Personal full electric vehicle PICAV: non linear dynamic model and simulation

F. Cepolina, E.M. Cepolina, R.M. Molfino

Abstract— Request of sustainable personalized transport is growing in different areas of service robotics, for aid to mobility of elderly and motion disabled people, for freight delivery in urban environment, for passengers transport in restricted zones as airports and greens because of the small dimensions, tiny footprint, on-board intelligence, friendly human car interface and zero environmental impact. The paper studies the feasibility of an electric vehicle with four non steering wheels considering as driving principle the skid steering that has been mainly used for tracked vehicles.The vehicle is a complex nonlinear multi body system with numerous mobilities either in stiff and in elastic motion. For evaluating the vehicle performances, the maneuverability and stability behavior it is needed the availability of a model able to describe all the significant motion modes in different operative conditions. The paper presents the PICAV model and some results of the simulation campaign that demonstrated its soundness and reliability.

Keywords— Full electric vehicle, Dynamic model, Manouvrability behavior, Simulation.

I. Introduction

MOBILITY and communication are markers of civilised society level: the restrictions on people or ideas always mean dark seasons. Sustainable development, however, requires today compatibility checks, with emphasis for highly pedestrianized areas. Many technical developments ought to be reconsidered, possibly, rethinking solutions accepted as obvious, that actually lay within the range of habits [1]. City-cars and personal-movers are example case, where innovations and non-conventional ideas have to be weighed to look after effectiveness. The paper refers to a new mobility concept for passengers ensuring accessibility for all in urban pedestrian environments and proposes a detailed dynamic model and simulation used for the vehicle design and control. The concept addresses a new Personal Intelligent City Accessible Vehicle (PICAV) and a new transport system that integrates a fleet of PICAV units. The transport system will ensure safe and secure accessibility for everybody [2], [3] 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 intelligent networking are the main drivers of PICAV design. The innovative electrical vehicle will present new frame-suspension structure, new seating sub-assembly, new efficient power supply module.

The PICAV transport system will provide an efficient and rational service to citizens within urban areas where traffic is restricted: the application fields of PICAV are pedestrianised areas, ‘shared space’ areas (where vehicles are allowed, but where the same space is shared between vehicles and pedestrians), pedestrian environments where conventional public transport services cannot operate because of the width and slope of the infrastructures, uneven pavements and the interactions with high pedestrian flows and indoor pedestrian areas (e.g. shopping malls). The vehicle because of its small size, tiny footprint, on-board intelligence and zero environmental impact is suitable for moving in these areas and it behaves almost as a pedestrian, disturbing other pedestrians as little as possible. Therefore the PICAV system usefully integrates the existing public transport system to help it become more accessible for older and disabled people by acting as a smooth link between walking, bicycle and conventional public transport and thus extending the availability of a public motorised transport service to cover the entire urban area.

These vehicles are developed for local traffic duty, worth for low speed and bounded autonomy; several auto-makers are becoming aware of the challenge [4], still the offers do not turn out from to many conventional technicalities. PICAV, Fig. 1, is a small electric motorised vehicle, able to follow paths and slopes, with given performance (payload, speed, acceleration, autonomy, etc.). Transport systems for pedestrian areas, based on a fleet of semiautonomous or fully-automated PICAVs have been proposed in [5], [6] and [7]. The paper reconsiders the driving and manoeuvrability operations, assuming four independently powered wheels [8], [9], [10]. The investigation builds up the vehicle dynamics moving from the behaviour of a driving wheel (with compliant tyre);

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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 dynamic model written in the general case of six degrees of freedom vehicle with four motorized steering wheels has been presented [11]. Here the dynamic model of PICAV with no steering wheels is proposed.

Legenda	Symbol	Value
Total mass	M	400 kg
Height of the center of gravity	r_{Gz}	0.58 m
Wheel rolling radius	R	0.2 m
Wheel moment of inertia	I	$0.1 kgm^2$

Fig. 1 PICAV FIRST digital mock-up (courtesy Aazir Khan) and main parameters

The actuation redundancy makes these models complex, but, at the same time, opens new opportunities, on condition that proper information is exploited. An interesting opportunity is to exploit the actuation torque supplied by each motor and the speed of the individual wheels, to reckon the useful traction force required at soil-tyre interfaces, once the adherence and creeping condition are assessed [12]. From the analysis performed by researchers in the field, has been shown that a four independent motor wheels vehicle can be driven along any path by simply controlling the slip, without necessarily impressing a turning angle to the wheels. On these premises, the manoeuvre dexterity and stability are considered the main performances for all the tasks a city vehicle is required to perform at low speed over urban roads [10].

II. Dynamic Model of PICAV

The study deals with electrically powered personal vehicles, used to transport one person with limited autonomy range (some 60 km), at low speed (max 25 km/h), assuming proper soil upkeep. The four wheels are individually actuated, but the driver, as usual, acts on two commands: steering and acceleration, while the controller needs modify the torque and the speed, so that the (four) soil/tyre interfaces grant the required manoeuvrability and stability [13]. The problem is consistent, by itself, with several issues, on condition that the vehicle dynamics is modelled with account of the pertinent degrees of freedom [14].

Quite often, indeed, the reference models are limited to ‘quarter car’ or to ‘bicycle’ cases, totally or partially neglecting roll and pitch motion. In this case, due to the PICAV special aim to guarantee the accessibility to city centers to all, including elders and mobility impaired people, stability and manoeuvrability are the main issues [15], [16]. So detailed reliable models are needed as a base for the vehicle mechatronic design and real time control system set-up.

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

The basic modules involved in the analysis are indicated in the Fig. 2. 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.

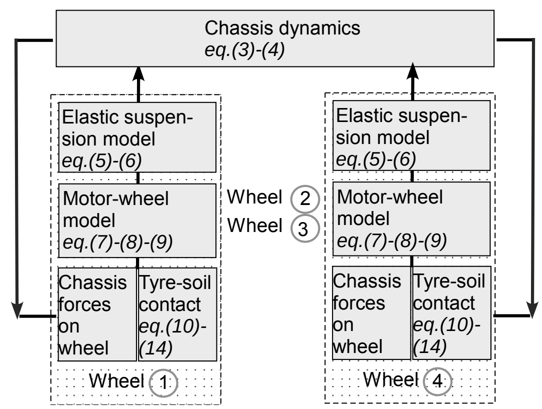


Fig. 2 Modular view of the 4 wheels vehicle model.

The basic reference frames are shown in Fig. 3a

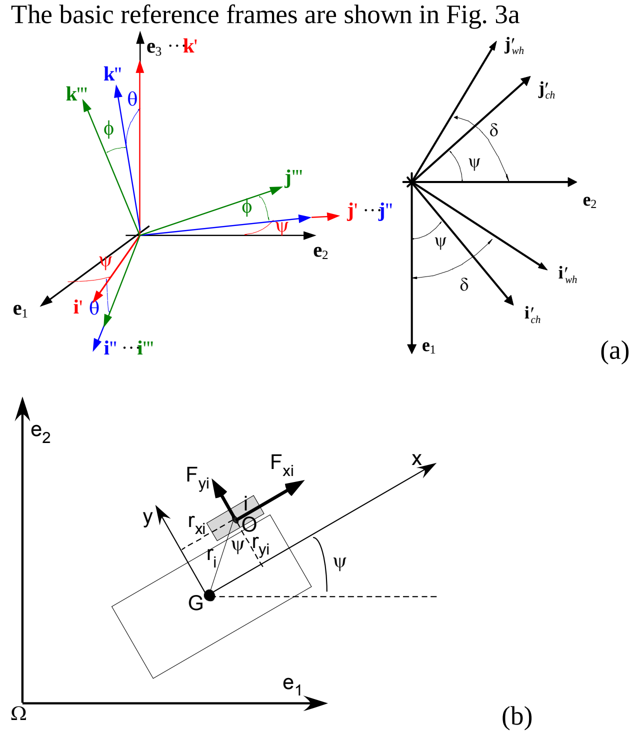


Fig.3 (a) Co-ordinate frames, (b) Wheel chassis outline.

The symbols in Fig. 3 refer to: 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, $\{e_1, e_2, e_3\}$ 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 $\{i' \; j' \; k'\}_{ch} \equiv \{i' \; j' \; k'\}_{wh}$.

The rotation transformation from the fixed to the mobile reference is:

$$\mathbf{R}_{ypr} = \mathbf{R}_{yaw}(\psi)\mathbf{R}_{pitch}(\theta)\mathbf{R}_{roll}(\phi) \tag{1}$$

The angular acceleration on the mobile reference frame, attached to the chassis,is:

$$\dot{\boldsymbol{\Omega}} = \begin{bmatrix} \ddot{\phi} - \ddot{\psi} s_\theta - \dot{\psi}\dot{\theta} c_\theta \\ \ddot{\theta} c_\phi - \dot{\theta}\dot{\phi} s_\phi + \ddot{\psi} c_\theta s_\phi - \dot{\psi}\dot{\theta} s_\theta s_\phi + \dot{\psi}\dot{\phi} c_\theta c_\phi \\ \ddot{\psi} c_\theta c_\phi - \dot{\psi}\dot{\theta} s_\theta c_\phi - \dot{\psi}\dot{\phi} c_\theta s_\phi - \ddot{\theta} s_\phi - \dot{\theta}\dot{\phi} c_\phi \end{bmatrix} \tag{2}$$

A. The chassis model

The chassis is considered as a rigid body with 6 degrees of freedom. The reference frames are shown in Fig. 3.

The dynamic model of the chassis has been written in [11] in the chassis reference frame, in the case of wheels null camber and chassis inertia diagonal matrix. This model is hyper static and difficult to solve in the general case. In the case of PICAV it is admitted that the suspension stiffness is very high so that roll and pitch motions can be neglected ((θ=0, ϕ=0). Further, considering that PICAV has no steering wheels, δ=ψ, the simplified model is:

$$\begin{bmatrix} \sum_{i=1}^{4} F_{xi} \\ -\sum_{i=1}^{4} F_{yi} \\ -\sum_{i=1}^{4} F_{zi} - m_{ch} g \end{bmatrix} = m_{ch} \begin{bmatrix} a_{Gx} \\ a_{Gy} \\ a_{Gz} \end{bmatrix} + m_{ch} \begin{bmatrix} -\dot{\psi} v_{Gy} \\ \dot{\psi} v_{Gx} \\ 0 \end{bmatrix} \tag{3}$$

$$\begin{bmatrix} r_{y1}F_{z1} + r_{z1}F_{y1} - r_{y2}F_{z2} + r_{z2}F_{y2} + r_{y3}F_{z3} + r_{z3}F_{y3} - r_{y4}F_{z4} + r_{z4}F_{y4} + \sum_{i=1}^{4} M_{xi} \\ -r_{z1}F_{x1} - r_{x1}F_{z1} - r_{z2}F_{x2} - r_{x2}F_{z2} - r_{z3}F_{x3} + r_{x3}F_{z3} - r_{z4}F_{x4} + r_{x4}F_{z4} + \sum_{i=1}^{4} M_{yi} \\ r_{x1}F_{y1} - r_{y1}F_{x1} + r_{x2}F_{y2} + r_{y2}F_{x2} - r_{x3}F_{y3} - r_{y3}F_{x3} - r_{x4}F_{y4} + r_{y4}F_{x4} + \sum_{i=1}^{4} M_{zi} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ I_{zch}\ddot{\psi} \end{bmatrix} \tag{4}$$

Where $\mathbf{I}_{zch}$ is the inertia of the chassis about z axis; m_{ch} is the chassis mass; $[r_x, r_y, r_z]^T_k$ is the arm vector of the force $\mathbf{F}_k = [F_x, F_y, F_z]^T_k$ applied to the chassis from the group suspension motor wheel k. $\mathbf{M}_i = [M_x, M_y, M_z]^T_i$ is the vector moment applied to the chassis from the i[th] suspension motor wheel group.

B. Motor-wheel-suspension group

The schema of the suspensions and terminology are given in Fig.4.

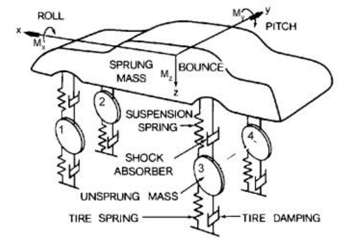


Fig.4 Schema of the visco-elastic elements between the road and the vehicle body (chassis); 1 and 3 indicate the left side wheels, 2 and 4 indicate the right side wheels, 1 and 2 are front wheels

The proposed dynamic model of the individual suspension is:

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

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

where ψ is the yaw angle, $\mathbf{F}_{wh}$ 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 suspensions; 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 where the suspension is linked to the chassis; $\mathbf{a}_G$ is the G acceleration; the superscript indicates the reference frame {**i', j', k'**}. A detailed model and Simulink scheme of suspensions is given in [17]

In the case of stiff suspensions the vertical acceleration is zero: $\ddot{z}_s = 0$.

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 (**e_3**), corresponding to steering torque M_{st}, camber γ around the current x axis (**i**), corresponding to camber torque M_c, see Fig. 5. **R**= $[R_x, R_y, R_z]^T$ is the road reaction on the tyre and $\mathbf{F}_{wh}$ is the force applied by the chassis suspension to the wheel.

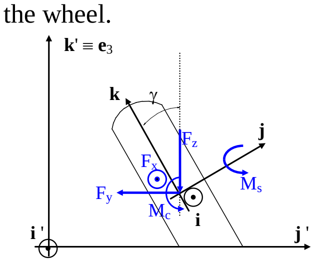


Fig.5 Motor-wheel sketch

The motor wheel dynamic model is derived in the general case in [11].

In the usual case of constant and small, negligible camber angle, the proposed wheel model is simplified in:

$$\begin{bmatrix} R_x + F_{whx} \\ R_y - F_{why} \\ R_z - F_{whz} \end{bmatrix} = m'R \begin{bmatrix} \alpha_s \\ \omega_{st}\omega_s \\ 0 \end{bmatrix} \tag{7}$$

$$\begin{bmatrix} M_c + RR_y - M_{whx} \\ M_s - RR_x \\ M_{st} - M_{whz} \end{bmatrix} = \begin{bmatrix} -I_y\omega_{st}\omega_s \\ I_y\alpha_s \\ I\alpha_{st} \end{bmatrix} \tag{8}$$

Where ω and α are the wheel angular velocity and acceleration while their subscripts *s, st, c* refer respectively to spin, steering, camber; the wheel-motor mass is m' and the mass quadratic moment **I** is diagonal with $I_x=I_z=I$

The in-wheel electric motor is modelled by:

$$\begin{bmatrix} \dot{\omega} \\ \dot{i} \end{bmatrix} = \begin{bmatrix} -K_m^2/I_m & K_t/I_m \\ -K_t/L_m & -R_m/L_m \end{bmatrix} \begin{bmatrix} \omega \\ i \end{bmatrix} + \begin{bmatrix} -T/I_m \\ V/L_m \end{bmatrix} \tag{9}$$

where the values of the winding resistance R_m and inductance L_m, rotor inertia I_m, motor constants K_t and K_m are characteristics of the used motors, given by the supplier catalogue; T is the motor torque, V the armature voltage and i the current.

The influence of the tire slip at the interface between soil and wheel is really important for the car dynamics and stability behavior. The semi-experimental nonlinear law proposed by Pacejka was used to model the tire behavior. With reference to the i^{th} wheel:

$$s_i = \frac{\omega_i R - v_{xi}}{|v'_{xi}|} \text{ with } |v'_x| = \max(|v_x|, 0.01), \tag{10}$$

where ω_i is the wheel angular velocity, R is the wheel radius, v_{xi} is the wheel longitudinal velocity.

The relation between the reaction force R_{xi} and the slip s_i can be approximated by a symmetric saturation law:

$$R_{xi} = k_i s_i = \mu_i R_{zi} \quad \text{if} \quad |s_i| \le s_{sat}; \quad R_{xi} = k_i s_{sat} = \mu_i R_{zi} \quad \text{if} \quad |s_i| > s_{sat} \tag{11}$$

where: k_i is the i wheel slip law constant, s_{sat} is the saturation slip and μ_i is the wheel adherence coefficient.

The single motor wheel state equation referred to the state $\begin{bmatrix} v_{xi} & \dot{v}_{xi} \end{bmatrix}^T$ is non linear, described by the Jacobian $J_x(q)$, where I' is the motor wheel inertia and:

$$q = \begin{bmatrix} \dot{v}_{xi} & -(\dot{v}_{xi} + K)\frac{\dot{v}_{xi}}{v_{xi}} \end{bmatrix}^T \qquad K = \frac{k}{m'}\left(\frac{m'R^2}{I'} + 1\right)$$

$$J_{\mathbf{x}}(q) = \begin{bmatrix} 0 & 1 \\ (\dot{v}_{xi} + K)\frac{\dot{v}_{xi}}{v_{xi}^2} & -2(\dot{v}_{xi} + K)\frac{\dot{v}_{xi}}{v_{xi}} \end{bmatrix}$$

Being q analytical, the Jacobian is continuous and the existence of a unique solution is guaranteed. It can be noted that there are initial conditions of the motor wheel motion that take the motion to infinity but the saturation of the traction forces prevents this unstable behaviour.

The lateral reaction R_y is considered proportional to the slip angle β_i and then to their tire cornering stiffness C_i

$$R_{yi} = C_i \cdot \beta_i = C_i \cdot \text{sgn}(v_{yi}) \cdot \text{atan}\left(\frac{|v_{yi}|}{|v'_{xi}|}\right) \tag{12}$$

Within the slip saturation limits, the motor wheel dynamics model is simplified in:

$$T_i - R_{xi} \cdot R = I'\dot{\omega}_i \quad F_{xi} = k_i s_i = m'\dot{v}_{xi} \tag{13}$$

where m' and I' are mass of the wheel and its moment of inertia referred to the wheel axis; k is the slip law constant.

Then, taking into account the expressions of s (10) and:

$$\dot{\omega}_i = \frac{\dot{v}_{xi}}{R} + m\frac{\ddot{v}_{xi}v_{xi} + \dot{v}_{xi}^2}{k_i R}$$

$$T_i = m'R\dot{v}_{xi} + \frac{I'}{R}\left(\frac{m'}{k_i}\left(\ddot{v}_{xi}v_{xi} + \dot{v}_{xi}^2\right) + \dot{v}_{xi}\right) \tag{14}$$

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

C. PICAV vehicle simplified state model

In the previous section the dynamic models of the vehicle single modules have been presented. The complete model of the vehicle is obtained by linking these modules. Admitting the following hypotheses: - 4 motor wheels with the same diameter 2R; - chassis suspensions connections sufficiently stiff compared to the forcing band due to the ground unevenness; - short suspension arms; - adopting the ground model proposed in [12], and working within the slip saturation limits; - zero steering angle relative to the chassis; the 2D model, written in terms of state equation, where the state vector is $\mathbf{x} = [\omega_1 \;\; \omega_2 \;\; \omega_3 \;\; \omega_4 \;\; \dot{x} \;\; \dot{y} \;\; \dot{\psi}]^T$ calling ω_i the i^{th} wheel angular velocity and $\dot{x} = v_x;\ \dot{y} = v_y;\ \dot{\psi} = {d\psi}/{dt}$,is $\dot{\mathbf{x}} = \mathbf{f}(\mathbf{x}) + \mathbf{B} \cdot \mathbf{u}$ with:

$$\mathbf{f(x)} = \begin{bmatrix} -\frac{k_1 R}{I_1} \cdot \left(\frac{\omega_1 R - (\dot{x} + \dot{\psi} r_{y1})}{\dot{x} + \dot{\psi} r_{y1}}\right) \\ -\frac{k_2 R}{I_2} \cdot \left(\frac{\omega_2 R - (\dot{x} + \dot{\psi} r_{y2})}{\dot{x} + \dot{\psi} r_{y2}}\right) \\ -\frac{k_3 R}{I_3} \cdot \left(\frac{\omega_3 R - (\dot{x} + \dot{\psi} r_{y3})}{\dot{x} + \dot{\psi} r_{y3}}\right) \\ -\frac{k_4 R}{I_4} \cdot \left(\frac{\omega_4 R - (\dot{x} + \dot{\psi} r_{y4})}{\dot{x} + \dot{\psi} r_{y4}}\right) \\ \sum_i \frac{k_i}{m}\left(\frac{\omega_i R - (\dot{x} + \dot{\psi} r_{yi})}{\dot{x} + \dot{\psi} r_{yi}}\right) + \dot{\psi}\dot{y} \\ \sum_i \frac{C_i}{m} \text{atan}\left(\frac{\dot{y} - \dot{\psi} r_{xi}}{\dot{x} + \dot{\psi} r_{yi}}\right) - \dot{\psi}\dot{x} \\ -\frac{1}{I_{zch}}\sum_i \frac{k_i}{m}\left(\frac{\omega_i R - (\dot{x} + \dot{\psi} r_{yi})}{\dot{x} + \dot{\psi} r_{yi}}\right) \cdot r_{yi} + \frac{1}{I_{zch}}\sum_i \frac{C_i}{m} \text{atan}\left(\frac{\dot{y} - \dot{\psi} r_{xi}}{\dot{x} + \dot{\psi} r_{yi}}\right) \cdot r_{xi} \end{bmatrix};$$

$$\mathbf{B}=\begin{bmatrix} \frac{1}{I_1} & 0 & 0 & 0 \\ 0 & \frac{1}{I_2} & 0 & 0 \\ 0 & 0 & \frac{1}{I_3} & 0 \\ 0 & 0 & 0 & \frac{1}{I_4} \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}; \quad \mathbf{u}=\begin{bmatrix} T_1 \\ T_2 \\ T_3 \\ T_4 \end{bmatrix} \tag{15}$$

As derived in [11] where: T_j, is the actuation torque reduced at each wheel axis and subscripts 1÷4 refer to the wheels. The model is non-linear and includes dynamic couplings in $\mathbf{f}(\mathbf{x})$.

This state model can be used in model based PICAV control systems [16] while it is too simplified to represent the dynamic behaviour of the vehicle in real operative conditions.

To check the feasibility of practical manoeuvres the equations of the modelled dynamics have to be solved and a suitable simulator has been written using Matlab/Simulink, and resorting to a library purposely written for vehicle dynamics, by fully exploiting the modelling modular approach. In the PICAV dynamics simulation the external aerodynamic forces were neglected due to the PICAV low velocity.

III. Simulation results

The models of the single bodies of the vehicle have been codified in Simulink modules, that suitably linked as in Fig.6 give the virtual dynamic mock-up of the PICAV vehicle.

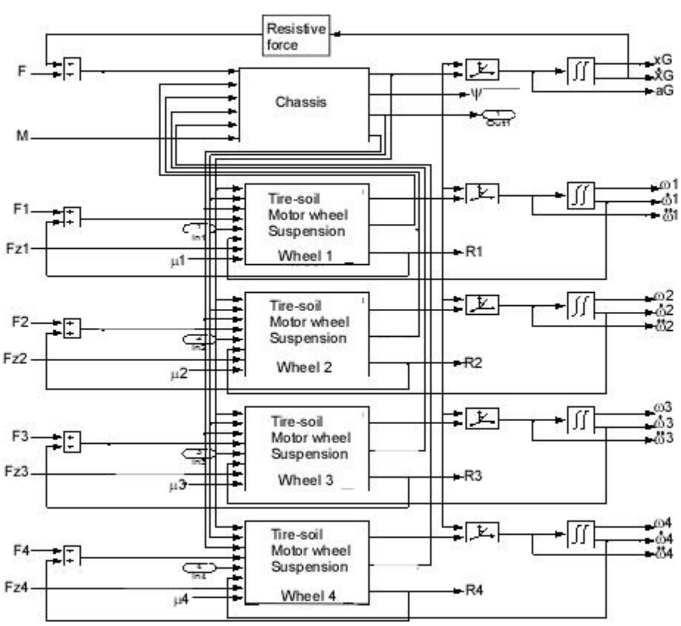


Fig. 6 Sketch of the PICAV dynamic model in Simulink

The vehicle PICAV is designed with not standard architecture suitably thought for weak, elderly and motion impaired people to move even in difficult city centers grounds, so the detailed dynamic model is considered a knowledge base necessary for the analysis of the motion behaviour and for the safety measure in terms of the manoeuvrability and stability that represent the main concern for this kind of vehicle.

The models derived in the previous section can be used for knowing the direct dynamic behaviour of the vehicle for manoeuvring, stability checks and design purposes as presented in Fig. 7. In case of vehicle semi-automatic open loop (driving assistant) [10], [17] or closed loop autonomous [15], [19] use the derived models can be used as described in the same Fig. 7.

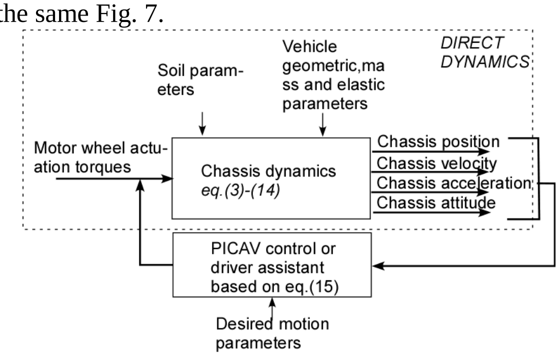


Fig. 7 Main I/O in the vehicle dynamics

The PICAV model and simulator were validated stand alone in different operative and environmental conditions. The most critical module is the motor wheel module: tests with braking and accelerating torques with different adherence conditions, with transversal force application, helped to be confident in the model describing the interaction of the motor wheel and the environment. Some results of the recalled simulation experiments are shown in [7].

A. PICAV on circular trajectory

The 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.

In Fig. 8 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 64 m radius circle. During this trajectory the chassis yaw is decreasing with constant speed and zero acceleration. Fig.9 and Fig.10 depict the trends of significant variables during this manoeuvre: the forces exchanged between soil and wheels, the forces applied from the wheels to the chassis. The results highlighted 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 the vehicle rotation.

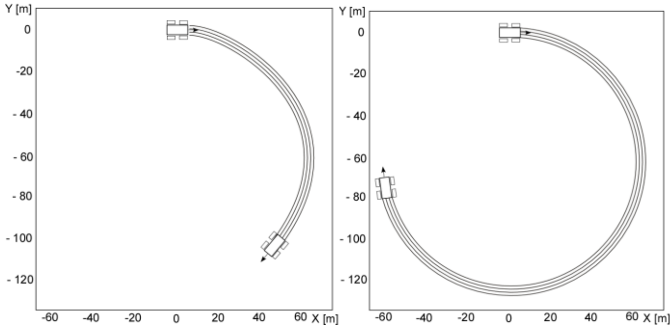


Fig. 8 PICAV circular trajectory at different times

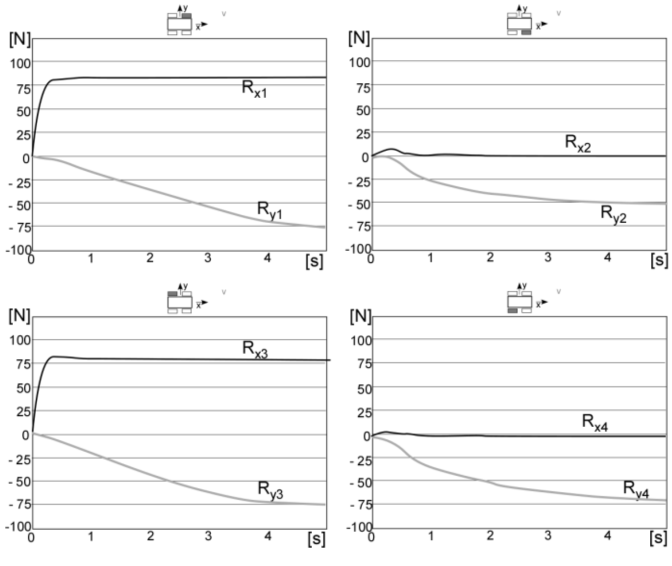


Fig. 9 Single wheel ground reactions during the path of Fig. 8.

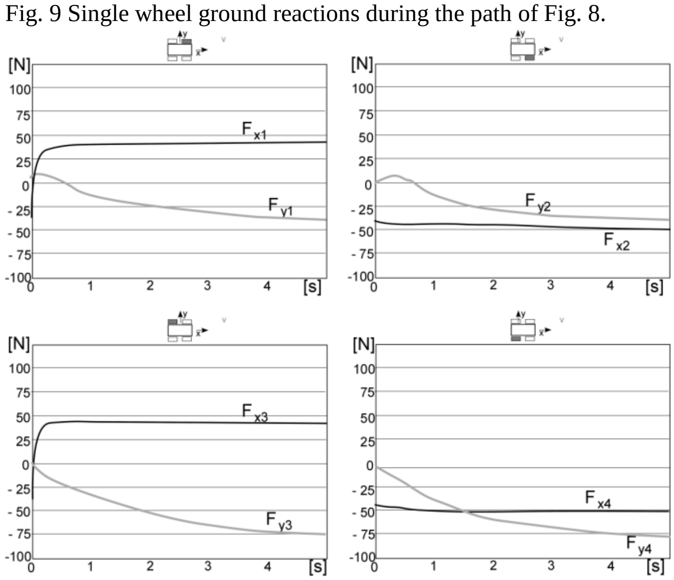


Fig. 10 Forces applied by the wheels on the chassis during the circular path of Fig. 8.

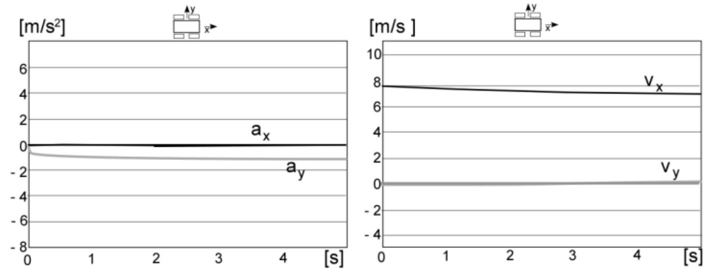


Fig. 11 trend of acceleration and velocity of the chassis center of mass during the circular path of Fig. 8.

It has to be noted, Fig.11, that the vehicle forward velocity is slightly 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 rolling reactions, the centripetal contribution. In any case the circular path closes with negligible errors.

B. PICAV behavior in case of adherence variation

In the test 12 simulation the torques applied to the four motor wheels are equal to 7.5 Nm while the adherence coefficient is μ=0.8 and only on the wheels 2 and 4, from time 0.5s to 2.0s, reduces to μ=0.2. The trajectory performed, with initial conditions $v_{Gx}(0)$=0.5 m/s, $v_{GY}(0)$=0.0 m/s is represented in Fig. 12.

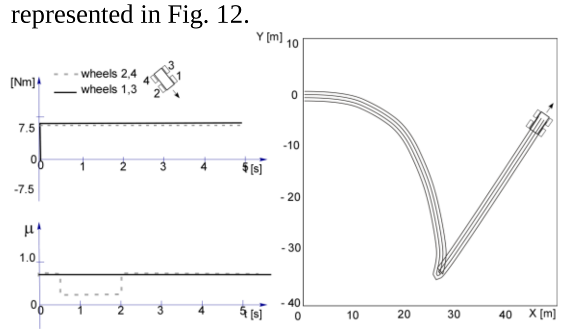


Fig. 12 PICAV trajectory test 12: influence of different adhesion coefficients

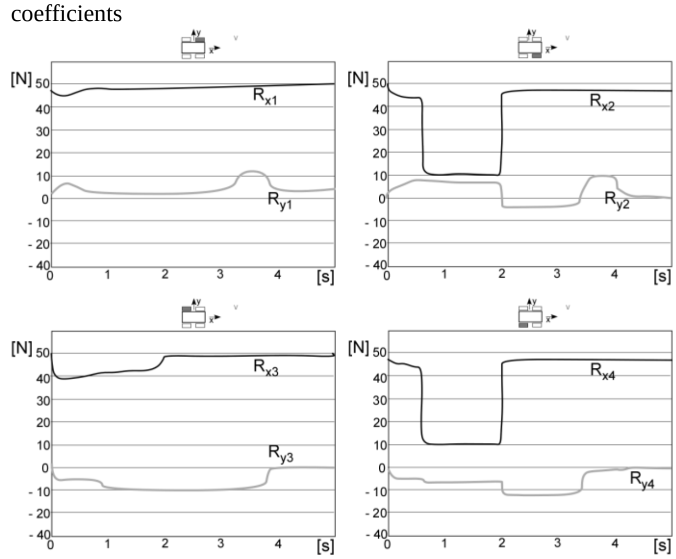


Fig.13 PICAV four wheels reactions during the test12

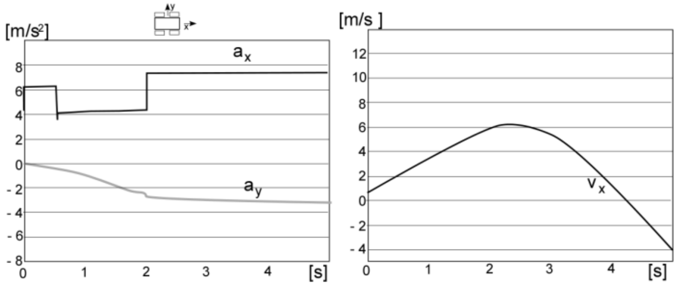


Fig. 14 Trend of absolute acceleration and velocity of the chassis center of mass in the **ijk** reference during test 12

The simulation results demonstrate the correctness of the slip model. The temporary velocity inversion is due to the different nature of the velocity components: the term ωR is influenced by the applied motion torque laws, while the term v_x is mainly influenced by the chassis attitude. So, also if the velocity module is about constant, a variation of the chassis attitude can sensibly modify the velocity component in the vehicle direction.

C. PICAV behaviour to impulsive torques actuation

To study the intrinsic stability of the vehicle, before to apply any control strategy, in order to assess its behaviour to reactions and yaw moments on the chassis, some simulations have been performed applying differential torques of short duration to the motor wheels, leaving the vehicle then move without actuation.

Test 15 simulation refers to very high torque actuation mimicking an impulsive torque: 170 Nm to the outer train and -170 to the inner from start to 0.3 s, then suddenly removing the torques, the results are shown in Fig. 15, Fig.16 and Fig.17.

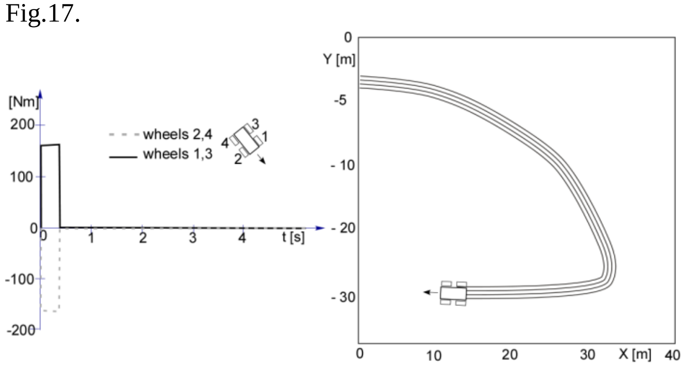


Fig. 15 Trajectory during the pulse torque test 15

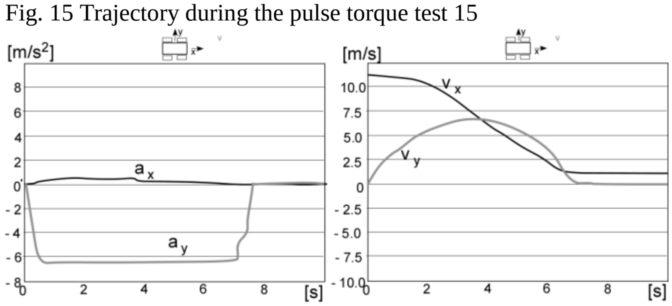


Fig. 16 PICAV chassis acceleration and velocity during the torque pulse test15

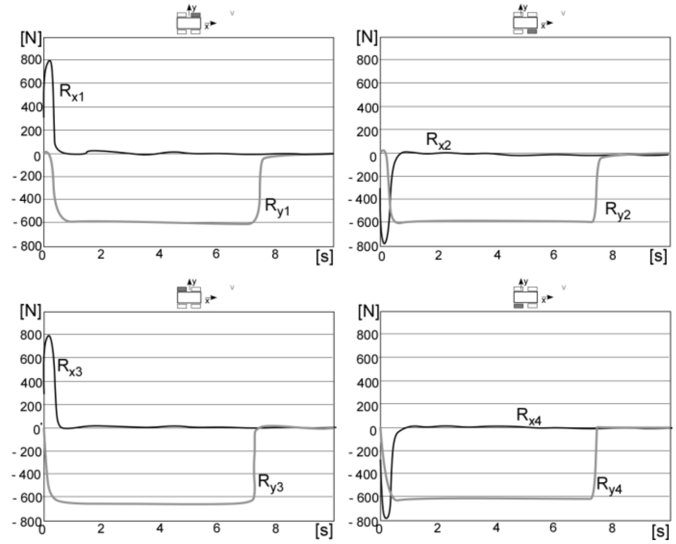
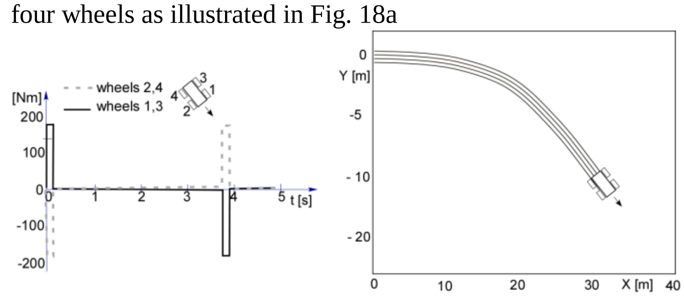


Fig. 17 The four wheels reaction during the torque pulse test15

The vehicle continues to rotate also without applied forces. Further the transversal reactions simultaneously saturate causing a null yaw moment. At this time the PICAV behaviour becomes independent from the transversal reactions and its yaw dynamics is mastered by the only longitudinal reactions. The behaviouris congruent with the one investigated for another city car [16] in similar operative conditions.

D. PICAV behaviour to bang bang torques actuation

The test 18 example case analyses the vehicle behaviour under the application of bang bang pulses of torques on the four wheels as illustrated in Fig. 18a



(a) (b)

Fig.18 Torque laws applied to wheels (a), performed path (b.) during bang bang test 18

The path tracked shows that the effect of the counter-torques is the vehicle stabilization, Fig. 18 (b), that happens very quickly; the counter-torques are applied when all the wheels are skidding and the yaw dynamics is mainly influenced by the longitudinal reactions, different from the applied torques. Fig. 20 reports the trends of the components of acceleration and velocity of the chassis center of mass during test 18. The slip on the front wheel 2 has the same trend as in front wheel 1; similar trends are obtained for the two rear wheels; the soil reactions are similar for the left side wheels and for the right side wheels, see Fig. 19.

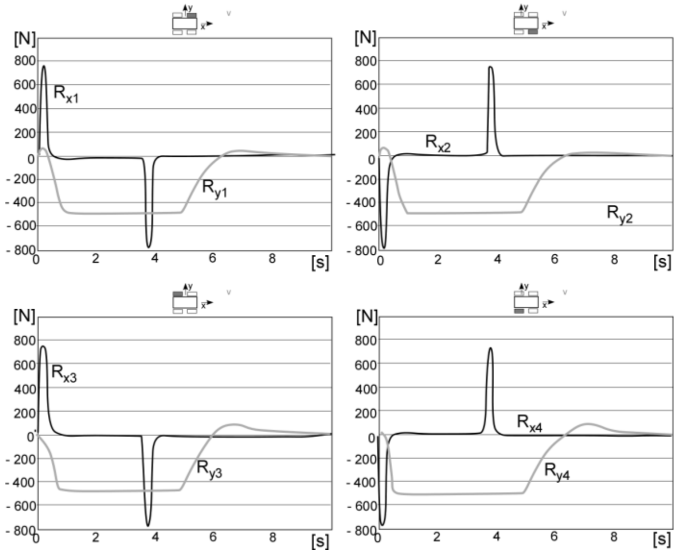


Fig. 19 Soil reactions on wheels during bang bang test 18

In Fig. 20 it can be seen that the corrective action is sufficient to take again the PICAV on the route guaranteeing the intrinsic stability of the vehicle.

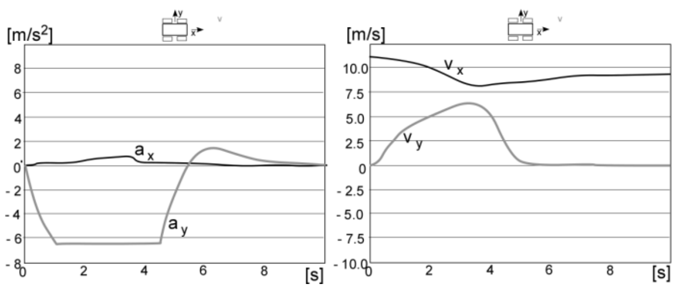


Fig. 20 PICAV vehicle acceleration and speed during the bang bang test 18.

IV. Concluding comments

The paper proposes a parametric modular model for a 4 non steering motor-wheels vehicle. The model is applied to the new full electric personal vehicle PICAV to study its open loop performances about dexterity in manoeuvring and stability. The dynamic mathematical models are proposed for the single modules composing a car; 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. Further a simplified model in terms of state variables is proposed: it is useful as a base for the driving assistant set up [10] and new control modes to adopt in case of some level of autonomous driving.

The presented models represent the knowledge base of the PICAV dynamics used within the discrete event simulation package, following the same microsimulation approach used in [17], developed as a detailed analysis tool of the PICAV system management, described in [5] and [6].

The simulation results addressed many ideas to exploit the actuation redundancy of four powered wheels to accomplish standard manoeuvres by directly controlling the torque and the speed actually supplied by each tyre-soil interaction. The actuation redundancy might also be exploited to have higher driving stability even when the road conditions vary abruptly and this conditions are typical of the PICAV environments.

PICAV is designed to be driven also by weak people in semi-autonomous way under the guide of the driver assistant module and, in autonomous way in special cases, such as the re-allocation of the vehicle fleet to the parking lots, during the night. Off line and on line control logics are then needed in order to fulfill the requirements on manoeuvrability and stability. For this reason the dynamic detailed model of the vehicle plays a unique important role allowing the definition and set up of the mechatronic system also in virtual critical conditions. The paper concerns the contribution of the authors to these aspects.

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