Path and speed planning for smooth autonomous navigation

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***Abstract*— This paper presents a path and speed planner for automated vehicles in unstructured environments. A global path planner has been designed with bounded continuous curvature and bounded curvature derivative to ensure smooth driving. This will allow the vehicle to know a priori which is the shortest path within a selected area that guarantees lateral accelerations and steering wheel speeds below given pre-set thresholds. A closed-form speed profiler uses semantic information provided by the path planner to set a continuous velocity reference that takes into account bounds on lateral and longitudinal accelerations consistent with comfort. The suitability of the above two features was compared to manual driving in a real instrumented vehicle on a test track.**

I. Introduction

Path planning for autonomous robots or vehicles has been extensively studied in recent years to meet a variety of kinematic, dynamic, and environmental constraints. General techniques to obtain optimal trajectories can be grouped into two categories: indirect and direct. Indirect techniques discretize the state/control variables, and convert the trajectory problem into one of parameter optimization which is solved via nonlinear programming (e.g. [1]) or by stochastic techniques (e.g. [2]). The latter use Pontryagin's maximum principle (PMP) and re-expresses the optimality conditions as a boundary value problem [3].

The complex and incomplete nature of most indirect techniques has motivated the development of optimal control techniques using PMP solutions. These have been based on Dubins' pioneering work [4] which presented the first set of paths (with straight line segments and arcs of circles) constrained to go from point to point with given initial and final orientations in a minimal time. In this context of path planning in a free environment, there have been several extensions of Dubins' result [5], [6].

A first analysis of these PMP results suggests that the resulting manoeuvres would introduce at least one discontinuity in the path's curvature profile at circle-segment transitions. To avoid this problem, several studies have been aimed at obtaining "nearly time-optimal paths" which correspond to smoother trajectories than those provided by Dubins' curves (cf. [7], [8], [9]).

[1]J. Villagra, V. Milanés, J. Pérez and J. Godoy are with AUTOPIA Program, Centre for Automation and Robotics (CAR, UPM-CSIC), Carretera de Campo Real, km 0.200, 28500 La Poveda, Arganda del Rey (Madrid), Spain `{jorge.villagra,vicente.milanes,joshue.perez, jorge.godoy,enrique.onieva}@csic.es`

In this connection, [7] uses the set of optimal curves described in Sussman's paper (straight line segments, arcs of circles, and clothoids) to implement an algorithm based on families of Dubins' curves, modifying simple turns into continuous-curvature turns (with the aid of the clothoids). With this strategy, the curvature profile along the path is continuous and trapezoidal in shape. However, the path presents discontinuities in the steering wheel angular velocity in each transition between circular arc and straight line segment generated by clothoids. Various researchers interested in path planning for very high speed vehicles have therefore proposed alternative fundamental curves (cf. [10], [11], [12]).

One of the interesting features of [7] is that not only is the curvature bounded but also the curvature derivative is constrained as pre-set by the user. As a result, this path planner may explicitly adapt the vehicle's technological (maximum steering wheel speed) and comfort (maximum lateral acceleration) constraints to its design parameters.

Furthermore, there has as yet been little attention paid to combining smooth path planning with obstacle avoidance. Work which has addressed this issue includes "elastic band" [13] and "rapidly-exploring random tree" [14] techniques in successfully generating paths for mobile robots or vehicles with obstacle avoidance and dynamic planning. However, these techniques share two main drawbacks: the shortest path (or a solution close to it) cannot always be guaranteed, and the computational burden is not re-usable to search for time-optimal paths within the selected area.

Finally, since one is not only looking for an adapted path planner but also a speed profile generator, a link between the two tasks would be desirable. In this connection, a semantic interpretation of the path can be useful both to help the autonomous navigator to understand the path to be followed and to reduce the computational cost of calculating the best speed for each situation.

As noted above, smoothness requirements impose constraints on both the path and the speed profile. The speed reference is commonly assumed to be continuously differentiable, and is often designed by optimizing an appropriate performance index (minimum time is the commonest criterion, but minimum jerk has also been used [15]).

Even though several interesting solutions have been presented in the literature (e.g. [16]), they all suffer from the same problem. Since a topological semantic map is not used in any case, iterative or optimization processes are required to satisfy a certain number of driving comfort constraints – maximum speed, longitudinal and lateral acceleration, and jerk.

In this connection, smooth trajectory generation has been one of the main concerns for accurate robot control. Thus, the studies of [17] or [18] present closed-form solutions –via different families of polynomials– to plan a speed profile guaranteeing upper limits on accelerations and jerks.

The present work describes a global solution both to the smooth path planning problem for autonomous vehicles in unstructured environments, and to the generation of an optimal speed profile for the resulting path. The solution to the former problem is based on the combination of the optimal continuous curvature path planner proposed by [7] to deal with obstacle-free environments, and the probabilistic roadmap for path planning introduced by [19] that is responsible for efficiently finding the minimum number of landmarks necessary to cover an obstacle-free space. The speed profile is determined from the information provided by the path planner and an adaptation of the polynomial-based smooth trajectory generation of [18].

With the above premises, the main contributions can be summarized as follows:

- A global path planner with continuous bounded curvature and curvature derivative aimed at providing smooth driving. This planner will allow the public transport system to know a priori which is the shortest path within a selected area that is consistent with a maximum lateral acceleration and steering wheel speed. Moreover, once the global planning learning phase has been completed, any pair of start and end points of the selected circuit will be quasi-instantaneously connectable by the path planner.
- A closed-form speed profiler, intelligently combined with the path planner, will provide a continuous velocity reference that takes into account comfort constraints not only on lateral and longitudinal accelerations, but also on longitudinal jerk.
- The suitability of the above two features was evaluated with a real instrumented public transport vehicle on a test track. To that end, several manual driving tests were compared with the planning algorithm in terms of time and comfort.

The remainder of the paper is structured as follows. Section II presents the formalism of the problem that is to be tackled, and gives an overview of the solution adopted which is, as mentioned above, based on a global planner that makes use of a continuous and bounded curvature metric. These characteristics of the local path planner will be highlighted in Sec. III, and the global planning algorithm will be described in IV. Some of the results will be compared with real driving tests and discussed in Section VI. Finally, Sec. VII presents some concluding remarks.

II. Statement of the problem

Given a start and end point configuration, the specific problem we face is to find a path and a speed profile such that: (i) the path respects local planner constraints, i.e., kinematic and dynamic vehicle constraints; (ii) the path is obstacle-free, i.e., it is entirely included in the free configuration space -provided by an electronic map, which will be assumed static; (iii) the speed profile respects dynamic comfort constraints (maximum speed, acceleration, and jerk), and (iv) the resultant path and speed profile provide the time-optimal trip solution

With these premises, a test-bed unstructured circuit was selected on the facilities of the Centre for Automation and Robotics to evaluate the proposed algorithm (see Fig. 2).

In the path planning literature, it is usual to solve the problem at hand by decomposing it into two hierarchical stages: a local algorithm computes a path between two configurations in the absence of obstacles. From that result, a global motion planning scheme (e.g. [19]) is used to deal with the obstacles and solve the full problem.

The family of paths used in the present work was based on the results of [7] which employed a straight line segment, circular arc, clothoid metric. If the resulting path is not obstacle-free and the initial and final configurations are still unconnected, then a global planner inspired by the Probabilistic Path Planner (PPP) [19] is used to intelligently select a new intermediate configuration. One of the main features of the proposed planner is that this phase of learning the obstacle-free configuration space will be available for any future query within the same area.

Finally, the semantic map provided by the local planner will be exploited to simplify the generation of the optimal speed profile. To this end, we adapted work by [18] to our specific trajectory planning imposing the longitudinal maxima of speed, acceleration, and jerk on the vehicle's motion for stretches in which there are no turning lateral dynamics.

III. Local planner

As mentioned above, [7] proposes an efficient solution that generates suboptimal paths with an upper bounded continuous curvature and an upper bounded curvature derivative. The resulting path will consist of straight line segments, circular arcs, and clothoids, which will be automatically combined to connect configurations with null curvature. Even if the algorithm does not strictly compute minimal length paths, it can be shown (cf. [7]) that it provides paths whose length is as close as desired to the optimal "Dubins" car paths. In fact, when the curvature derivative bound tends to infinity, the paths computed by [7] tend to the optimal Dubins paths.

If the sub-optimal path exists, the local planner will provide the set of parameters that defines that path (i.e., circle radius centres, length, and deflection -difference in the orientations of the start and end points of a turn, and if necessary, segment lengths). The basic steps of the algorithm are the following:

1) Compute all 6 Dubins [4] optimal length path possibilities: lrl, rlr, lsr, rsl, lsl, rsr, where left turns (l), right turns (r), and/or straight line segments (s) are concatenated.
2) Transform each turn in the above paths into a clothoid/circular-arc/clothoid set or, in the case of a degenerate turn, into a clothoid-clothoid concatenation – when the turn deflection is very small.
3) Evaluate the length of each of the resulting continuous curvature paths and take the shortest solution.
4) Verify that the selected path is obstacle-free, i.e., that it is entirely included in the test-bed's free configuration space

IV. Global planner

The global planning algorithm proceeds in two steps: the learning phase and the query phase.

In the first phase, a probabilistic technique is used to construct a directional weighted graph whose nodes correspond to obstacle-free configurations and whose edges correspond to feasible paths between configurations (only path lengths will be stored). This graph is represented by an $n \times n$ adjacency matrix A_{adj_n}, where n is the number of nodes, and a vector A_{Coord_n} of the coordinates of those nodes.

The exploration of the environment is done by successively adding to the graph a random configuration p_i –a data set consisting of x_i, y_i, θ_i– and trying to directionally connect this configuration to a maximum number of nodes of the graph with the local path planner.

As the aim of the planner is to find the shortest possible path, the graph weight J will be the Fourier transform of the path curvature – in other words, a measure of the frequency of the steering angle motion.

We modified the original path planner [19] in order to achieve better graph connectivity over complicated access zones. To that end, two main refinements were introduced into the initial algorithm:

- Increase the probability of generating intermediate points in sensitive areas by assigning priorities related to the search zones geometric characteristics, i.e., $P_z \in [0,1]$, with 1 being a critical zone and 0 a very easily connectable zone (see [20] for further details).
- Decrease the probability of obtaining intermediate points in a given area -characterized by a ball of center pi and radius r $B_r(p_i)$- when many configurations $p_i = [x_i, y_i, \theta_i]^T$ have already been tried in this area, and the connectivity rate is sufficiently high. To that end, the following function $P_d \in [0,1]$ is used

$$P_d = \max(1 - \sum_{j=1}^{n} \frac{k_d}{\sqrt{(x_i - x_j)^2 + (y_i - y_j)^2}}, 0), p_1 \dots p_n \in B_r(p_i)$$

Thus, for a new node p_i, the local planner tries to connect it with each node belonging to the graph whose weight J is less than a pre-set value $J_{\max}$. However, if the resulting associated value $P_t = P_z + P_d$ is lower than the most adapted heuristic value $P_c = 1$, the new node c is not included in the graph, and a new node is generated until it satisfies the previous condition. This process continues until a graph connectivity condition has been fulfilled (for instance, to obtain at least one solution to a specific query) and a fixed number of nodes has been reached. This selective process leads to a significant reduction in the number of intermediate points needed to attain a given degree of connectivity (see [20] for a detailed study).

If both of the above conditions are fulfilled, the learning phase ends. Otherwise, a connectivity refinement process is initiated. To this end, forward and backward unconnected nodes are automatically detected, and connections of the latter with the closest nodes in configuration space are sought by iteratively using different curvature and curvature derivative bounds (cf. [20] for more details).

In the query phase, given start and final configuration are connected to the two closest nodes of the graph using the local planner, and then a graph search is performed between these two nodes. This step is carried out with the aid of the Dijkstra algorithm [21] which finds the least-cost (the smoothest in the present case) path from a single source node to all other nodes.

In the case that a path with bounded curvature and curvature derivative cannot be found, the algorithm was designed to enhance the graph's connectivity by looking for intermediate paths with more permissive constraints.

V. Speed planner

As mentioned above, the concatenation of continuous curvature paths provides a semantic interpretation of the overall trajectory. In other words, any path in an unstructured environment can be decomposed, with the help of the proposed path planning algorithm, in a succession of turns -composed of clothoids and arcs of circles- and straights lanes. This result is extremely useful in finding closed-form optimal speed profiles because both straight line segments and circle arcs can be associated with constant speeds. More precisely, when a turn is initiated the maximum velocity will be constrained by the comfort lateral acceleration threshold, and when a straight segment is being tracked, the maximum longitudinal speed, acceleration, and jerk will be the limits imposed on the reference speed.

With these premises, the overall speed profile will consist of 3 families of curves:

1) Constant speed curves at a minimum value $V_{\min}$ when the curvature profile is a circular arc or its preceding clothoid. The minimal speed is fixed by the curvature bound for the curve $\kappa_{\max}$, i.e., by combining kinematic model equations [20] to yield $V_{\min} = \sqrt{(\gamma_y/\kappa_{\max})}$, where γ_y is the maximum lateral acceleration.

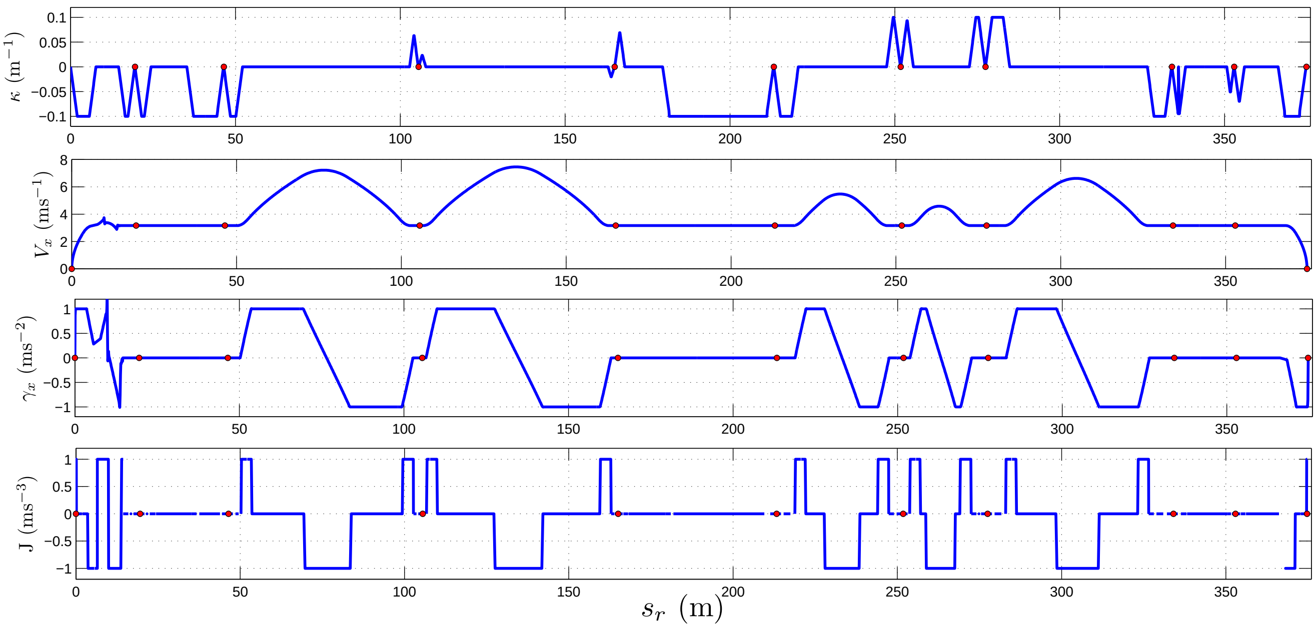

Fig. 1. Speed planning scheme: curvature, speed, longitudinal acceleration, and jerk.

2) A smooth transition from the minimum value $V_{\min}$ to a maximum allowed speed $V_{\max}$ and back again to $V_{\min}$ that fulfills the acceleration and jerk constraints.
3) A set of 1 or 2 smooth transition curves (of type 2 above) that go from zero to the maximum speed, and vice versa. This passage will be performed with a single curve if no turns are necessary in the corresponding path. Otherwise, a straight line segment will be introduced between 2 transition speed curves whose length will be determined by the turn deflection.

Figure 1 shows the concatenation of curvature profiles between nodes whose positions are represented by red dots, and the associated speeds, accelerations, and jerks.

In order to obtain closed-form expressions for the second type of curve, the work from [18] was used because it not only provides a deterministic optimal speed fulfilling the length and comfort constraints –bounds on speed, acceleration, and jerk– but also allows the speed profile to be regenerated on-line in case a dynamic obstacle is detected so that the path planner can take it into account.

VI. Experimental results

Note that the obstacle-free configuration space used in the learning phase can be significantly reduced in the specific case considered in this work (see Fig. 2). Thus, the search over x_i and y_i will follow 3 basic steps [22]. First, the boundaries of the polygonal obstacles are approximated by subdividing each side of the original polygon into small segments. Second, the Voronoi diagram is computed for the resulting points. And third, the Voronoi edges which have one or both end-points lying within any of the obstacles are eliminated.

Once the Cartesian coordinates of the reduced obstacle-free points have been determined, their orientations θ_i are found using a non-slipping hypothesis ($\theta_i = \arctan\left(\frac{y_i - y_{i_c}}{x_i - x_{i_c}}\right)$, where x_{i_c} and y_{i_c} are the coordinates of the closest position in the reduced search space.

The maximum curvature derivative will be $\sigma_{\max} = 0.05$, and, since there is no solution to the problem for $\kappa_{\max} \leq 0.1$, this value is the bound chosen for the curvature (see [20] for a deep analysis for such choices).

Several trials were performed with a vehicle, whose characteristics are summarized in [20], driven manually. The start and end points were the same as in our path planning problem, and the different drivers were requested to choose the route such that turns, accelerations, and braking provided a sensation of comfort to the vehicle's occupants while minimizing trip time. With the aim of covering a large spectrum of driving attitudes, 15 people have been selected for such a task, which can be classified in three different categories: Slow Drivers (SD), Medium Drivers (MD) and Aggressive Drivers (AD). In the sequel, these three driver typologies will be compared with our Path and Speed Planning (PSP) algorithm.

Since [23] sets the limit to a fairly uncomfortable motion at 1 ms^{-2}, the maximum overall acceleration will be set at $\gamma_t = \sqrt{\gamma_x^2 + \gamma_y^2} = 1$ ms^{-2}.

To quantify the comfort all through the circuit, two different indicators are taken into consideration:

- the integral squared difference between the total acceleration of the vehicle and the maximum allowed acceleration $I_\gamma = \frac{1}{T}\int_0^T (\gamma_t - \gamma_{t_{\max}})^2$, which measures

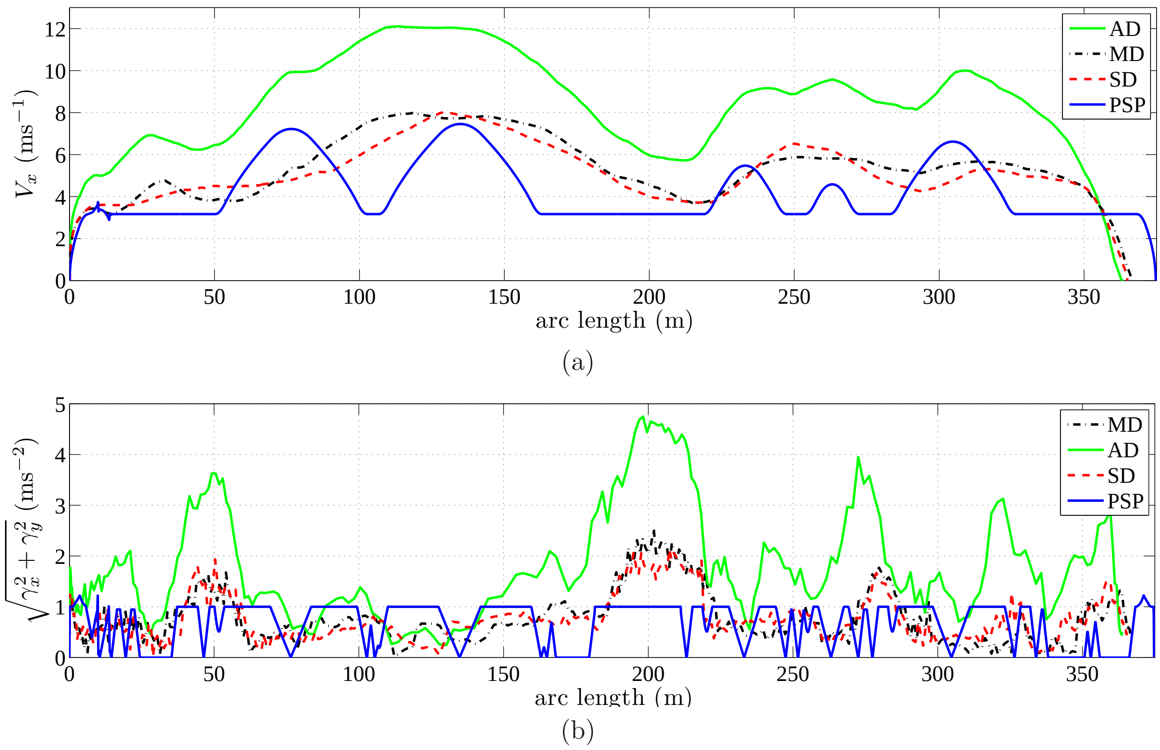

Fig. 3. Comparison of human drivers' behaviour with the theoretical dynamics in experimental circuit (a) speeds; (b) total acceleration.

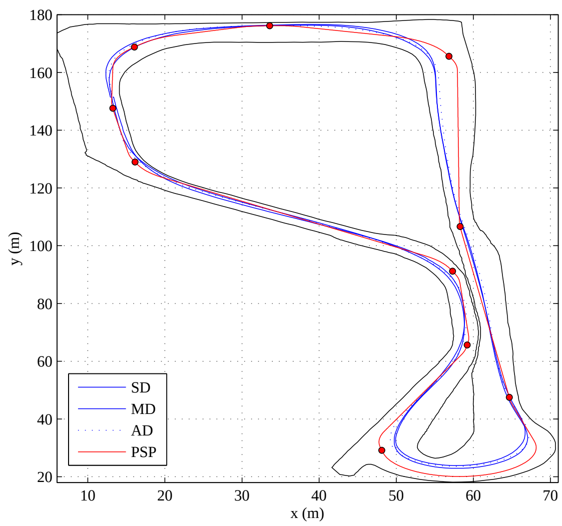

Fig. 2. Comparison of human drivers' paths with the theoretical ones

the mean trip comfort

- the maximum difference between the total acceleration at any instant of the trial and the maximum allowed acceleration $M_\gamma = \max|\gamma_t - \gamma_{t\max}|$, which quantifies the most abrupt turn that the vehicle's occupants feel during the trip.

Table I summarizes the mean, maximum and minimum values of these two comfort estimators and of the trip time in the considered circuit. Note that the blue figures highlight the maximum values, while the red ones emphasize those with the worst result.

In Fig. 2 a representative path of each driver group lie almost on top of each other, while the result of the path planner plotted in deviates somewhat from them. In particular, one notes that the planned path is in general similar to those taken by human drivers, especially on the left of the circuit, although there appear some differences at the top right and the bottom of the circuit. These divergences reflect the imposition of a maximum curvature of $\kappa_{\max} = 0.1$ on the algorithm, while the driver intuitively looks for the shortest comfortable path.

We were interested of course in contrasting the planned speeds provided by the two alternatives detailed in Sec. V with the three manual driving groups speed profiles. The former were obtained with a maximum speed of $V_{\max} = 10$ ms^{-1}, a maximum longitudinal acceleration of $\gamma_{\max} = 1$ ms^{-2}, and a maximum jerk of $J_{\max} = 1$ ms^{-3}.

One notes in Fig. 3 that all the manual driving tests exceeded the critical value $\gamma_{t\max} = 1$ ms^{-2} in the interval $s_r \in [170, 230]$ (corresponding to the sharp turn at the bottom part of the circuit), while the PSP approach respect this critical value to a far greater extent.

One observes from Table I that PSP clearly provides the best I_γ and M_γ results while obtaining a trip time approximatively equal or shorter than that of all the human trials except that driven aggressively.

It is evident from Table I –in which the minimum and

TABLE I

Path and speed planning versus manual driving.

		PSP	SD	MD	AD
$\mathbf{I}_\gamma$	mean	0	0.09	0.61	1.72
	max	–	0.12	0.73	2.05
	min	–	0.10	0.55	1.47
$\mathbf{M}_\gamma$	mean	0.22	1.23	1.42	3.74
	max	–	1.31	1.53	4.02
	min	–	1.18	1.10	3.48
T	mean	74.9	87.3	73.1	53.2
	max	–	91.5	76.8	55.1
	min	–	79.8	69.8	49.6

maximum values are given in blue and red, respectively– that PSP provides very interesting path and speed profiles in the sense that they represent better combinations of trip time and comfort than the human drivers were able to achieve in this unstructured environment.

VII. Concluding remarks

A new approach to planning smooth path and speed profiles for automated vehicles in unstructured environments has been presented. It comprises three layers: (i) an optimal local continuous curvature planner for obstacle-free situations; (ii) a global planner that finds intermediate points to connect the configuration space to the desired degree, taking obstacles into account; and (iii) a speed planner that uses the set of curves of the previous layer to compute analytically a comfort-constrained profile of velocities and accelerations. The results of the algorithms were satisfactorily contrasted in an automated public transport vehicle with real driving manoeuvres performed by human drivers.

The next natural stage of our work is, once the bus has been fully automated, to include the path planner in an overall control scheme in which an adapted robust control algorithm [24], [25] will be used to track as closely as possible both the planned path and the planned speed.

Acknowledgement

This work was supported by the Spanish Ministry of Science and Innovation through Research Grant ONDA-F TRA2011-27712-C02-01 and by the Spanish Ministry of Development through Research Grant GUIADE P9/08.

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