceleration profiles.

II. Problem description

Given a smooth geometric path for an automated vehicle to follow, as in [16], the next problem is to plan a speed profile that leads the vehicle from point A to point B. This speed planner has to be time effective, with an optimal comfort and avoiding to exceed speed and acceleration limits. The comfort is evaluated as the minimization and smoothness of acceleration and jerk profiles, while maintaining a coherent speed profile with respect to traffic rules, the geometry of the path and the lateral accelerations associated to it.

The aforementioned problem is addressed in the literature with the Jerk Limitation method implemented in [12], [6] and [17]. In this method, the jerk is set as three different levels, according to whether the vehicle needs to accelerate, cruise or decelerate (details are explained in Section III). However, in this case the jerk is discontinuous and the acceleration profile is, most of the time, not smooth. Moreover, the speed is computed in terms of time, having inaccuracies in the distance covered over velocity changes due to delays in the control systems, deficiencies of the system adding noise, actuators' time reaction, among others.

To overcome these issues, a new speed planning algorithm implementing quintic Bézier curves is presented. These curves are continuous and smooth, meaning that the jerk profile is also continuous and smooth. The proposed method computes the velocity in terms of the length of the path, instead of time, reducing the inaccuracies described before. Specific objectives of our contribution are described as follow:

- Compute a smooth and continuous speed profile considering acceleration limits (longitudinal, lateral and total acceleration) according to ISO 2631-1 standard [11].
- Address the distance error problem by associating the speed profile in the path speed planner instead of the time.
- Compare the Jerk Limitation implementation and our proposal with quintic Bézier curves.

In order to achieve the latter, the authors implemented the Jerk Limitation algorithm in equal conditions as the Bézier algorithm to have a proper comparison. The implementation of both algorithms is as presented in the following sections.

III. Jerk limitation speed planner

The computation of a comfortable speed trajectory with the Jerk Limitation method, consists on constructing a proper jerk function $j(t)$. It should be able to form speed and acceleration profiles without abrupt changes [12]. Figure 1 depicts in green the seven regions of jerk action for a speed profile.

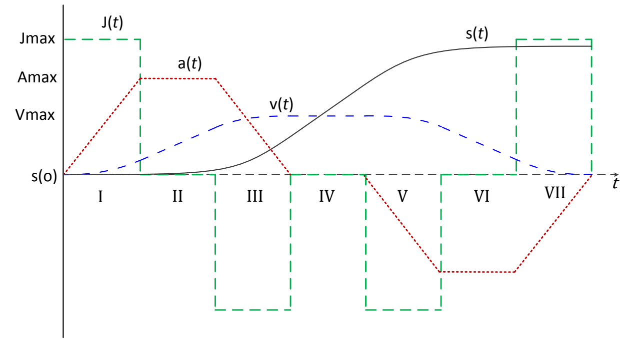

Fig. 1. Intervals for the speed profile generation

$$j(t) = \begin{cases} J_{max}, & \text{if } t = I, VII \\ 0, & \text{if } t = II, IV, VI \\ -J_{max}, & \text{if } t = III, V \end{cases} \quad (1)$$

Equation 1 shows the jerk assignment according to the time intervals t, from I to VII (as depicted in Fig. 1). *Jmax* is chosen as a small value to ensure comfort and smooth changes in acceleration. In [6], this constant value is chosen as $1m/s^3$. The duration of each time interval will depend on the acceleration limit and the distance available to accelerate or decelerate. Based on the given Jerk, the acceleration, speed and distance profiles are computed in Equations 2, 3 and 4 respectively.

$$a(t) = a_0 + j_0 t \quad (2)$$

$$v(t) = v_0 + a_0 t + \frac{j_0 t^2}{2} \quad (3)$$

$$s(t) = s_0 + v_0 t + \frac{a_0 t^2}{2} + \frac{j_0 t^3}{6} \quad (4)$$

where t is the current time interval; and j_0, a_0, v_0, s_0 are the initial jerk, acceleration, speed and distance respectively for the current interval t. The duration of each time interval can be computed as:

$$t_I = t_{III} = t_V = t_{VII} = \frac{A_{max}}{J_{max}} \quad (5)$$

$$t_{II} = t_{VI} = \frac{V_{max} - V_0}{A_{max}} - \frac{A_{max}}{J_{max}} \quad (6)$$

where A_{max} and V_{max} are the maximum values for the acceleration and the velocity respectively. To calculate the cruise time of the vehicle (interval IV of Fig.1), it suffices to compute the distance needed to accelerate (intervals I, II, III) and decelerate (intervals V, VI, VII), in relation with the whole path available, as follows:

$$S_{(t_I - t_{III})} = (V_{max} + V_0)\frac{A_{max}}{J_{max}} + \frac{\left(V_{max} - \frac{A_{max}^2}{2J_{max}}\right)^2 - \left(V_0 + \frac{A_{max}^2}{2J_{max}}\right)^2}{2A_{max}} \quad (7)$$

$$t_{IV} = \frac{D_{total} - S_{(t_I - t_{III})} - S_{(t_V - t_{VII})}}{V_{max}} \quad (8)$$

where Eq. 7 is the distance needed for the acceleration and deceleration segments, however this last is with respect to V_{end} instead of V_0. Equation 8 gives the cruise time of the vehicle at V_{max}. Here D_{total} is the path distance, $S_{(t_I - t_{III})}$ is the distance to accelerate and $S_{(t_V - t_{VII})}$ is the distance to decelerate. For further details in the equations, the reader is referred to [12], [6]. The limit velocity in all equations (V_{max}) is given by the speed limit of the road. The acceleration limit—lateral and longitudinal (A_{max})—is set by the user as the desired comfort level with respect to [11]. Levels are: *Not uncomfortable* ($0.315m/s^2$), *A little uncomfortable* ($0.63m/s^2$), *Fairly uncomfortable* ($1.0m/s^2$), *Uncomfortable* ($1.6m/s^2$) and *Very uncomfortable* ($2.5m/s^2$).

To compute the lateral acceleration limits according to [11], the maximum speed is set for each point in the pre-planned geometrical path, in such a way that the lateral acceleration w.r.t. the curve is not greater than the limits (see Eq. 9).

$$V_{max} = \sqrt{\frac{a_w}{kC}} \quad (9)$$

$$a_w = \sqrt{{k_x}^2 {a_{wx}}^2 + {k_y}^2 {a_{wy}}^2 + {k_z}^2 {a_{wz}}^2} \quad (10)$$

where $k_x, k_y = k = 1.4$, $k_z = 1$ are multiplying factors, a_w is the Euclidean sum of a_{wx}, a_{wy} and a_{wz} which are the r.m.s. accelerations in the different axis. Since the vehicle operates in a two dimensional space, the a_{wz} component of Eq. 10 is neglected. C is the maximum curvature of a turn.

IV. QUINTIC BÉZIER SPEED PLANNER

Bézier curves generation has been widely applied in the robotics field. In this paper our speed planning approach benefits from their low computational cost, invariability, smooth and continuous characteristics to construct a comfortable speed profile for passengers in automated vehicles. To build a Bézier curve it suffices to set the control points of the curve (P_0 to P_n) in the desired shape of the curve.

$$\mathbf{B}(t) = \sum_{i=0}^{n} \mathbf{P}_i \binom{n}{i} (1-t)^{n-i} t^i \quad t \in [0,1] \quad (11)$$

Equation 11 shows the definition of a Bézier curve of nth degree, where t parametrizes the curve from zero to one. In the following the authors explain the considerations to conform a speed profile with this kind of curves.

A. Computation of Bézier curves for a smooth profile

The implementation of Bézier curves in speed planning requires joints between curves to be continuous. Moreover, jerk continuity is only addressed if the speed curve is G^2 continuous. To achieve this we recur to quintic Béziers, since is possible not only to joint two consecutive curves, but also curves and straight segments (e.g. accelerate and then cruise speed), without losing smoothness.

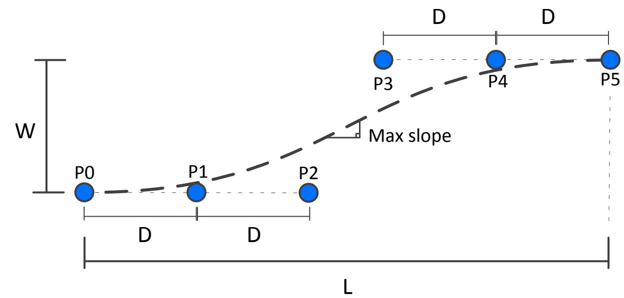

Fig. 2. Fifth degree Bézier curve and its control points

Figure 2 depicts a quintic Bézier curve. Control points are set in a symmetrical way, with distance D between them. This setup allows an intuitive manipulation of the curve, where the maximum slope is at $t = 0.5$, the change in the speed is represented by W; and L is the distance needed for the speed change. For optimal longitudinal speed generation without violating the maximum acceleration of Eq. 10 and, at the same time, minimizing the jerk, is necessary to optimize the curve. Firstly, acceleration limits are set as follows:

$$A_{max} \geq M(t)V(t) \quad (12)$$

$$M(t) = \frac{\mathbf{B}'_y(t)}{\mathbf{B}'_x(t)} \quad (13)$$

where $M(t)$ is the slope of the curve and $V(t)$ is the velocity, both with respect to the parameter t of Eq. 11. $\mathbf{B}'_y(t)$ and $\mathbf{B}'_x(t)$ are the cartesian derivatives of the Bézier curve at the parameter t. Equation 12 is presented in this form due to the abscissa axis being distance instead of time. The optimization of the curve is done iteratively, looking for the lowest curvature profile (smoothest jerk). The curvature of a parametric curve is represented as:

$$K(t) = \frac{\mathbf{B}'(t) \times \mathbf{B}''(t)}{||\mathbf{B}'(t)||^3} \quad (14)$$

$$K(t) = \frac{300WD(2t^3 - 3t^2 + t)}{||\mathbf{B}'(t)||^3} \quad D > 0 \quad (15)$$

$$D = \frac{1.875(W - LM)}{(5M(1 - 1.875)} \quad (16)$$

where Eq. 14 is the signed curvature, Eq. 15 is the curvature for this specific setup of the Bézier curve[2], as in Fig. 2. Notice that to achieve G^2 continuity with previous segments it suffices to set P_0, P_1 and P_2 in the same horizontal vector. This assures that every change in the velocity will have zero jerk at $t = 0$ and also at $t = 1$ (P_3, P_4 and P_5 in the same horizontal vector), making the speed profile G^2 continuous in its whole domain. Expressions in Eq. 15 and 16 come from the development of Eq. 14 and Eq. 13 at $t = 0.5$, respectively.

[2]The position of the control points will be defined by D and has to be different from zero to ensure **B**'(t) is different from zero

For the sake of clarity, let's explain the approach as a two stage optimization problem:

- First, Eq. 12 is evaluated at $t = 0.5$ as a first guess of where the critical point of acceleration might be, taking the maximum slope as $M_{(0.5)} = A_{max}/V_{(0.5)}$. With this first slope, the control points interdistance D can be computed with Eq. 16 and L is biased as four times the control points distance ($L = 4D$). Since the objective is to have the minimal jerk (proportional to the curvature, i.e. Eq. 15), the algorithm searches iteratively L around a value of $4D$ to find the minimum curvature profile (e.g. dichotomy since the algorithm looks in the region of the global minima) assuring the minimal jerk for this slope.
- However, the critical slope is not necessarily at $t = 0.5$ due to the characteristics of velocity manipulation w.r.t. distance (see Eq.12). Therefore a new iteration step is needed, varying the velocity in Eq. 12 ($V \in [\frac{V_0+V_{max}}{2}, V_{max}]$) and verifying that each new curve complies with the slope and acceleration limits, i.e. Eq. 12. This constraints the longitudinal acceleration of the speed profile.

The generation of these curves for deceleration profiles is done in a symmetrical way, where $W = (V_{max} + V_{target})/2$, being V_{target} the velocity limit in the highest curvature point of turns in the given geometric path. This allows to respect the maximum speed throughout the navigation distance associated to lateral accelerations (see Eq. 9 and Fig. 4).

B. Considerations on acceleration limits

The comfort limits of ISO 2631-1 [11] describe acceleration actuating in the whole body. In a vehicle, longitudinal and lateral accelerations are the ones taken into account since the vehicle navigates in a plane. To respect the comfort limits in the plane, Bézier curves are only set at the beginning and at the end of the turning area for the speed profile. This is done aiming to accelerate as soon as possible and decelerate as late as possible, while respecting comfort limits.

The previous behavior is depicted in Fig. 3. Longitudinal and lateral acceleration profiles are presented in blue and red. Notice that blue curves which represent absolute longitudinal acceleration arrive to their limit (i.e. $1m/s^2$ for this example) just before encountering the beginning of the physical curve. This is done to force one component to zero while the other one is at is maximum (see Eq. 10). The total acceleration is depicted in the same figure as a black line, showing that the maximum total acceleration of $1m/s^2$ is never surpassed.

Figure 4 presents the speed profile associated to accelerations presented in Fig.3. If the Bézier length is minor or equal to the turn length, then the maximum slope point of the Bézier curve is fixed to the beginning of the curve (the end of the curve for the acceleration profile as in Fig. 4). Otherwise, both speed curves meet at the middle point of the turn.

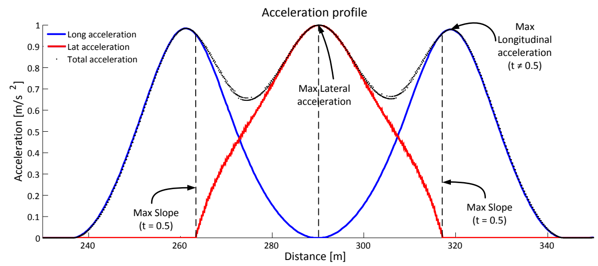

Fig. 3. Absolute longitudinal and lateral acceleration profiles in blue and red respectively. The euclidean sum is represented in black

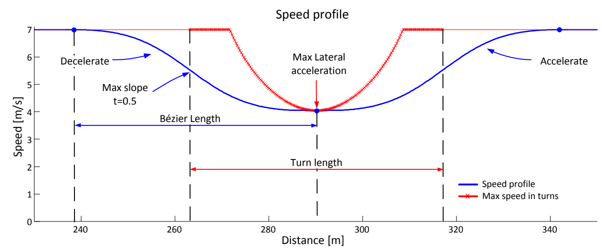

Fig. 4. Speed profile presented in blue. Maximum speed in red (limited to $1m/s^2$ of acceleration)

V. Validation tests

Several tests were carried out in simulation using Matlab/Simulink. This section firstly introduces the simulated scenario; then, the Quintic Bézier speed profile generator for the given scenario as well as the Jerk Limitation speed profile approach are compared, in order to validate the novel proposed method.

A. System Description

The path planning algorithms implemented is described in [16]. The lateral vehicle response is modeled using a dynamic bicycle model that provides good results for urban environments, whereas the longitudinal behavior is modeled as a second order function already tested in real vehicles (Cybercars) in [18]. The control implemented is a Proportional-Derivative controller (PD) for the longitudinal, as in [19], and a weight function with proportional variables as in [20] for the lateral control. Considering this model (e.g. INRIA cybercar model response), the validation experiments have been carried out.

B. Experimental Results

The chosen scenario represents a comfortable speed profile for a geometrical path with three turns that emulates an urban environment. The vehicle needs to travel $2.1Km$ approximately, accelerating and decelerating avoiding to overpass the comfort acceleration (i.e. $1.6m/s^2$ for this experiment) but attempting to achieve the maximum speed possible at all times (the maximum speed is $15m/s$ for this urban scenario).

Figure 5 presents the speed profile for the path that encounters turns at $375m$, $694m$ and $1535m$, being consecutive the two first ones, where the second one is curvier

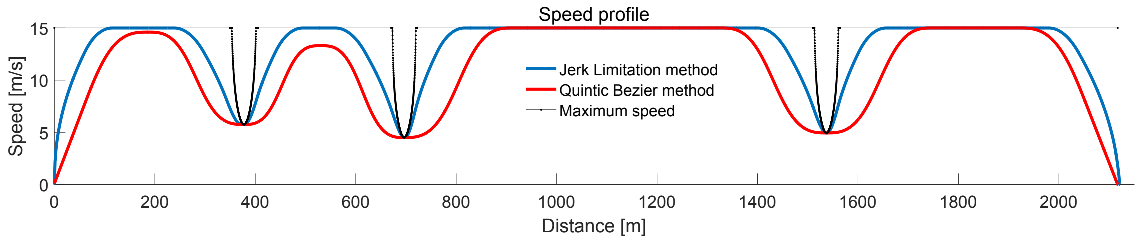

Fig. 5. Speed profile of both methods

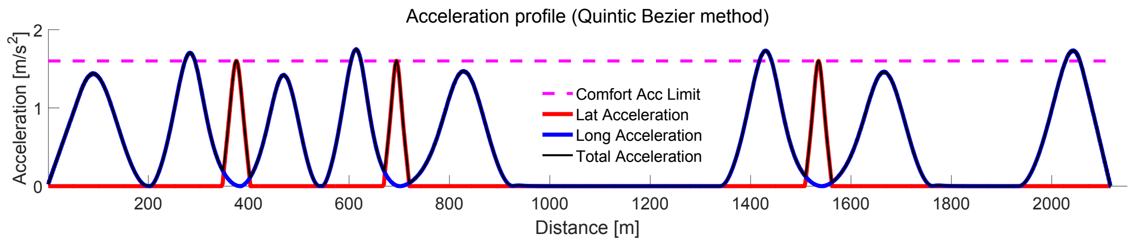

Fig. 6. Acceleration profile from the Quintic Bézier method

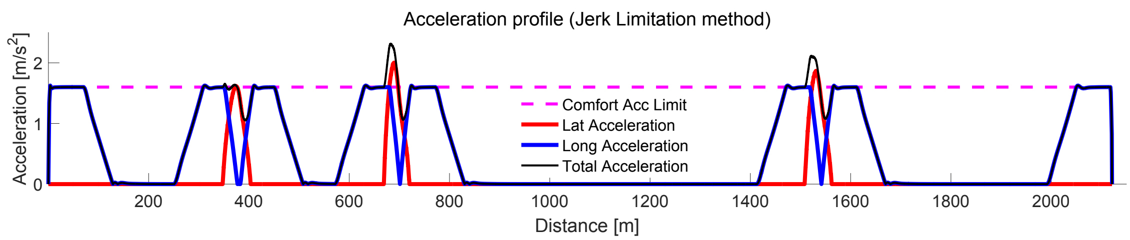

Fig. 7. Acceleration profile from the Jerk Limitation method

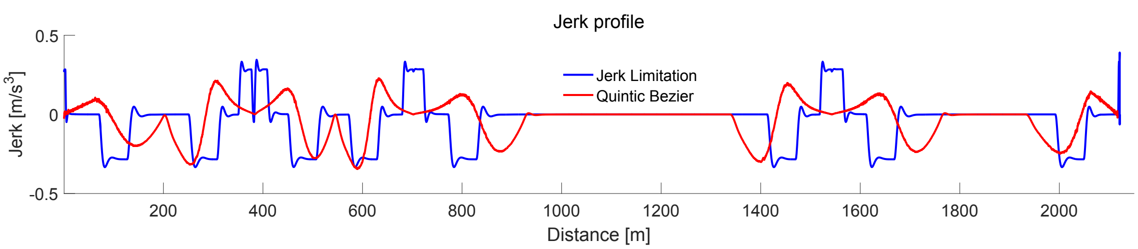

Fig. 8. Jerk profile comparison of both methods

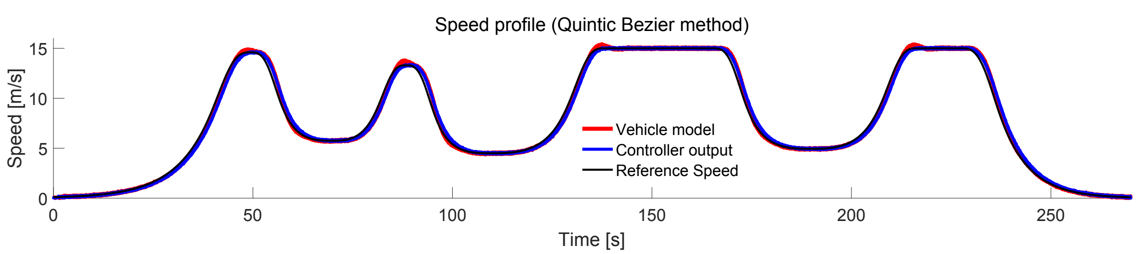

Fig. 9. Controller and vehicle model behavior

than the first one. The black line represents the maximum speed which is lower in turns, respecting lateral acceleration limits (see Eq.9). The Jerk Limitation method is depicted as the blue profile, with a more aggressive behavior than the Quintic Bézier method (depicted in red). In Figure 6 the acceleration profile for the Quintic Béziers only surpasses the maximum acceleration when braking (4% overshoot at most), due to the simulated vehicle inertia and delays in the control stage (theoretical results show no overshoot, see Fig. 3). Figure 7 depicts the acceleration profile associated to the Jerk Limitation algorithm. One can appreciate how that the acceleration is continuous but non-smooth. It is important to notice that, even if the longitudinal accelerations are within limits, the euclidean sum in Eq. 10 overshoots at almost each turn (i.e. the total acceleration overshoots by a factor of at most 44%).

Notice that at the second turn of Fig. 7, the lateral acceleration (in red) surpasses the limit (marked by the dotted line). This is due to: 1) The speed profile surpasses the maximum velocity allowed due to distance errors inserted by the time-based planner, the delays in control and the vehicle model; and 2) The planner does not have the capacity to separate deceleration and acceleration curves as the Quintic Bézier method and therefore, the lateral acceleration (in red) goes out of bounds.

Figure 8 presents the jerk response for the Jerk Limitation method in blue and the jerk profile for the proposed method (Quintic Béziers) in red. Notice that the blue line is not continuous, neither smooth. On the other hand, our method assures a continuous and smooth jerk. Values of our approach outperform the previous method and are below $0.3 m/s^3$ most of the time.

Fig. 9 presents the behavior of our controller and vehicle model when following the Quintic Bézier speed profile. The performance is good with approximately $1.2s$ of stabilization time with respect to the speed profile for the model and slightly less for the control signal (i.e. $0.7s$).

VI. CONCLUSIONS AND FUTURE WORKS

In this paper a smooth speed planner based on Quintic Bézier curves is presented. The introduction of polynomial curves in the speed planning process can significantly enhance passengers comfort by smoothing acceleration and jerk profiles. The speed profile generated is G^2 continuous, thanks to Bézier curves characteristics and a proper curve concatenation. Acceleration profiles have been evaluated, allowing to manage acceleration/deceleration profiles with good results. Longitudinal accuracy errors have been reduced, since the planner is distance-based, allowing a precise behavior throughout the geometric path.

A comparison with the Jerk Limitation method has also been made in Section V-B, evidencing a clear improvement in acceleration and jerk smoothness. This provides a more pleasant travel without surpassing comfort levels described in ISO 2631-1 standard [11]. Finally, the speed profile was tested in our simulation environment to validate the algorithm. In future works, a real time implementation in our electric platforms will be considered. It will manage dynamic environment by re-planning the speed profile when necessary, specially in emergency situations.

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