Determination of wheelchair stability for development and control

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Abstract. *The aim of this article is methodologically to define the dynamics limits of the system composed by a child and a wheelchair in terms of the constructive variables like width, length, center of gravity position of the system. For modelling the system was used the Newton-Euler equations As results of this paper was possible to determine the limit for the linear velocity of the wheelchair, in order to avoid accidents like tumbling in many different situations, the limit was found as being 1,33 m/s, what is like a person walking quickly. Another important result is about the constructive variables through the dynamic modeling are possible to determine which affect more or less the system stability and how it would be the limit if the constructive variable was changed. It was determined that the dynamic limit could be increased if the height of the system gravity center was decreased or the width of the wheelchair was increased.*

***Keywords**. Modeling, Stability, Control, Wheelchair*

1. INTRODUCTION

Wheelchairs are usually the only solution (or at least the most accessible) available to solve mobility problem, however they still now allow some activities associated with the independent and healthy existence. For handicapped people the necessity of equal opportunities means accessibility and independent mobility.

Advances on wheelchair design increased the mobility, but did not decreased the limitations about the use of wheels, mainly when it comes to children necessities face to the problem of dependent locomotion.

The world, which the wheelchair users take part it is largely defined through the capabilities of the wheelchair used. In reality only 5% of the world surface is accessible by wheelchair, even in urban environment there are many architectonic obstacles.(Smith R. V. & Leslie Jr, J.H. 1990).

In recent studies, by (Arva, 2000; Buttler, 2000; Cooper and Boninger, 1999; Cooper and Boninger, 1998, Corfman et. Al, 2000) can be proved the importance of having a more independent life contributes a lot to have a better development of usual abilities as it says it speech, learning how to communicate, and the most important thing the skill of living in a society and as effect the capacity to have a independent life.

It is necessary firstly to know about the wheelchair dynamic comportment and after that it is possible to design a new concept of wheelchair, which is able to improve the child mobility and the muscular upper extremities aptness.

It to drive at a more realistic analysis for the dynamic behavior wheelchair, in this paper it will be determinated the dynamic stability limits. The wheel modeling has the fundamental importance in this study, factors like sliding or rolling movement, wheel type (elastic or rigid) and the wheelchair directionality will influence on the dynamic limits.

Looking at for commercial trading wheelchair, it can be observed that the majority of manual wheelchairs, could have its wheels considered as rigid, thus it can be utilized the linear model (Huston, 1982 e Becker, 1997) which it will be incorporated later into movement equations of the wheelchair for the stability and dirigibility analysis.

The dynamic limits is important to be known whereas our public ownership is composed basically by children who do not have the skills to detected and to correct imminent danger situations, this action in our conception belongs to the control system which will identify and will prevent/correct the dangerous elements (as velocity, acceleration, directionality, etc) in the movement, thus preventing accidents.

2. LINEAR MODELLING OF WHEEL

In their work Huston 1982; Chang e Lee, 1990; Becker 1997 and Lombardi Jr. 2002; consider a stiffness wheel and a perfect rolling between the track and the wheel, but the effects of velocity and compression and traction of the wheel filaments were not considered.

This assumption is very important because the equations for the longitudinal and transversal movements became independent.

The linear modeling of wheel is related with the transversal force acting over the wheel and the lateral stability during the forward movement. Based on the works of Becker, 1997 and Lombardi Jr., 2001, it is possible to assert that the velocity limit for the lateral stability movement is too high for the wheelchair application, so it is inconsiderate.

In the works mentioned before as important conclusion, which is corroborated in this paper is that the stability limit is increased when the center of gravity (Cg) is near to the front shaft in the wheelchair.

3 STABILITY

3.1 Tumbling

Applying a lateral force F in a height h over the wheelchair and calculating the sum of moments, when this sum is bigger then zero the wheelchair tumble.

Tumbling axis is called in the Fig. (1) as ET which is the axes where will be forced the tumbling. Having this definition the tumbling criterion is derived from the momentum in relation with the axes ET and forces on the axes y, resulting in the follow expression:

$$\begin{cases} F < \dfrac{b}{2.h}.W \\ F = Fy < \mu.W \end{cases} \qquad \text{Eq. 1}$$

Observing the Eq. (1) it can be concluded that friction coefficient μ must be minor than b/(2.h), thus the wheelchair will slide over the paving before the tumbling occurs. The same equation suggests that b/(2.h) being the major as possible to prevent the tumbling, what is mean, that h (height of Center of Gravity) must be the minor as possible implying that the Cg must be the near as possible of the paving.

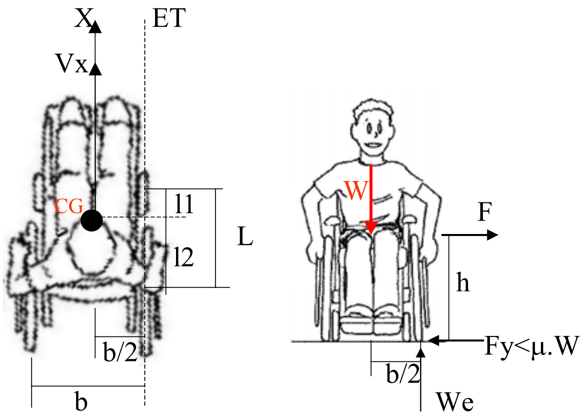

Figure 1. Modeling of wheelchair with linear movement submit to linear force.

3.2 Tumbling in incline plane, linear movement and constant velocity

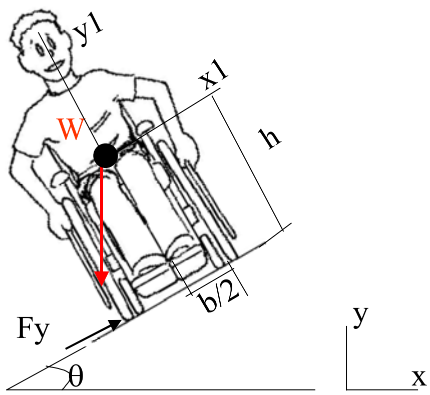

Figure 2. Modeling of wheelchair with linear movement in an incline plane.

Again it is necessary to write the sum of momentum over the tumbling axes over the reference system *x1y1,* represented on Fig. (2) and applying the previous considerations, the sum of momentum must be smaller the zero, the resultant two equations are shown following, Eq. (2):

$$\begin{cases} \theta < arctag\left(\dfrac{b}{2.h}\right) \\ \mu.W > Fy = W.\sin\theta \end{cases} \qquad \text{Eq. 2}$$

Observing the Eq.(2) it is possible to deduce that ($sin\theta < \mu$) is the limit for the plane inclination, which the wheelchair is able to move, otherwise the tumbling can happen.

Therefore observing the Fig.(3), which is based on the Eq.(2), the wheelchair will more stable in terms of tumbling as lower the Cg being, represented by the variable h, and major the distance between the shafts, represented by the variable b.

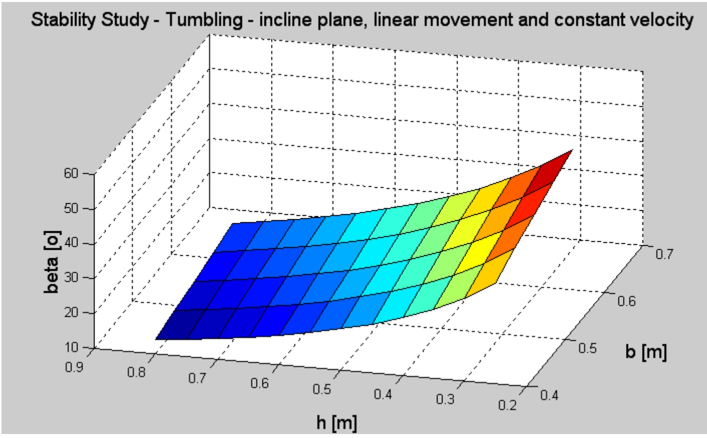

Figure 3. Critical angle θ comportment relative to variables b e h

3.3 Tumbling in slope and linear movement

This parameter is important because define the maximum angle (for positive or negative slope) which the wheelchair can transpose without the risk of tumbling.

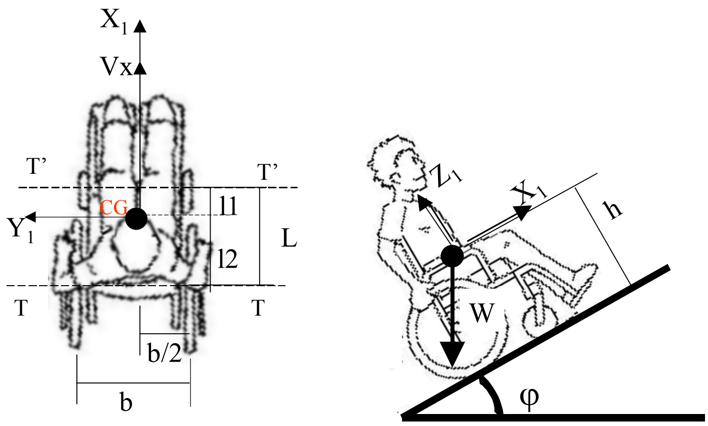

Figure 4. Modeling of the wheelchair in the slope with the linear movement

Accomplishing the momentum sum in relation to the axes TT as shown in the Fig. (4) and assuming that this sum is negative, we have the Eq.(3) for the ascent:

$$\sum M_{TT} = W.l2.\cos\varphi - W.h.\sin\varphi < 0$$

$$\therefore \varphi < arctag\left(\frac{l2}{h}\right) \qquad \text{Eq. 3}$$

Analogizing the momentum sum in relation to the axes T'T' results, for descending

$$\varphi < arctag\left(\frac{-l1}{h}\right) \qquad \text{Eq. 4}$$

As example, it will be shown the graphic for the positive slope, Fig. 5, where can be deduced that for positive slope the l2 must be major and for negative slope the l1 must be major, but in both case the variable h (height of Center of Gravity) must be the lower as possible for a better stable condition.

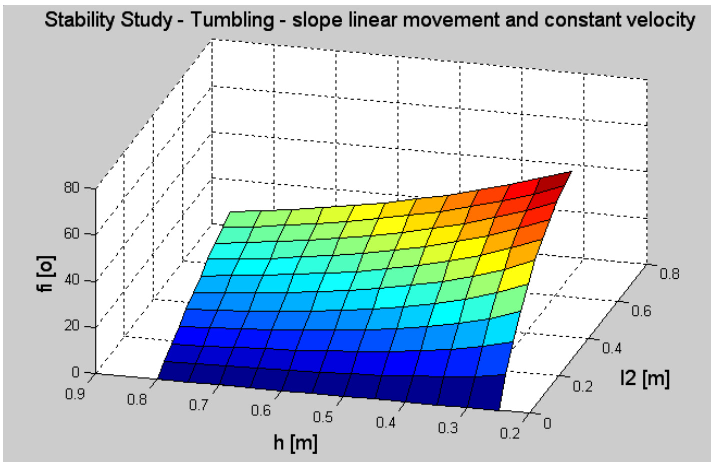

Figure 5. Critical angle ψ comportment relative to variables b e h

3.4 Plane curve with aceleration

It is important to consider the influence of acceleration over the wheelchair movement, so we must consider the inertia forces induced by the longitudinal acceleration, Eq.(5) and Eq.(6):

$$|Flong| = m.a \qquad \text{Eq. 5}$$

and the force induced by the lateral acceleration:

$$|Flat| = \frac{mV^2}{R} \qquad \text{Eq. 6}$$

Where, R is the radius of the circular movement. Now considering this force and analyzing the force diagram system in the Fig.6:

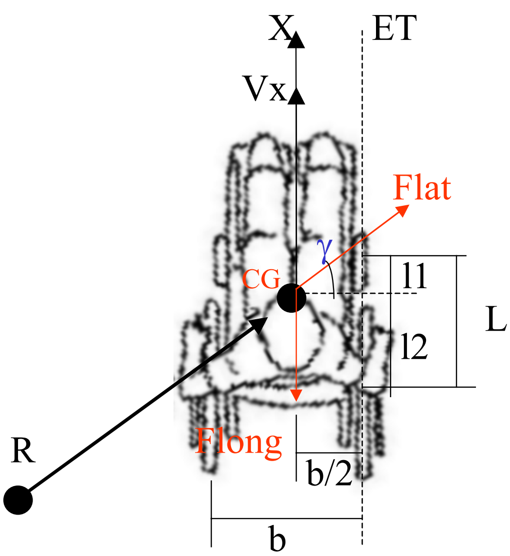

Figure 6. Modeling of wheelchair with curve movement and acceleration

Repeating the development shown in the previous sub-section, which it takes us the eq (7) which represent the stability condition for the system:

$$Flat < \frac{W.b}{2.h.\cos\gamma} \qquad \text{Eq. 7}$$

Combining the Eq. (6) and Eq. (7):

$$V\,\text{lim}it = \sqrt{\frac{g.R.b}{2.h.\cos\gamma}} \qquad \text{Eq. 8}$$

It will be observed in the Fig. (7 (a) and (b)) the wheelchair will more stable in terms of tumbling in curve movement and accelerations as lower the Cg (h) being and major the distance between the shafts (b), the variables R influence the stabability and the critical velocity will increase as this variable increase, but γ has no influence on the critical velocity.

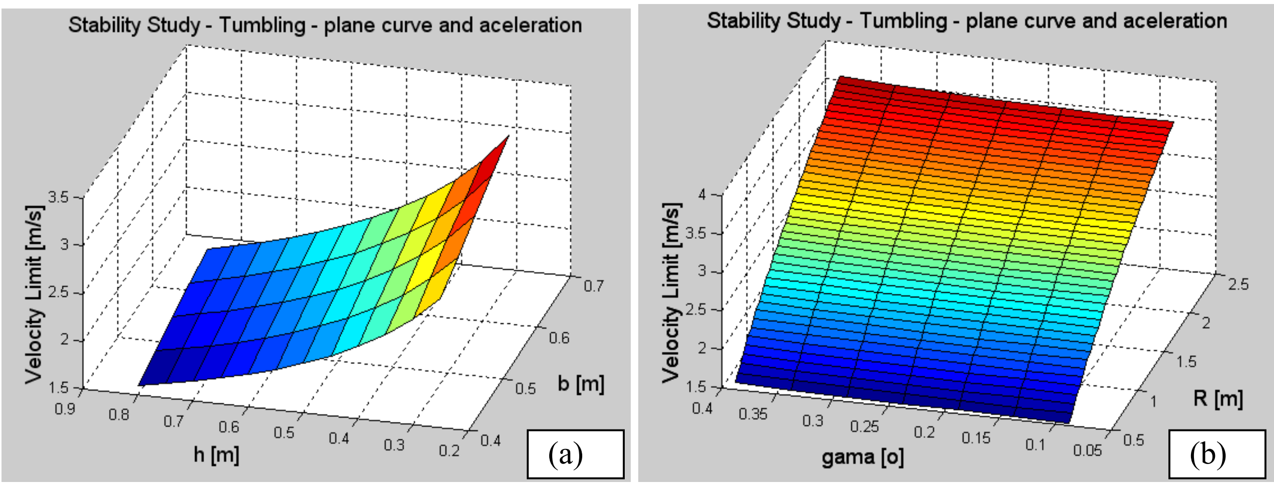

Figure 7. (a) Critical velocity comportment relative to variables b e h (b) Critical velocity comportment relative to variables R e γ

3.5 Inclined curve and aceleration

For this kind of utilization the analysis is a mix of section 3.4 and 3.3, only important thing is that we must too consider the forces induced by the linear acceleration and lateral acceleration, and the result equations are expressed by the equations Eq.9 and Eq.10:

$$Flat < \frac{1}{\cos\gamma}\left(\frac{2.W.h.sin\theta + W.b\cos\theta}{2.h.\cos\theta - b.sin\theta}\right) \qquad \text{Eq. 9}$$

and for the velocity limit:

$$V\,\text{limit} < \sqrt{\frac{g.R}{\cos\gamma}\left(\frac{2.W.h.sin\theta + W.b\cos\theta}{2.h.\cos\theta - b.sin\theta}\right)} \qquad \text{Eq. 10}$$

It is important to note that the limits are higher when the angle θ is positive, what it means ascent, the inverse occurs when, negative. Again can be observed that the stability increase as lower is the Cg (h) being and as higher the distance between the shafts (b), as shown in Fig.(8).

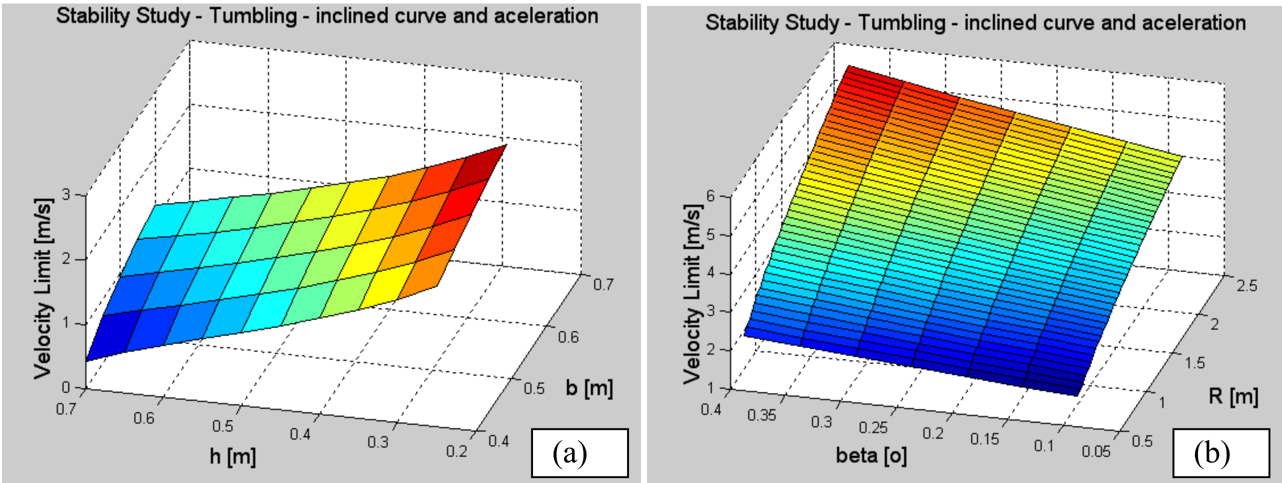

Figure 8. (a) Critical velocity comportment relative to variables b and h (b) Critical velocity comportment relative to variables R and β

3.6 General Situation – Duble angle in paving, curve movement and acceleration.

The previous sections modeled particular situations, however the user can be submitted to situations much more complex. Thus it is important to model the wheelchair movement in terms of movel basis which makes easy the comprehending of the movement.

Coordinate system definition, represented in Fig.(9):

- Inertial System I positioned in the wheelchair center of gravity and defined by XYZ and i,j,k;
- Movel System B1 fized to wheelchair CG and defined by: X1Y1Z1 and i1,j1,k1;

The angles *How, Pitch and Yaw,* are defined to determine the wheelchair rotations, and the coordinates transformation matrix are determined by the following equations Eq.(11), Eq.(12) and Eq.(12):

$$R_{x,\gamma} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\gamma & -\sin\gamma \\ 0 & \sin\gamma & \cos\gamma \end{bmatrix} \qquad \text{Eq. 11}$$

$$R_{y\beta} = \begin{bmatrix} \cos\beta & 0 & \sin\beta \\ 0 & 1 & 0 \\ -\sin\beta & 0 & \cos\beta \end{bmatrix} \qquad \text{Eq. 12}$$

$$R_{z,\alpha} = \begin{bmatrix} \cos\kappa & -\sin\kappa & 0 \\ \sin\kappa & \cos\kappa & 0 \\ 0 & 0 & 1 \end{bmatrix} \qquad \text{Eq. 13}$$

The angle Yaw, κ, which represents the axes Z rotation can be expressed directly by the formula relating the curve radios (R) as observed in the follow equation Eq.(14):

$$\kappa = \sin^{-1}\left(-\frac{l2}{R}\right)$$ Eq. 14

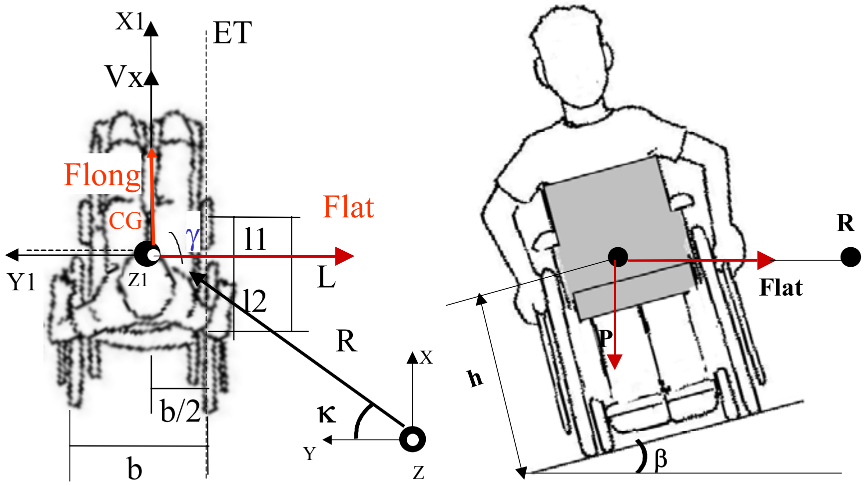

Figure 9. Forces diagram for the wheelchair in superior and posterior view.

The forces modulus induces accelerations radial (Flat) and tangential (Flong) over the wheelchair Cg, and the weight are defined by the equations Eq.(15), Eq.(16) and Eq.(17):

$$_1\vec{Flong} = m.a_x.\begin{Bmatrix} 1 \\ 0 \\ 0 \end{Bmatrix}$$ Eq. 15

$$_1\vec{Flat} = \frac{mV_x^2}{R}.\begin{Bmatrix} 0 \\ -1 \\ 0 \end{Bmatrix}$$ Eq. 16

$$_1\vec{W} = m.g\begin{Bmatrix} 0 \\ 0 \\ -1 \end{Bmatrix}$$ Eq. 17

The coordinate transformation between the noninertial system to inertial (Eq.18), is defined as;

$$R_0^1 = R_{z,\kappa}.R_{y,\beta}.R_{x,\gamma}$$ Eq. 18

Determine the momentum sum relating to the tumbling axes ET:

$$\sum M_{ET} = {}_1\vec{R}.{}_1\vec{F}_{long} + {}_1\vec{R}.{}_1\vec{F}_{lat} + {}_1\vec{R}.{}_1\vec{W} = 0$$ Eq. 19

Transforming the vectors represented on Eq.(15, 16 and 17) to movel basis using the Eq.(18) and solving the Eq.(19) in function of the velocity Vx, wheelchair linear velocity, results in, Eq.(20):

$$V_x = \sqrt{\tfrac{1}{2}.\cos(\beta).g.\frac{R}{h}(b.\cos(\gamma) - 2.h.sin(\gamma))}$$ Eq. 20

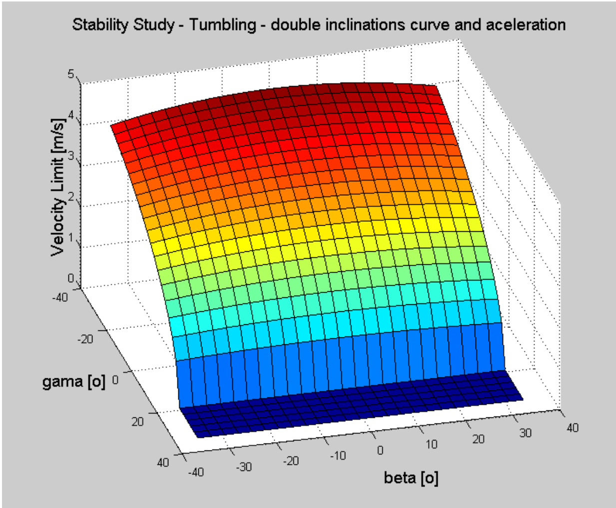

Figure 10. Representation for the velocity limit for the wheelchair over a double angle in paving, curve movement and acceleration

The graphic, shown on Fig.10, is very similar to the previous and the conclusions are: the limit for the critical velocity is the lowest than the previous but is confirmed the assumption about the stability increase as lower is the Cg (h) being and as higher the distance between the shafts (b), and the curvature circumference have to be the biggest as possible.

With the equations obtained in this section is possible to determine all the previous velocity limits as the shown in the sections 3.5, section 3.4, but it makes clear only after solving the conditions individually.

All simulations in this paper were made using: μ = 0,015 (rolling resistance); wheelchair dimentions: L = 0,5 m; l2 = 0,2 m; l1 = 0,3 m; h = 0,5 m; b = 0,70 m (ABNT 9050); m = 110 kg; e R = 2,5 m (radius curvature) slope angles β = 10 º e γ = 15 º

4. CONCLUSION

To sum up the simulations are shown below a table, Tab.(1), which contains the limits for a standard wheelchair for all situations modeled in this paper.

Table 1 – Limits for the wheelchair movement

	Uniform Movement			Variable Movement		
Sliding Velocity [m/s]	Lateral tumbling Angle (º)	Frontal tumbling angle (º)	Rear tumbling angle (º)	Plan Curve Velocity Limit [m/s]	Slope Curve Velocity Limit [m/s]	Duble Slope Curve Velocity Limit [m/s]
274	19,3	21,8	-31	2,98	3,77	1,33

This limits obtained are very important because with control system can restrict velocity in safe utilization range. Using the equations developed in this paper is possible to determine the global velocity limit the value of 1,33 m/s what is equivalent to the velocity of a person walking quickly.

This limit, obviously, was indicated for the standard wheelchair simulated in this paper, but the equations are general and must be applied before any attempt to develop a new kind of wheelchair.

Knowing the velocity limit for a specific wheelchair or system (wheelchair + user) is fundamental for avoiding accidents.

Nowadays the wheelchair has become more and more fast but the security is a important factor when new projects are development and this paper, using a methodological study, set some equations that can help and remember designer to pay attention about the users security.

Two variables have fundamental importance over stability limit; they are the center of gravity height and wheelchair width, the stability increase as the first decrease and the second increase.

5. ACKNOWLEDGEMENT

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