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APC Military Vehicle - Lateral Dynamics Case Study

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Abstract. *The Armored Personnel Carrier (APC) Brazilian military vehicle called APC URUTU EE-11 was developed in the 70s by ENGESA to fulfill the Brazilian army needs at the time. Nowadays, this vehicle's use has been redirected to civil police operations, where it takes personnel to urban areas of difficult access due to narrow streets, sharp turns and low adherence inclined pathways. Therefore, this work proposes replacing ENGESA's boomerang rear axle, a double wheel axle with dedicated gear boxes, with a single rear steering axle. The adaptation for an all wheel steering vehicle aims at reducing it's weight and making it more agile, once the unsprung vehicle mass is reduced and the rear wheel steering system increases it's maneuverability. Furthermore, a Matlab/Simulink simulation is conducted to compare the agility of both versions of the vehicle, testing their lateral dynamics performance in different speeds and curvature radii, through a bicycle model of each steering configuration. Finally, a conclusion is presented to address the viability of this adaptation.*

Keywords: *boomerang axle, all wheel steering, URUTU, armored vehicle, roll over.*

1. INTRODUCTION

1.1 Goals

The present study aims to evaluate, by means of a mathematical model, the feasibility of replacing the boomerang axle of an APC vehicle, which includes four wheels and two gearboxes, with a two-wheel steerable axle, promoting greater maneuverability and weight reduction of the vehicle. The mathematical model adopted is a half vehicle model and will be developed in Simulink/MATLAB.

1.2 Justification

Over time, the world's armies have developed several ways of searching for information in hostile territories, in order to assist their commanders in battles. Such mission of reconnaissance and data collection is attributed to the Cavalry, and the reconnaissance of territories is accomplished by the Brazilian Army's Mechanized Cavalry, adapted to national needs and specificity's.

The Mechanized Cavalry is equipped with means that are vectors of modernity and state-of-the-art military technology (de Paula, 2020), and over time had to be idealized, equipped and instructed. Therefore, in the 60s, it was necessary to develop an Armored Personnel Carrier (APC) that would supply the needs of the Brazilian Army, so the URUTU APC was developed by the ENGESA company. Later, this vehicle was exported to other countries and was tested in several conflicts, such as the Civil War in Colombia, the Iran-Iraq War, the Kuwait War, the United Nations mission in Haiti, among other conflicts (Damasceno, 2018).

As already mentioned, the URUTU was developed in the 60s, with state-of-the-art technology at the time, but several decades have passed since then and new technologies have been discovered, making the URUTU outdated. Among the disadvantages of the vehicle, one can highlight:

- Blind armor consisting of an $8mm$ bimetal plate, with a hard steel external part, in order to add rigidity, and a viscous material internal part, to protect against shattering. Such set has a relatively low weight but does not add effective protection against high caliber ammunition, a fact witnessed during the Peacekeeping Mission in Haiti, where shots from short distance put the driver in critical situations, where one projectile even hit a driver and wounded him; and (Damasceno, 2018)

- Even though it has smaller dimensions than Guarani, another Brazilian army AWS military vehicle, the URUTU has more pronounced mobility limitations, such as minimum radii of curvature and speeds reached, with the use of the APC Guarani is preferable over the APC URUTU in urban perimeters in law and order guarantee missions, since the last is not able to cover all necessary routes with its current system (da Silva, 2022).

Therefore, currently the URUTU vehicle is being replaced by the Guarani military vehicle in Law and Order missions, but there are programs that aim to modernize the URUTU so that it can be employed in these missions again. Given the great simplicity of the vehicle's systems and its ease of maintenance, apart from the modular system that allows several configurations of this car.

However, to redeploy this APC vehicle for urban missions, it needs adaptations, such as the rear steering and reducing its overall weight. In this new environment, the vehicle's working space is limited and the streets are narrow, there are many sharp curves and winding stretches. Also, for operations in slums, the vehicle faces stretches with high inclination and potentially low ground adherence. Thus, it is necessary to reduce the total weight of the vehicle to help its longitudinal dynamics, as well as to increase its agility and maneuverability, considering that it is a long vehicle, with a large wheelbase.

1.3 Literature review

Different strategies can be applied to improve the vehicle's agility regarding the minimum radius of curvature it is capable of performing. Commonly seen in cargo vehicles is the separation between the driver's cabin and the trailer, which are connected by a hinge (articulated vehicles), so the cabin operates with a radius of curvature limited by the steering of the front wheels, while the trailer has a radius of curvature based on its angle with the cabin.

This strategy of separating the front and rear of the vehicle by a pivot point is also adopted on construction tractors working in narrow spaces. The angle of the pivot point can be controlled to optimize the yawing movement of the machine, for example through active braking control. In (Iida *et al.*, 2010), the yaw moment is controlled by an active braking system based on the tractor's articulation angle. This control allows the vehicle's bending radius to be reduced by 37% at low speeds.

Another option is to include rear axle steering, which directly affects the lateral dynamics of the vehicle, assisting it in changing direction. Although not commonly seen in today's passenger cars, rear-axle steering has been studied since the 60s (Shibahata *et al.*, 1986). Major Japanese manufacturers such as Honda, Mazda, and Mitsubishi and Nissan developed their rear-steering systems in an effort to improve chassis dynamics and bring greater stability to the vehicle.

In these cases, the rear wheel steers in phase with the front wheels, i.e. in the same direction. However, the rear steering angle is proportional to the front one, not necessarily equal, and can be limited by a maximum angle. For example, in (Hiraoka *et al.*, 2003) an active four-wheel steering system is developed that aims to zero the side slip angle and control the lateral acceleration of the vehicle. With the use of this system there are significant gains in the response of acting on a double lane change at high speed, with a shorter response time and also with less oscillations.

Later, as the technology developed, independent actuation systems were tested on each wheel. With each wheel being braked by means of a hydraulic actuator independently, as done in (Oksanen and Linkolehto, 2013), which discusses a technique for simultaneously braking the wheels of an agricultural vehicle with four-wheel steering.

Recently, the idea of rear-steering has been explored again by luxury brands such as Mercedes and Audi and other pickup truck manufacturers, but in the context of improving the vehicle's maneuverability at low speeds. Since these vehicles have a large wheelbase, rear-steering helps the vehicle to take corners with smaller radius and access narrow streets. In this case the wheels turn in opposite directions to the front wheels.

In (Shibahata *et al.*, 1986) a vehicle is designed to be steered conventionally on the front wheels and electronically on the rear wheels. The purpose of the rear-steering calculation is to keep the lateral slip of the vehicle at zero, and the wheels rotate in phase opposition at low speeds or in phase at high speeds. This results in optimum maneuverability and high stability, although it is difficult to find a control solution that encompasses both situations.

In the case of the URUTU military vehicle, the insertion of a pivot point to transform it into an articulated vehicle would lead to major changes in its chassis, besides harming its dynamics at high speeds. Therefore, the most feasible adaptation, aiming to improve the maneuverability of the vehicle, is the inclusion of an electronic rear-steering system. This work studies the feasibility of replacing the rear axles by steerable wheels, in conjunction with the vehicle's weight reduction. To enable its use in narrow streets with small radius curves.

2. Vehicle Model

2.1 URUTU Data

According to the literature available, the URUTU data available for this study is summarized in table 1 - (da Silva, 2022), (Damasceno, 2018) and (de Paula, 2020).

Table 1. URUTU data

Dimension	Urutu	Unit
Overall length	6100	mm
Overall width	2650	mm
Overall height	2125	mm
Distance between front and rear axles	3770	mm
Distance between front and middle axles	2340	mm
Distance between middle and rear axles	1410	mm
Tire width	240	mm
Tire radius	600	mm
Weight	**Urutu**	**Unit**
Weight on front axle	42,8	kN
Weight on middle axle	39,4	kN
Weight on rear axle	38,1	kN

This work proposes replacing the double rear axle with a single steerable one, which may cause problems concerning the normal force that the new tires and axle must hold. The new axle must withstand $38.1 + 39.4 = 77.5kN$ of weight, that is, a weight equivalent to 7900 kg. Which is adequate, considering that there is a military grade tire in the market that holds a maximum load of 5600 kg (each wheel) and its radius is close to the one used in the URUTU (589.75mm). The tire suggested is Michelin's X® FORCE™ 2/XZL2 specified as 395/85R20 TL 168K MI (Portugal).

2.2 Bicycle Model

In order to study the performance of the vehicle in sharp turns, the bicycle model is chosen to represent the URUTU's lateral dynamics. The bicycle model simplifies the vehicle axles unifying left and right wheels. First, the dynamics without the proposed adaptations will be drawn as a comparison, however, the APC URUTU E-11 has three axles, one steering axle in front and two non-steering in the rear. This requires another hypothesis to implement the analyses. In a multi-axle vehicle with front wheel steering only, wheelbase is not easily defined and it is problematic to calculate the turning radius since the two rear axles are parallel. Therefore, an approximated model is proposed, in which the rear axles are merged and the wheelbase is the distance between the front axle and the mid line between the rear ones (Jazar, 2008), this hypothesis is illustrated in figure 1 by distance "l".

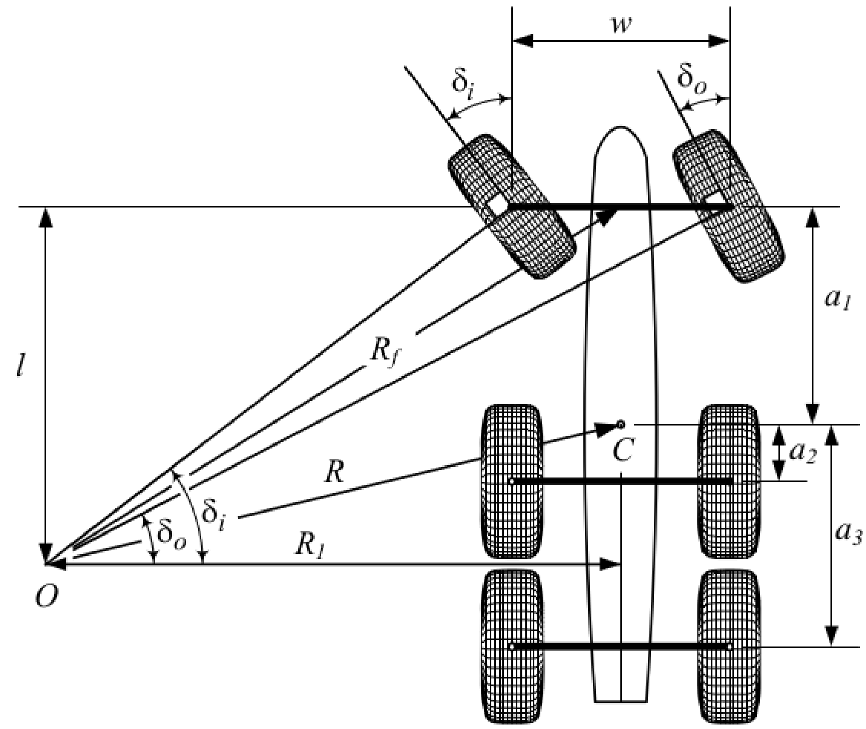

Figure 1. Wheelbase calculation for a three axle vehicle

As a result, the virtual wheelbase for the URUTU without adaptations is 3.065 m, and this is considered as the distance from the front axle to the rear steering axle in the new vehicle. Furthermore, the bicycle model allows to calculate the curve radius using the wheel and car geometry, based on figure 2, for a front-wheel steering vehicle, the turning radius is calculated as:

$$R_{fws} = \frac{l}{\sin\delta}. \tag{1}$$

Where l is the wheelbase, R is the turning radius and δ is the steering angle.

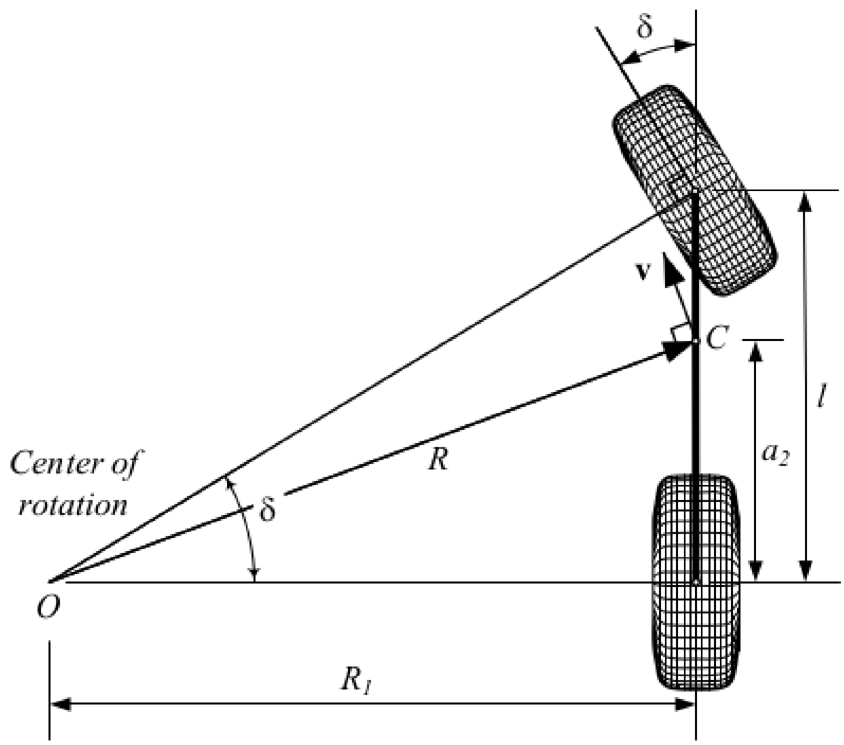

Figure 2. Bicycle model of front wheel steering

Now, for a all-wheel steering vehicle, with δ_f being the front steering angle and c_1 is the distance between the front axle and the turning center at the vehicle's mid axis. Considering that the rear wheels steer in the opposite direction of the front ones as shown in figure 3, the turning radius is computed as:

$$R_{aws} = \frac{c_1}{\sin\delta_f}, \tag{2}$$

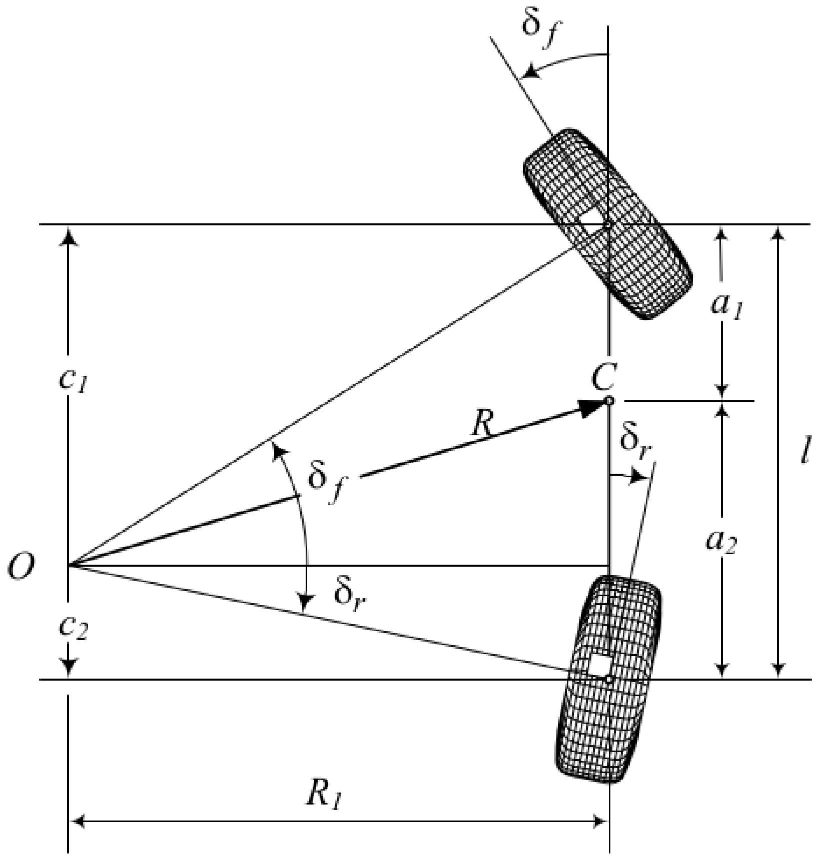

Figure 3. Bicycle model of all-wheel counter steering

this equation can be written in function of the wheelbase using the relation of the front and rear steering angle, δ_r:

$$\begin{cases} \frac{c_1}{\tan \delta_f} = \frac{c_2}{\tan \delta_r} \\ c_1 + c_2 = l \end{cases} . \quad (3)$$

As a result, the turning radius can be expressed as a function of the steering angles and the wheelbase

$$R_{aws} = \frac{l}{\sin \delta_f} \left(1 - \frac{\tan \delta_r}{\tan \delta_f + \tan \delta_r} \right). \quad (4)$$

In the special case where $\delta_f = \delta_r = \delta$, renders:

$$R_{aws} = \frac{l}{2 \sin \delta}. \quad (5)$$

Comparing equations 1 and 5, when a steering wheel is added to the rear axle of the vehicle and the steering angles are equal in magnitude, the turning radius is reduced in half. Which greatly increases the agility of the vehicle.

Moreover, a reduction in the turning radius will also affect the weight transfer of the vehicle, as the centripetal acceleration can be written as $a_{cp} = \frac{V^2}{R}$, for a constant velocity curve. Therefore, we must calculate the maximum speed allowed with rear counter steering. The weight of the inner wheel of a vehicle in a constant speed turn follows the equation:

$$W_w = \frac{W_v}{2} - \frac{W_v h V^2}{Rtg}, \quad (6)$$

where W_w and W_v are the weights in the wheel and of the vehicle respectively, h is the center of mass height, t is the track width, V the speed and R the turn radius. When the normal force in the inner wheel is null, the vehicle is in the eminence of rolling over, which results in the equality:

$$R_{min} = \frac{2hV^2}{tg}. \quad (7)$$

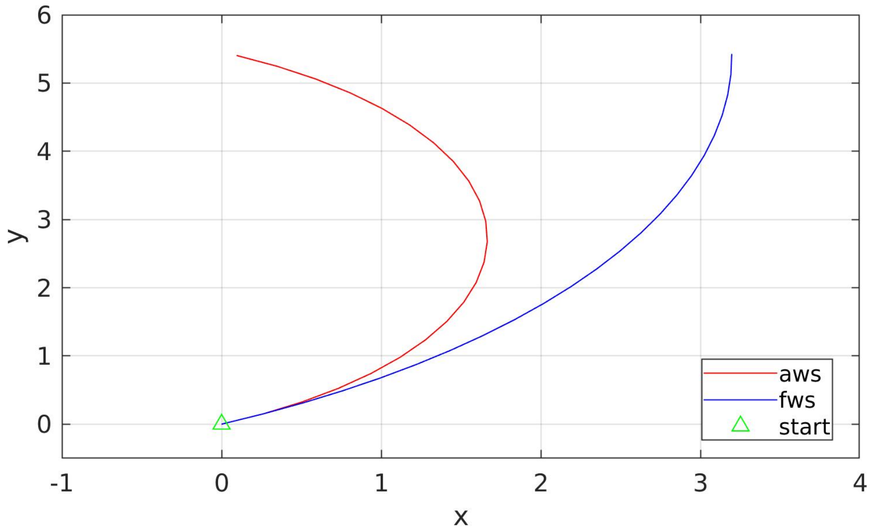

Figure 4. URUTU Agility with AWS vs FWS

As a result, the minimum turn radius allowed, that is, the radius that the maximum steering must not overstep, is a function of the vehicle's track width, center of mass height and speed. Choosing a fixed speed, the radius can be computed directly.

In order to maximize the range of operations of the APC URUTU, for speeds above the limiting speed, the rear wheels can steer parallel to the front ones. This way the turn radius increases instead of decreasing, as a result the vehicle translates to the side in a maneuver such as a lane change.

Thereafter, a computer unit can switch the rear wheels from counter-steering to parallel-steering depending on the limit speed determined by equation 7, resulting in great comfort and safety during high speeds, and great maneuverability in slow speeds.

3. Results

Plugging in the data from the APC URUTU E11 for the maximum steering angle in the equations above, the values for each turning radius in the front-wheel configuration and all-wheel with equal steering angles are shown in table 2. In practical terms, this means that when the rear wheel steer, the vehicle is able to perform much tighter turns.

To illustrate that, figure 4 shows the trajectory using all-wheel steering (AWS) and only the front-wheel steering (FWS), with the vehicle moving at 30 km/h and the steering angle fixed at 30^o. It starts the trajectory from point $(0, 0)$ and the AWS vehicle is able to complete a 180^o turn, while the FWS one only turns 90^o.

Table 2. Turning Radius comparison

URUTU (fws)	URUTU (aws)
6.13 m	3.065 m

As already mentioned, the URUTU military vehicle is used in Law and Order missions. Such missions require good drive-ability and maneuverability, once they happen in the middle of the streets of Brazil, often in the slums.

Therefore, one of the requirements for such vehicles to be used in those situations is the ability to make sharp curves, in other words, smaller turning radius. Table 2 summarizes both of the URUTU performances, it is noticeable that the performance of the URUTU is improved when the steering system is adjusted to an all-wheel one.

Table 3 presents a comparison of the turning radius of the most used vehicles in such missions. Both the Ford Ranger and Guarani presents worst results than both of the URUTU versions, but one of the most used vehicles used in such missions is the Hilux. Initially it has a better turning radius, but with the change of the steering system, URUTU accomplishes a better result.

With that in mind, the URUTU advantages over the regular vehicles is not only its armoury and fire power, but also its maneuverability, that is better in terms of turning radius over other vehicles used in Law and Order missions.

Table 3. Turning Radius of other vehicles used in Law and Order missions

Guarani	Hilux	Ford Ranger
9.9 m	5.9 m	12.2 m

To implement the rear steering an electric motor is used to turn the wheels, thereby the rear steering angle can be variable according to any chosen parameter. As the speed of the vehicle combined to hard steering conditions may cause rolling over, a correlation between the vehicle's speed and the rear steer angle can be drawn.

Figure 5 shows the percentage of the front wheels maximum steering angle allowed for the rear wheels, according to the speed of the vehicle. That is, for speeds below 22 km/h, the rear steering angle can be equal or even greater the front ones. However, taking into account the space provided by the suspension system, it is safe to say that rear steer is limited to 100%. As a result, this is the limiting speed for the smallest turning radius possible for the new URUTU.

This graph also indicates the maximum speed that the URUTU can fully turn its wheels without the rear steer adaptation, for speeds above 33 km/h it can roll over. With this information, the electric motor can adapt the rear steering to a safe condition proportional to its speed. Also, a parallel steering can be used to increase comfort and stability in higher speeds.

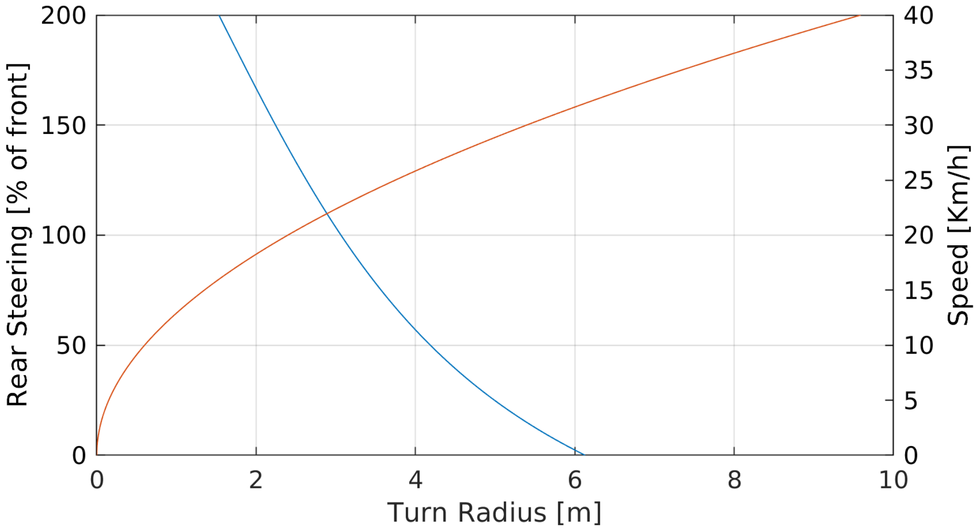

Figure 5. Maximum speed and rear steering relation

4. Conclusion

This paper proposes an adaptation for a military vehicle of the Brazilian Army to allow its use in a specific area of interest, which is Brazil's slums. The rear axles of the URUTU are replaced with a single rear steering axle, that uses an electric motor to steer the wheels proportionally to the vehicle's speed.

The rear steering takes into account the vehicle's speed to guarantee its safety and avoid rolling over. Also it results in a tighter turning radius to increase the agility of the military unit. Because it has a smaller turning radius, the URUTU is a more agile vehicle, and moves faster in urban perimeters when turning.

As a result, an interesting optimization for the Brazilian Army law and order missions is to invest in the modernization of the URUTU APC, where the vehicle's ability to access certain areas is increased offering a better protection to the soldiers being deployed.

5. REFERENCES

da Silva, F.P., 2022. *Comparação da VBTP Guarani e a VBTP EE-11 Urutu em Operações de Garantia da Lei e da Ordem em Ambiente Urbano*. Trabalo de Conclusão de Curso, Academia Militar das Agulhas Negras, Resende - RJ.

Damasceno, R.C., 2018. *Utilização da VBTP Guarani em Substituição à VBTP Urutu nas Operações GLO*. Trabalo de Conclusão de Curso, Academia Militar das Agulhas Negras, Resende - RJ.

de Paula, I., 2020. *A Evolução da Cavalaria Mecanizada Brasileira Após a Segunda Guerra Mundial*. Trabalho de Conclusão de Curso, UNISUL.

Hiraoka, T., Nishihara, O. and Kumamoto, H., 2003. "Active Four-Wheel Steering System for Zero Sideslip Angle and Lateral Acceleration Control". *IFAC Proceedings Volumes*, Vol. 36, No. 14, pp. 371–376. ISSN 1474-

6670. doi:10.1016/S1474-6670(17)32448-5. URL https://www.sciencedirect.com/science/article/pii/S1474667017324485.

Iida, M., Tomiyama, H., Oh, T. and Nakashima, H., 2010. "Steering/Braking Control of Articulated Vehicle for Small Turning". *IFAC Proceedings Volumes*, Vol. 43, No. 26, pp. 197–202. ISSN 1474-6670. doi:10.3182/20101206-3-JP-3009.00034. URL https://www.sciencedirect.com/science/article/pii/S1474667015310624.

Jazar, R.N., 2008. *Vehicle Dynamics - Theory and Apllication*. Springer, 2nd edition.

Oksanen, T. and Linkolehto, R., 2013. "Control of four wheel steering using independent actuators". *IFAC Proceedings Volumes*, Vol. 46, No. 18, pp. 159–163. ISSN 1474-6670. doi:10.3182/20130828-2-SF-3019.00061. URL https://www.sciencedirect.com/science/article/pii/S1474667015349776.

Portugal, M., ???? "Pneus para camião Michelin X® FORCE™ 2 / XZL2 | MICHELIN Portugal". URL https://pro.michelin.pt/pneus/michelin-x-force-2-xzl2.

Shibahata, Y., Irie, N., Itoh, H. and Nakamura, K., 1986. "The Development of an Experimental Four-Wheel-Steering Vehicle". *SAE Transactions*, Vol. 95, pp. 862–869. ISSN 0096-736X. URL https://www.jstor.org/stable/44725440. Publisher: SAE International.

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