MANOEUVRING SIMULATIONS OF THE PERSONAL VEHICLE PICAV

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ABSTRACT

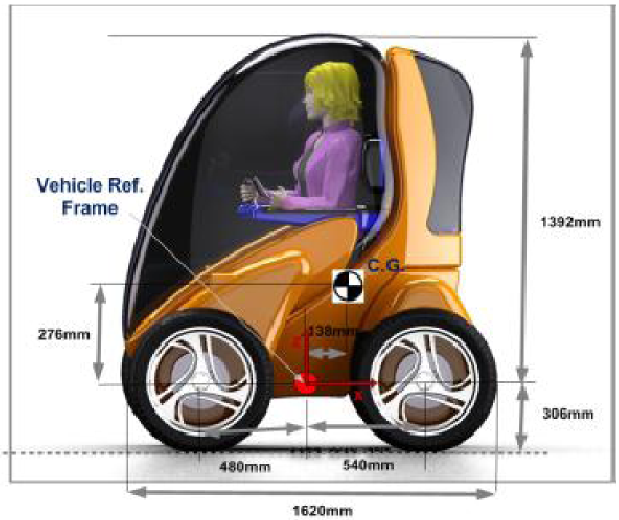
The greening of surface transport, ensuring sustainable urban mobility and improving safety and security are the three main paradigms reflecting the present and future urban transport strategic and policy challenges. The PICAV unit is a one person vehicle that is meant to ensure accessibility for everybody and some of its features are specifically designed for people whose mobility is restricted for different reasons, particularly (but not only) elderly and disabled people. Ergonomics, comfort, stability, assisted driving, eco-sustainability, parking and mobility dexterity as well as vehicle/infrastructures and intelligent networking are the main drivers of the PICAV design. The PICAV case is considered, investigating the advantages of four independently powered wheels and exploring how actuation redundancy could be used to grant proper manoeuvrability, at least, within the expected operative conditions and transport modes.

Keywords: Green cars, Personal vehicle, Mathematical model, Simulation

1. INTRODUCTION

In the last ten years governments, organizations and citizens in general have been involved, with great effort, to create green zones in downtown, touristic areas and public parks; ensuring citizens have an economic, social and environmentally sustainable mobility system. A particular effort has been dedicated to the juridical substance of the right to mobility for all people, avoiding any kind of social exclusion and changes in personal habits, culture and quality of life, especially for the less able (elder and handicapped) users who cannot resort to the typical efficient and clean walking and cycling mobility resources powered by human muscles. Taking these paradigms in consideration and having as a primary objective to overcome them; arises then the Personal Intelligent City Accessible Vehicle (PICAV) system funded by the European commission under the 7th framework program.

PICAV, Figure 1, is a small full electric vehicle, able to move in outdoor pedestrian environments, where usual public transport services cannot operate because of the width and slope of the infrastructures, uneven pavements and the interactions with high pedestrian flows.



Legenda	Symbol	Value
Total mass	M	400 kg
Wheel moment of inertia	J	0.8 kgm^2

Figure 1: The PICAV reference make-up: sketch and main parameters

Transport systems for pedestrian areas, based on a fleet of PICAVs have been proposed in (Cepolina and Farina 2012) and (Cepolina and Farina 2014).

The paper considers the manoeuvrability characteristics of this untraditional vehicle with four independently powered wheels (Silva et al. 2008; Esmailzadeh et al. 2001; Shino and Nagal 2003) that are very important in order to assure comfortable and safe travel to the user.

Some brief hints are given on the construction of the vehicle dynamic model moving from the behaviour of a driving wheel (with compliant tire); modelling the group motor wheel suspension and then assembling the four groups to the chassis to find out the motion of the centroid and around it when the four actuators operate while the vehicle moves on varying soil surfaces. The model was modularly implemented in Simulink/Matlab environment.

Simulation results are presented and discussed.

2. MODELING THE PICAV DYNAMICS

The PICAV vehicle is modelled as a multi bodies system (Cho and Kim 1995): the chassis connected, through viscous-elastic joints, to four masses including suspensions and motorized wheels, each one coupled with the road.

Due to the low speed and the comparatively smooth soil, finally, a 14-degrees-of-freedom model is obtained: 6 for the car body (3 of the centroid and 3 around it); 2 for each of the four suspended masses (the linear motion at joints and the rotation of the wheels); namely, in body-axes and assuming small angular deflections, the reference dynamics is set, as in the following sections.

The model refers to the coordinate frames shown in Figure 2.

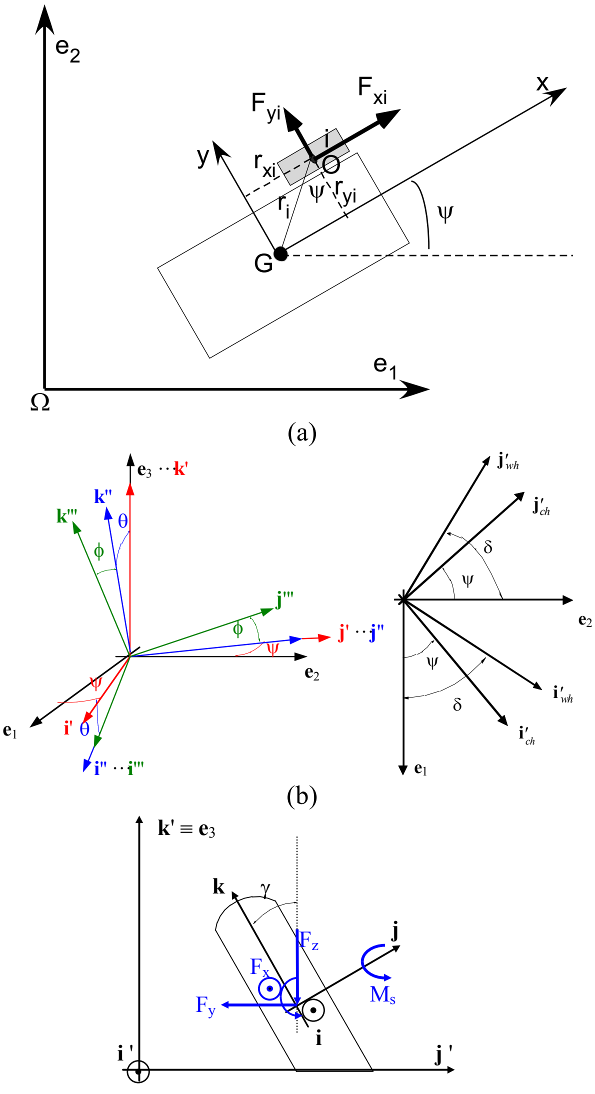


Figure 2: Wheel chassis outline (a). Co-ordinate frames, roll (ϕ), pitch (θ), yaw (ψ) and steering (δ) angles for basic rotations. The subscript ch refers to the chassis, wh refers to the wheel, {e1, e2, e3} is the fixed frame. These frames and angles refer to the general vehicle model. In the case of PICAV (no steering wheels) δ=ψ and $\{i' j' k'\}_{ch} \equiv \{i' j' k'\}_{wh}$ (b). Wheel frames (c).

2.1. Tire-soil contact model

The tire-soil contact model is hereafter written for a generic i^{th} wheel. The hypothesis of vehicle with all identical wheels is considered and the geometry and mass parameters are considered the same for all the wheels.

The model of wheel dynamics, including the slip non linear behaviour allows to find the wheel torque T_i and the maximum torque that can be applied to the wheel before creep.

The forces exchanged between tire and soil depend on complex phenomena but the basic technical literature (Pacejka and Besselink 1997; Wong 2001) suggests simple proportionality relations for micro-slip contacts (say, out of extended creep situations):

$$T_i = mR\dot{v}_{xi} + \frac{J}{R}\left(\frac{m}{k_i}\left(\ddot{v}_{xi}v_{xi} + \dot{v}_{xi}^{\,2}\right) + \dot{v}_{xi}\right) \qquad (1)$$

$$\omega_i = \frac{v_{xi}}{R} + m\frac{v_{xi}\dot{v}_{xi}}{k_i R} \qquad (2)$$

Where: m and J arethe mass of the wheel and its moment of inertia referred to the wheel axis, ω_i is the wheel angular velocity, R is the wheel radius, v_{xi} is the wheel longitudinal velocity, k_i is the constant of the i wheel slip law.

2.2. Motorwheel model

The motor wheel dynamic model considers all the degrees of freedom supplied from the rotations around three non-orthogonal axes: spin θ around the current y axis (**j**), corresponding to spinning torque M_S, steering δ around the z fixed axis (**e3**), corresponding to steering torque M_{st}, camber γ around the current x axis (**i**), corresponding to camber torque M_C, see Figures2b and 2c. **R** is the road reaction on the tire and **F** is the force applied to the chassis by the wheel.

The motor wheel model is hereafter written in the general case indicating m’ the mass of motor and wheel:

- Translation equilibrium:

$$\begin{bmatrix} R_x + F_x \\ R_y - F_y \\ R_z - F_z \end{bmatrix}_i = m'R\begin{bmatrix} \alpha_{st}s\gamma + 2\omega_{st}\omega_c c\gamma + \alpha_s \\ -\alpha_c c\gamma + \left(\omega_{st}^2 + \omega_c^2\right)s\gamma + \omega_{st}\omega_s \\ -\alpha_c s\gamma + 2\omega_{st}\omega_s c\gamma s\gamma + \omega_c^2 c\gamma \end{bmatrix}_i \qquad (3)$$

- Rotation equilibrium:

$$\begin{bmatrix} M_c + RR_z s_\gamma + RR_y c\gamma \\ M_s c\gamma - RR_x c\gamma \\ M_s s\gamma + M_{st} - RR_x s\gamma \end{bmatrix}_i =$$

$$= I \begin{bmatrix} \alpha_c + \omega_{st}^2 c\gamma s\gamma \\ -\left(\alpha_{st} s\gamma c\gamma - 2\omega_{st}\omega_c s_\gamma^2\right) \\ \left(\alpha_{st} c\gamma^2 - 2\omega_{st}\omega_c s\gamma c\gamma\right) \end{bmatrix} + \tag{4}$$

$$+ I_y \begin{bmatrix} -\omega_{st}\omega_s c\gamma - \omega_{st}^2 c\gamma s\gamma \\ \left(\alpha_s c\gamma + \alpha_{st} c\gamma s\gamma + \omega_{st}\omega_c c\gamma^2\right) - \omega_c\left(\omega_{st} s\gamma^2 + \omega_s s\gamma\right) \\ \left(\alpha_s s\gamma + \alpha_{st} s\gamma^2 + \omega_{st}\omega_c s\gamma c\gamma\right) + \omega_c\left(\omega_{st} s\gamma c\gamma + \omega_s c\gamma\right) \end{bmatrix}_i$$

Where: ω and α are the wheel angular velocity and acceleration while their subscripts *s, st, c* refer respectively to spin, steering, camber; the mass quadratic moment **I** is diagonal with $I_x=I_z=I$, $I_y=J$; because identical wheels are considered, the variables R, m’, I, I_y have no subscript; sε=sinε, cε=cosε.

2.3. Suspension model

The proposed dynamic model of the individual suspension is:

$$\begin{bmatrix} F_{whx} - F_x \\ F_{why} - F_y \\ F_{whz} - F_z - c_{susp}\dot{z}_s - k_{susp} z_s \end{bmatrix}_i = m_{susp} \begin{bmatrix} a'_{Gx} - \ddot{\psi} r'_{GSy} - \dot{\psi}^2 r'_{GSx} \\ a'_{Gy} + \ddot{\psi} r'_{GSx} - \dot{\psi}^2 r'_{GSy} \\ \ddot{z}_s \end{bmatrix}_i \tag{5}$$

$$\begin{bmatrix} z_s F_{why} + M_x - M_{whx} \\ -z_s F_{whx} + M_y \\ M_z - M_{whz} \end{bmatrix}_i = \begin{bmatrix} 0 \\ 0 \\ I_{susp}\ddot{\psi} \end{bmatrix} \tag{6}$$

Where $\mathbf{F}_{wh}$ and $\mathbf{M}_{wh}$ are force and moment due to the motor wheel; m_{susp} and I_{susp} are the mass properties of the suspension, k_{susp} and c_{susp} are the elastic and damping parameters of the suspension; z_s is the quote of the suspension mass m_{susp} considered concentrated; $\mathbf{r'}_{GS}$is the vector between the chassis center of mass G and the suspension contact point S; the superscript indicates the reference frame {**i’, j’, k’**}.
In the case of stiff suspensions the vertical acceleration is zero: $\ddot{z}_s = 0$

The equations of motor wheels and suspensions can be assembled together to have the model of the group motor wheel suspension.

2.4. Chassis model

The chassis is considered as a rigid body with 6 degrees of freedom.

The dynamic model of the chassis, in the case of PICAV with no steering wheels, is:

$$\sum_{i=1}^{4}\left(F_{xi}\mathbf{i}'_{ch} - F_{yi}\mathbf{j}'_{ch} - F_{zi}\mathbf{k}'_{ch}\right) - m_{ch} g \mathbf{k}'_{ch} = \tag{7}$$

$$= m_{ch}\mathbf{a}_{Gxyz} + m_{ch}\left(-\dot{\psi} v_{Gy}\right)\mathbf{i}'_{ch} + m_{ch}\left(\dot{\psi} v_{Gx}\right)\mathbf{j}'_{ch}$$

$$\begin{aligned}&\left(r_{y1}F_{z1} + r_{z1}F_{y1} - r_{y2}F_{z2} + r_{z2}F_{y2} + r_{y3}F_{z3} + r_{z3}F_{y3} - r_{y4}F_{z4} + r_{z4}F_{y4}\right)\mathbf{i}'_{ch} + \\ &+\left(-r_{z1}F_{x1} - r_{x1}F_{z1} - r_{z2}F_{x2} - r_{x2}F_{z2} - r_{z3}F_{x3} + r_{x3}F_{z3} - r_{z4}F_{x4} + r_{x4}F_{z4}\right)\mathbf{j}'_{ch} \\ &+\left(r_{x1}F_{y1} - r_{y1}F_{x1} + r_{x2}F_{y2} + r_{y2}F_{x2} - r_{x3}F_{y3} - r_{y3}F_{x3} - r_{x4}F_{y4} + r_{y4}F_{x4}\right)\mathbf{k}'_{ch} \\ &+\sum_{i=1}^{4} M_{xi}\mathbf{i}'_{ch} + \sum_{i=1}^{4} M_{yi}\mathbf{j}'_{ch} + \sum_{i=1}^{4} M_{zi}\mathbf{k}'_{ch} \\ &= I_{zch}\ddot{\psi}\mathbf{k}'_{ch}\end{aligned}$$

where $\mathbf{I}_{ch}$=diag$[I_x,I_y,I_z]_{ch}$ is the inertia matrix of the chassis; m_{ch} is the chassis mass; $[r_x, r_y, r_z]^T_k$isthe arm vectorof the force $\mathbf{F}_k$ applied to the chassis from the motor wheel k, $\mathbf{a}_G$ is the acceleration vector of the chassis center of mass.

3. SIMULATION RESULTS

The PICAV manoeuvring has been studied through two operative conditions: the execution of on spot turn and the execution of a path with large radius. The vehicle model considered neglects secondary effects (at the tire-soil interface) and does not explicitly deal with the control strategies required to compensate unwanted effects. The sketch of the implemented Simulink model is shown in Figure 3.

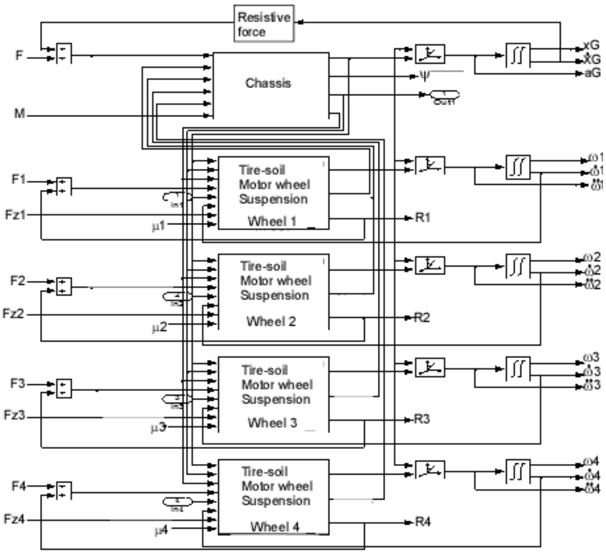
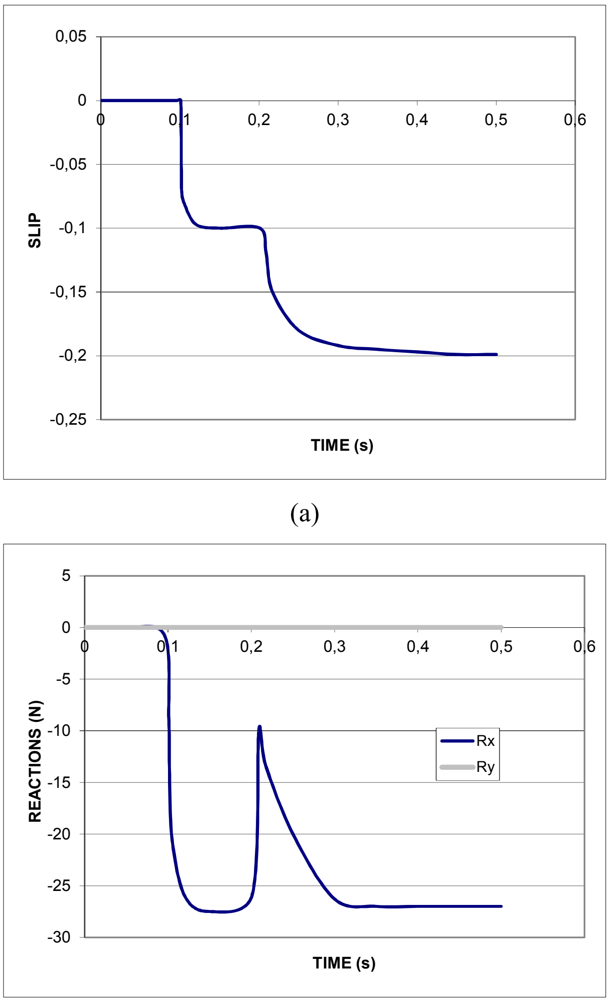


Figure 3: Sketch of the PICAV simplified model in Simulink

A set of simulation trials have been performed, achieving results to assess the usefulness of the proposed (unusual) driving opportunity for 2D motions. As first instance, it has been properly verified that fully balanced actuation leads to straight trajectories while circular paths are tracked when outer wheels rotate at equal speed, faster than inner wheels.

Simulations have been performed to test the effects of a variation of the adherence corresponding to a ground friction varying from 0.7 to 0.2 on a mono-wheel during braking. At 0.1s a braking torque of -6 Nm is applied and taken constant; a adherence coefficient $\mu=0.7$ was applied to the wheel for $t<0.2$s, then this coefficient was lowered to $\mu=0.4$. Details on the simulation results are shown in Figure 4. In this case the applied torque is lower than the torque corresponding to the adherence limit: the slip grows and then arranges on a new value. In the case of a braking torque higher than the adherence limit, when the adherence lowers the wheel is too much braked respect to the ground conditions and the wheel blocks.



(a)

(b)

Figure 4: Slip (a) and reactions (b) of a mono-wheel undergoing a sudden change of adhesion coefficient.

3.1. PICAV turning on the spot

PICAV is designed to move people in restricted areas sharing it with pedestrians, like city centers, parks, malls. So it is very important the dexterity of the car, allowing the PICAV to reach every position with whatever desired orientation, while minimizing the manoeuvring space. To check the PICAV maneuverability a skid steering manoeuvre (radius zero plane trajectory) has been simulated. During the on the spot path test starting from zero speed and powering by equal torques, +130 Nm outer train forward, -130 Nm backward the other, the velocity and acceleration of the chassis kept zero while the values of the forces applied from the wheels to the chassis varied as shown in Figure5.

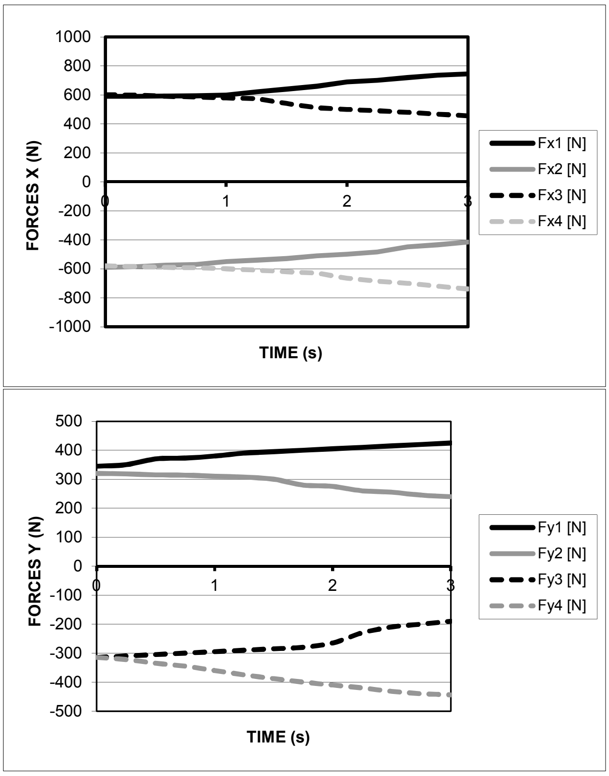


Figure 5: Forces exchanged between wheels and chassis respectively in x and y direction during on-spot turn with reciprocal actuation law (skid-steering)

3.2. PICAV on circular path

The steady state motion along a circular path is characterized by constant yaw velocity and therefore zero acceleration due to the equilibrium between the torques generated by the transversal and longitudinal reactions. Many tests have been performed on PICAV tracking curved path with different local radius (Cho and Kim 1996). In Figure 6 are shown the results obtained applying on the outer train 20 Nm torques and on the inner one 1.2 Nm torques, the reference trajectory is a 100 m radius circle. During this trajectory the chassis yaw is decreasing with constant speed and zero acceleration. Figure 7 depicts the trends of significant variables during this manoeuvre: the forces exchanged between soil and wheels, Figure 7a, the forces applied from the wheels to the chassis, the yaw rate, Figure 7b, the slip angles, Figure 7c. In Figure 7c can be noted that the slip angles on the front wheels are inferior to the rear wheels slip angles resulting in a lightly oversteering behaviour. This is understandable because each wheel velocity is determined by the sum of the velocity of the vehicle center of mass plus the velocity due to its rotation.

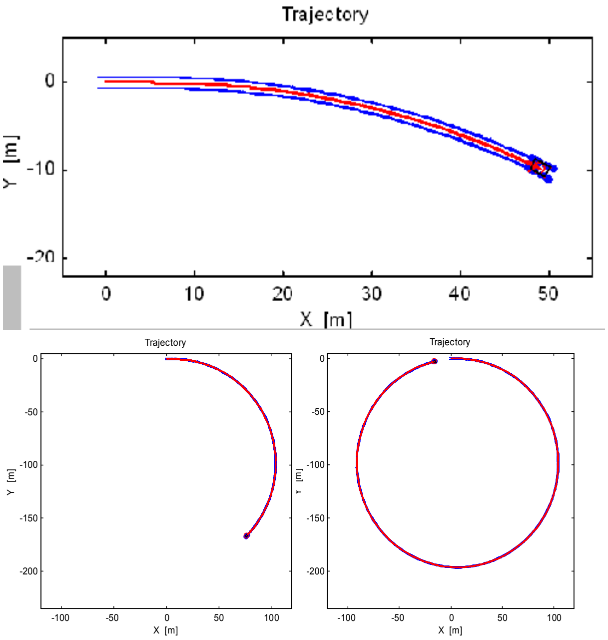
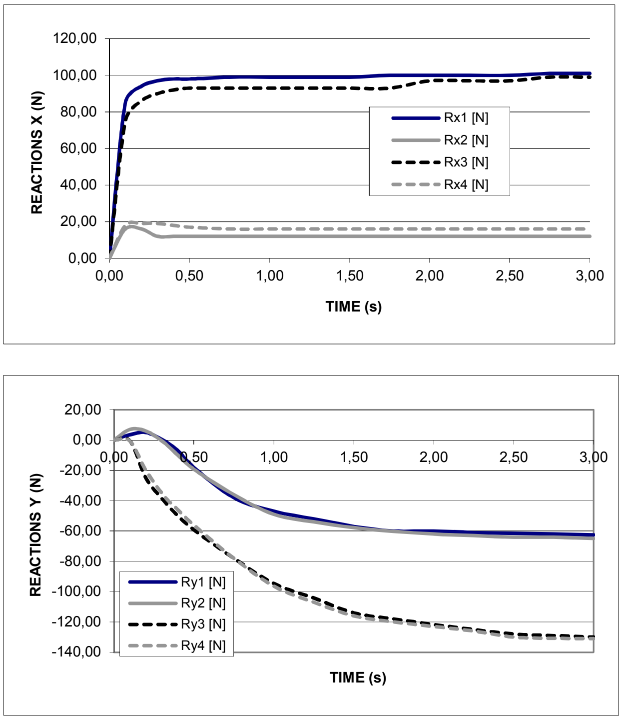
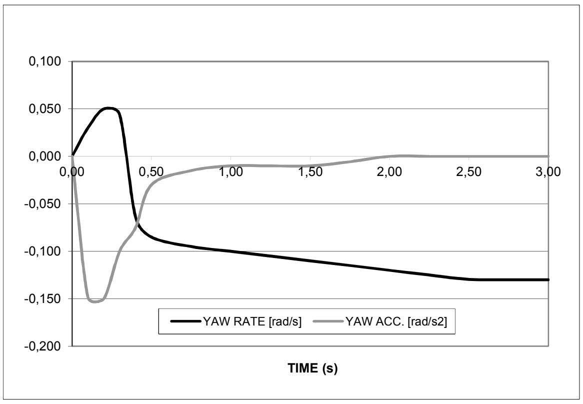


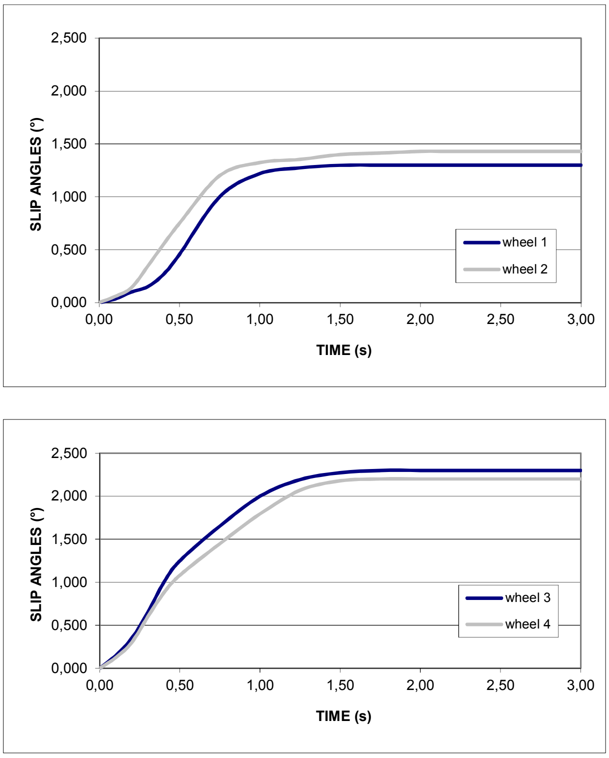
Figure 6: PICAV tracking a circular path at 10s, 50s and 100s



(a)



(b)



(c)

Figure 7: Forces exchanged between wheels and soil (a), respectively in x and y direction; yaw rate (b) and slip angles (c) during a 100 m radius circular path.

It has to be noted that the vehicle forward velocity is lightly reducing because the actuation torques have been computed in open loop trying to estimate the torque distribution guaranteeing a circular path performed at constant speed, balancing beyond the aerodynamic and rolling reactions, the centripetal contribution. In any case the different circular paths close with negligible errors.

4. CONCLUDING COMMENTS

The paper proposes the model for a 4 non steering motor-wheels vehicle. The model is applied to the new personal vehicle PICAV to study its open loop performances about dexterity in manoeuvring and stability. First the general mathematical models are derived for the single modules composing a car with different level of approximation; then the preliminary architecture and geometry mass parameters of PICAV have been used in the simulation to explore its behaviour and results are shown and commented.

PICAV is designed to join semi-autonomous mobility with the basic requirements on technological sustainability. The main results on the vehicle manoeuvrability will be directly transferred to the driving assistant and the dynamic model will be used for implementing a suitable compensator of the non linearities with the aim to achieve a near linearized modelsimplifying and improving the robustness of the control system.

ACKNOWLEDGMENTS

The research is developed within the PICAV project funded under the Seventh Framework Program (Collaborative Project SCPS-GA -2009-233776). We kindly acknowledge the funding and assistance of European Commission.

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