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MODELING AND SIMULATION OF THE TERRAIN VEHICLE WITH FOUR WHEEL STEERING

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Abstract: This paper presents early development of the special four wheels driven vehicle intended for use in rough off road conditions. Especially attention is focused on the development of the steering and suspension system that should fulfill pretentious requirements about the stability, safety and maneuvering ability. To fulfill the requirements from the check list as better as much the new design of both mentioned systems are proposed. The analytics and computer modeling including the simulation of the vehicle equipped with improved new suspension and steering is done by considered two main regimes. First regime takes into account the vehicle traveled at low speed and second at higher speed. Few chosen suspension and steering systems are analyzed into the very details in order to find out the optimal design of it. Afterwards the results of computer kinematics simulation are accomplished and detailed discussed in order to precisely point out the influence of turning radius in maneuvering ability. Finally it is clearly shown how the vehicle behavior at low speed regimes is limited by the cornering radius in dependence of terrain roughness. It is also clearly demonstrated how at higher speed regimes stability conditions are decisional. On the basis of the presented investigation the new special mechanical steering system is proposed that on the one hand ensure quite good driving characteristics of the treated vehicle that includes good maneuvering at low speed and on the other hand this design ensure satisfactory stability at higher speeds. Achieved results that are presented may in general help the designer of modern vehicles equipped with all wheels drive.
Keywords: four wheels steer, steering system, suspension system, computer analysis

INTRODUCTION

The aim of this paper is to conceive and design the suspension and steering system of the four wheels driven and four wheels steered in special terrain vehicle (off road vehicle), Figure 1. The subject treated here is research and development work of the terrain vehicle that is conceiving for special purposes.

The suspension system should be done by mechanical way including standard components such as beams, bearings, mechanical and hydraulic springs, dumper, etc. The steering system should be done by mechanical way also. It should contain some kind of transmission and drives. All the components of both systems should be chosen in order to keep the weight as low as possible and to ensure the highest reasonable efficiency. The number of components should be low in order to satisfy the reliability conditions.

The wider aim of this paper is to use simple and more or less standard components that are positioned on the best way on the vehicle chassis.

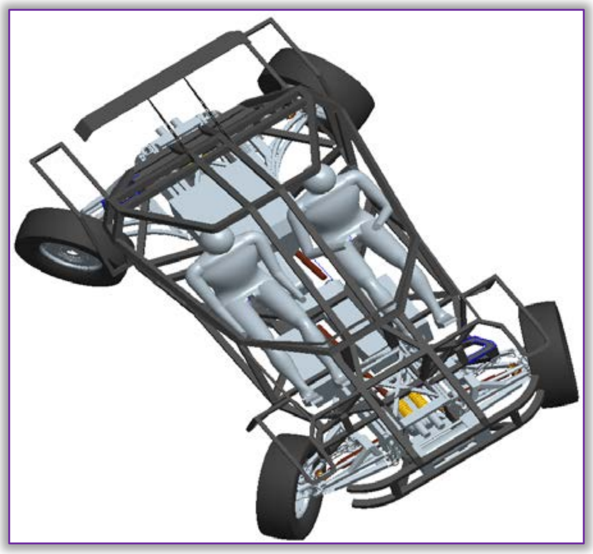

Figure 1: Top view of special terrain vehicle [1]

In Table 1 check list are presented in order to meet the requirements counted in it as better as much the many original and new concepts of suspension and steering system are checked and carefully analyzed [1].

Table 1: Check list with characteristics and factors, which impact the suspension and steering systems

No	Characteristics	Value	Unit	Remarks
1.	Engine: P_e =	400	kW	Limit
2.	Power transmission: Gearbox	Mechanical		Request
3.	Driving speed: v =	0 - 180	km/h	Limit
4.	Maximal grade angel of road: α =	50	deg	Wish
5.	Geometric dimensions: Wheelbase: l = Track: w = Distance: a = Distance: c =	2800 2100 1400 1700	mm	Limit
6.	Mass of vehicle: M =	1150	kg	Limit
7.	Dimensions of front and rear wheels: Diameter: D = Width: B =	800 250	mm	Request
8.	Number of seats: n =	2		Request
9.	Camber angle γ =	0	deg	Limit
10.	Radius of turning center	2.24	m	Limit
11.	Suspension system design:	Mechanical		Request
12.	Steering system design:	Mechanical		Request
13.	Vertical displacement of wheels up to	500	mm	Request

SUSPENSION AND STEERING SYSTEM

In the paper is focused into the suspension and steering system design for the terrain vehicle. It is required four wheels drive, four wheels steering, good maneuverability and good comfort. Good comfort requires great vertical movements. Good maneuverability requires extensive rotations of the wheels around kingpin axles. Consequently the four wheel drives is space consuming and all counted requirements should be compensate by the development of completely new steering system. On the basis of the previous experiences it is clear in advance that conventional steering system won't meet the expected and prescribed conditions. It is assumed to equip the terrain vehicle with the same steering and suspension systems on all wheels, front and rear.

Suspension system

Suspension system of the vehicle performs multiple tasks such as maintaining the contact between tires and surface, providing the vehicle stability, protecting the vehicle chassis of the shocks excited from the terrain unevenness [2-4].

The suspension system is in general done by some mechanical way. The design of it is divided into two main groups: dependent suspension system (Figure 2) that consists mainly from solid axis and independent suspension system (Figure 3) that include a plenty of moving members. Dependent suspension system is easily to make but has a lot of weaknesses.

For example the own mass is to large, the decisional angels are changed by vertical movement drastically etc. Because of counted reasons dependent suspension is not acceptable solution for terrain vehicles at all.

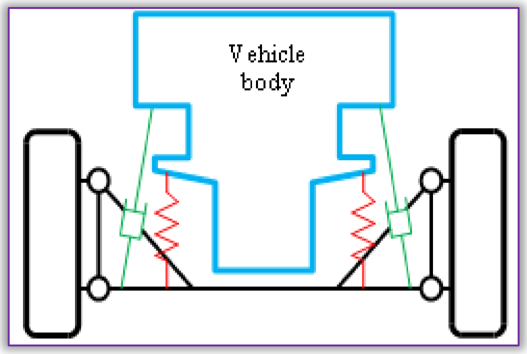

Figure 2: Dependent suspension system

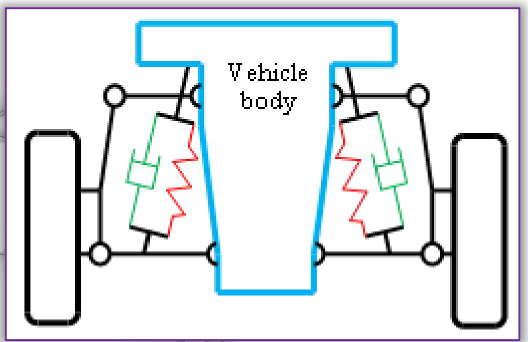

Figure 3: Independent suspension system

The only acceptable solution seems to be an independent suspension system. Independent suspension has roughly more consisting parts, but by using it can be successfully controlled all the decisional characteristics of the suspension such as many angels, etc. The problem is that this kind of suspension for all wheels driven and all wheel steered terrain vehicle is not a 'standard' design. It should be developed yet.

In general, most of independent suspension systems could be categorized in three groups: MacPherson, double wishbone and multi – link suspension system, Figure 4.

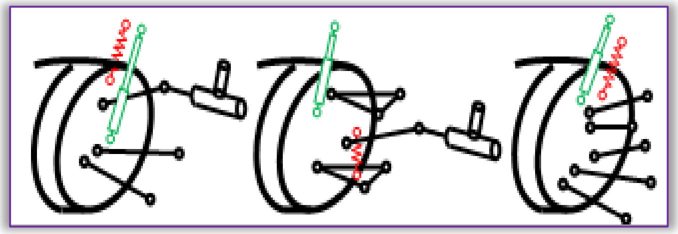

Figure 4: Independent suspension system: a) MacPherson, b) Double wishbone and c) Multi link [4-6]

Nearly all type passenger cars, many light track and some of terrain vehicle use independent front suspension because it provides a quite good insulation about the steering vibration for example. Counted systems ensure also enough space for engine installation and on some way they ensure a higher performance of the vehicle including the passenger comfort. The design of front and rear suspension system of the passenger cars may be different. The main disadvantage of already described suspension systems is basically in fact that they not allow the vertical movement of the tires big enough to give good characteristics of the terrain vehicles.

Steering system

The steering system design is a decisional component of all type vehicles. It represents a connection between driver and vehicle. The main task of this system is to steer the vehicle to follow in advance provided trajectory. This should be done safety and easy as much. The traditional steering system design is usually done by some kind of mechanical way. By such mechanism the safety is ensured. Mechanical system consists from steering wheel that is operated by driver, the steering shaft that transmits driver's commands to the power steering and the steering linkage that is connected indirectly to the steered wheels (Figure 5).

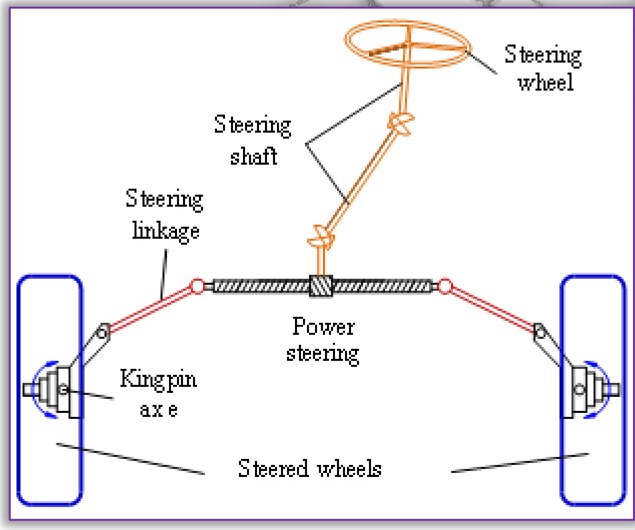

Figure 5: Traditional steering system

In general, the driver not only steers the vehicle but he gets a feedback from the road that is expressed by the contra torque on the steering wheel. The steering mechanism is exposed to the wheel forces that are generated by moving the vehicle over the different terrains. The design of the steering components is limited by these forces and by many other geometrical limits such as vertical movements, etc.

However, nowadays the mechanical steering mechanisms are good enough developed to fulfill the expectations for the most more or less ordinary vehicles. On the safe way they ensure quite good maneuverability of the vehicle by a maximum rotating angle of the front steered wheels approximately 30° that is characteristics for the passenger car and about 55° that is characteristics for the common terrain vehicle, busses and trucks. Meanwhile already all mentioned vehicles mostly run on the let say perfect flat roads the terrain vehicles should conquer much bigger surface roughness. It means the terrain vehicle should move his tires much more in vertical direction and that could represent a lot of problems by the efficient steering mechanism (Figure 6).

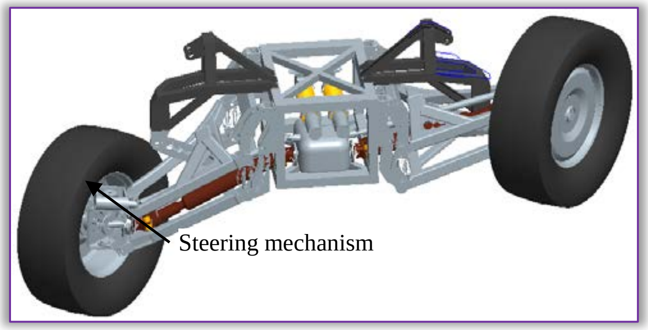

Figure 6: Design of new mechanism of steering system

These already described problems are multiplied by the greater wheels and by shorten wheelbase, which is certainly characteristics for the modern development of the terrain vehicles.

Four driven wheels is additional deepening the problem of terrain vehicle steering because of the place shortage. The power supply to the wheel and steering mechanism share now the same place. The mass is complete when four driven wheels and four steered wheels are requested at the once.

In order to ensure good maneuverability of the terrain vehicle that is first of all defined by steering mechanism firstly the suspension system should be properly designed.

DEVELOPMENT OF THE SUSPENSION SYSTEM OF TERRAIN VEHICLE

Development of suspension system (multi – link suspension system) should be more complex than conventional suspension system because as is mention above the terrain vehicles require the biggest vertical displacement of the wheel up to 500 mm or more from lowest point to the maximum (Figure 7), while in passenger vehicles such displacement are considerably smaller. For domination of the vertical displacement of the wheel required the new design. This suspension mechanism except acting dynamic vertical loads at the same time acting the lateral and longitudinal loads due of contact between wheels and surface of road which increases even more the complexity of building mechanism from which is required with successfully dominates these loads.

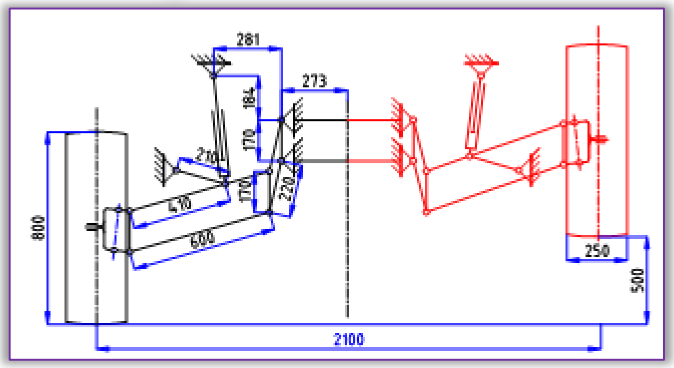

Figure 7: Front view of developed suspension system

The mechanism of suspension system is creating by few components connected to the chassis, on side, and to the wheel hub, on the other side. Mostly of these components are standard elements such as revolute joins - bearing (free maintenance), beams, linkages, springs, dampers, etc. Upper and lower arm of suspension system is connected to the chassis by four longitudinal revolute joints and others parts also are connected with a lot of revolute join, Figure 8.

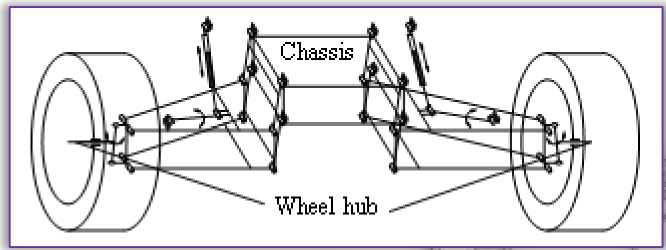

Figure 8: 3D developed suspension system

Other problems that may occur during large vertical displacement of the wheel is increasing the camber angle (angle between the vertical axis of the wheels and the vertical axis of the vehicle when viewed from the front or rear), which will directly affect in reducing of stability of vehicle as a result of small contact of wheel with the road. Developed suspension mechanism enables camber angle to be zero ($\gamma = 0$) during the vertical movement of the wheel and directly increase stability of the vehicle. In suspension system special attention should be paid designing of the best point of connection suspension mechanism with shock absorber and spring with improving ride comfort.

DEVELOPMENT OF STEERING SYSTEM OF TERRAIN VEHICLE

Conventional steering system includes a kind of power gear that is steered by the steering wheel and by a kind of mechanical transmission that consists of simple levers, arms and trusses mainly. To make the proper steering system it is foreseen that develop new transmission and drives that are located on each wheel separately is to be developed. Transmission is not standard component. It works such as reduction and multiplication because when vehicle cornering on the left or right the steer angle of the left and right wheels are different. Developed steering box consists from several pairs of gears such is cylindrical, variable gear ratio, etc. Variable gear ratio used to adjust steer angle of wheels. Connection between steered front and rear axles is realized by propeller shaft which is possible to lock in high speed.

New drives are fitted close to or even on the kingpin on each drive. The working principles of these drives are probably based on worm gears (Figure 9).

All counted new component are rarely used in steering systems but in case of terrain vehicle offer these components probably the best solution. However, it is expected that newly designed suspension system enables even bigger turning of the steered wheel as conventional one. On that way the good maneuverability is ensured. Because all wheels of the vehicle are steered it is assumed that the cornering radius of the vehicle is much lower as it would be by using the conventional Ackermann steering geometry. Of course this characteristic comes to point by lower speeds of the vehicle only. At higher vehicle speed it is proposed to lock the steering of the rear wheels. That enables to the vehicle riding on the regular roads to behave as all other vehicles, which are designed according to the standard Ackermann steering directions.

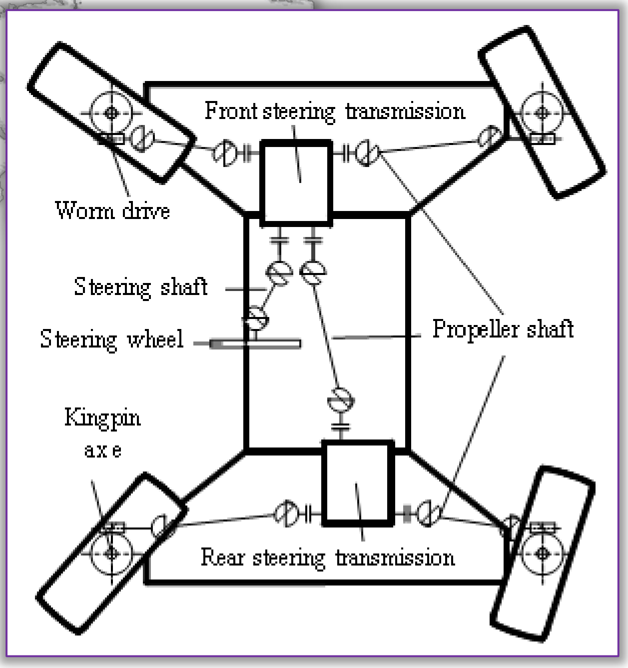

Figure 9: Developed new steering system

To control the stability of the vehicle during the ride across the troubled surface the very effective steering system is necessary.

KINEMATIC OF FOUR WHEEL STEERING

The scope of this paper is to review some aspects of the kinematical theory of four wheels steer vehicle and present some results and conclusions that we came across during research.

Turning radius of four wheel steer (R_{4ws})

In these analyses, it assumed the sideslip angel of the wheels is negligible. That is valid for low speed of motion of the vehicle [8]. Kinematic steering condition is the perpendicular lines to each wheel and to intersect at one point. The intersection point is the turning center of the vehicle, Figure 10.

The longitudinal distance between point O and turning center of the vehicle are indicating by c and d, in Figure 10.

Steer angles of the left and right front wheel (δ_{LF} and δ_{RF}) it is calculated from the triangle ΔOAC and ΔOBD, while steer angles of the left and right rear wheel (δ_{LR} and δ_{RR}) calculated from the triangles ΔOCE and ΔODF as follow:

$$\tan\delta_{LF} = \frac{2\cdot c}{2\cdot R_{4ws} - w} \quad (1)$$

$$\tan\delta_{RF} = \frac{2\cdot c}{2\cdot R_{4ws} + w} \quad (2)$$

$$\tan\delta_{LR} = \frac{2\cdot d}{2\cdot R_{4ws} - w} \quad (3)$$

$$\tan\delta_{RR} = \frac{2\cdot d}{2\cdot R_{4ws} + w} \quad (4)$$

when are:

δ_{RF}, [°] – steer angles of the right front wheel,
δ_{LF}, [°] – steer angles of the left front wheel,
δ_{RR}, [°] – steer angles of the right rear wheel,
δ_{LF}, [°] – steer angles of the left rear wheel,
w, [mm] – track (width of the vehicle) and
l, [mm] – wheelbase (length of the vehicle).

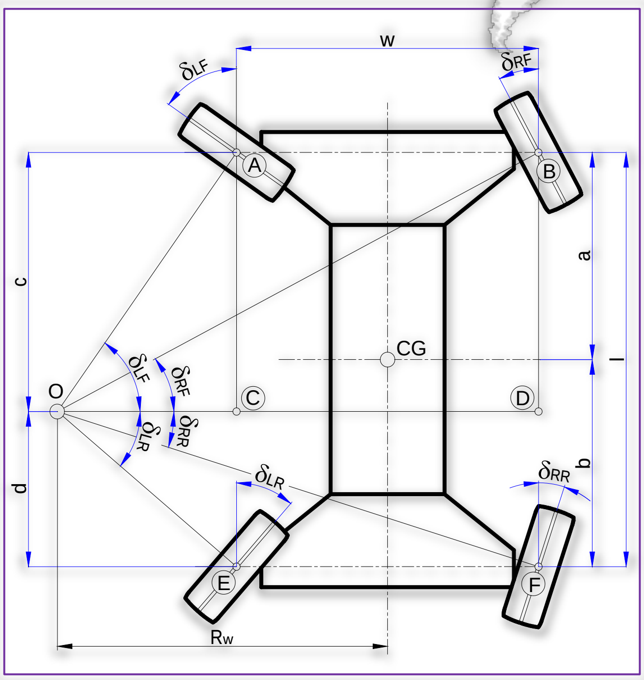

Figure 10: Four wheel steering of terrain vehicle

From equation (1) and (2) turning radius of four wheels steer (R_{4ws}) can be calculated by expression:

$$R_{4ws} = \frac{c}{\tan\delta_{LF}} + \frac{w}{2} = \frac{c}{\tan\delta_{RF}} - \frac{w}{2} \quad (5)$$

After some mathematical arrangement in expression (5) it gets the kinematic condition between the front steering angle δ_{RF} and δ_{LF}, by expression:

$$\cot\delta_{RF} - \cot\delta_{LF} = \frac{w}{c} \quad (6)$$

In the same way deal with expression given in (3) and (4) and turning radius calculated by expression:

$$R_{4ws} = \frac{d}{\tan\delta_{LR}} + \frac{w}{2} = \frac{d}{\tan\delta_{RR}} - \frac{w}{2} \quad (7)$$

Kinematic condition between the rear steering angle δ_{LR} and δ_{RR} is given by expression [7]:

$$\cot\delta_{RR} - \cot\delta_{LR} = \frac{w}{d} \quad (8)$$

From Figure 10 indicate that:

$$c + d = l \quad (9)$$

By combining equation (6) and (8), the expression obtained:

$$\frac{w}{\cot\delta_{RF} - \cot\delta_{LF}} + \frac{w}{\cot\delta_{RR} - \cot\delta_{LR}} = l \quad (10)$$

Relation (10) also can be written as:

$$\frac{(\cot\delta_{RR} - \cot\delta_{LR}) + (\cot\delta_{RF} - \cot\delta_{LF})}{(\cot\delta_{RF} - \cot\delta_{LF})\cdot(\cot\delta_{RR} - \cot\delta_{LR})} = \frac{l}{w} \quad (11)$$

Equation (10) and (11) present kinematic condition between the steer angles of the front and rear wheels for a four wheel steer vehicle (4WS).

Four-wheel steering it is applied on special terrain vehicles to improve maneuvering response, increase the stability at high speeds by locking the rear steering axis, or decrease turning radius at low speeds [9-10].

Turning radius of front wheel steer (R_{2ws})

In these analyses, it assumed that the rear wheel steering angle is zero (δ_{LR}=0 and δ_{RR}=0) and sideslip angel of the wheels also is negligible. To have all wheels turning freely on a curved road, the normal line to the center of each wheel must intersect at a common point. Figure 11 illustrates a vehicle turning left. This is the Ackerman condition.

Steer angles of the left and right front wheel (δ_{LF} and δ_{RF}) it is calculated from the triangle ΔOAC and ΔOBD as follows:

$$\tan\delta_{L} = \frac{2\cdot l}{2\cdot R_{2ws} - w} \quad (12)$$

$$\tan\delta_{R} = \frac{2\cdot l}{2\cdot R_{2ws} + w} \quad (13)$$

From equation (12) and (13) turning radius of front wheels steer (R_{2ws}) can be calculated by expression:

$$R_{2ws} = \frac{l}{\tan\delta_{L}} + \frac{w}{2} = \frac{l}{\tan\delta_{R}} - \frac{w}{2} \quad (14)$$

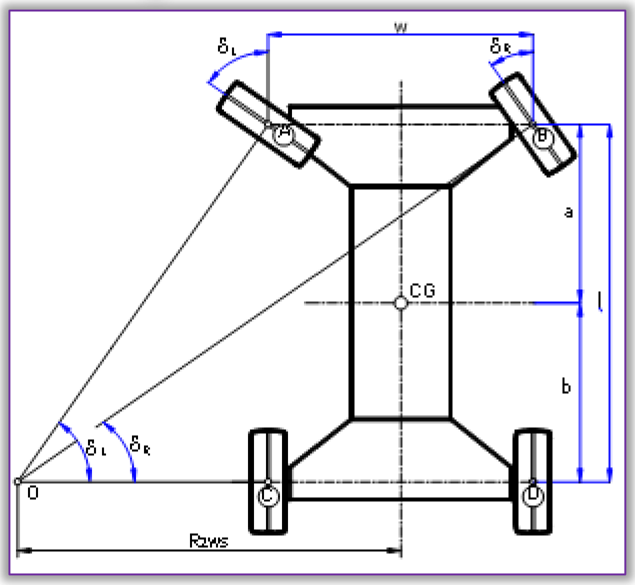

Figure 11: Front wheel steering of vehicle (2WS)

After some mathematical arrangement in expression (14) it gets the Ackerman condition between the front steering angle δ_R and δ_L, by expression:

$$\cot\delta_R - \cot\delta_L = \frac{w}{l} \tag{15}$$

Expression (15) present Ackerman condition.

CALCULATION OF THE STEERING ANGLES AND TURNING RADIUS OF TERRAIN VEHICLE

Expression (1), (2), (3) and (4) for determine left and right steer wheel angles on the front and rear axis also can given by matrix form through expression:

$$\begin{bmatrix}\delta_{LF}\\ \delta_{RF}\\ \delta_{LR}\\ \delta_{RR}\end{bmatrix} = \begin{bmatrix}1 & 0 & 0 & 0\\ 0 & 1 & 0 & 0\\ 0 & 0 & 1 & 0\\ 0 & 0 & 0 & 1\end{bmatrix}^{-1} * \begin{bmatrix} a\tan\left(\dfrac{2\cdot c}{2\cdot R_{4ws} - w}\right)\\ a\tan\left(\dfrac{2\cdot c}{2\cdot R_{4ws} - w}\right)\\ a\tan\left(\dfrac{2\cdot d}{2\cdot R_{4ws} - w}\right)\\ a\tan\left(\dfrac{2\cdot d}{2\cdot R_{4ws} - w}\right)\end{bmatrix} \tag{16}$$

After replacing values in expression (16) that are given in Table 1 by check list, steer wheels angles are:

$$\begin{bmatrix}\delta_{LF}\\ \delta_{RF}\\ \delta_{LR}\\ \delta_{RR}\end{bmatrix} = \begin{bmatrix}55.00\\ 27.33\\ 42.75\\ 18.49\end{bmatrix}, deg \tag{17}$$

To fulfill the requirements of terrain vehicle given in Table 1, as better as much, required the steer wheels angle to have same values given in expression (17).

It is assumed that the return of wheels around kingpin axis from straightaway position to the maximum position on the left or on the right to be realized with 540° rotation of the steering wheel. This means that if the vehicle turns on the left, driver turn on the left steering wheel for 540° and left front wheel will turn 55° around kingpin axis. Transmission ratio will be 540°/55° = 9.82, while the right wheel will turn in same direction for 27.32° and also creates a transmission ratio of 540°/27.32° = 19.76 (Figure 12).

It is required designing transmission which allows the same wheel rotates 55° in one direction and in the other direction 27.32°. Transmission will work as reduction and multiplication. The diapason of regulation of the transmission will be:

$$D = \frac{i_{max}}{i_{min}} = \frac{19.76}{9.82} = 2.01 \tag{18}$$

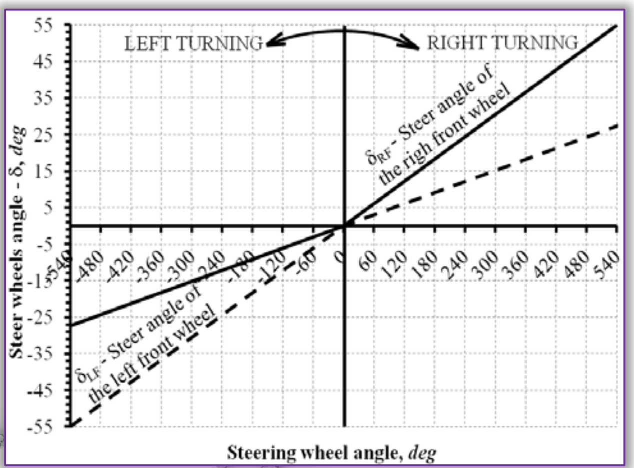

Figure 12: Steer angle of front wheels of 4WS

To have better maneuvering of the terrain vehicle required the wheels in rear axis to rotate around kingpin axe in the opposite direction with front wheels and in this case the rotation angles are not identical with the front wheels (Figure 13).

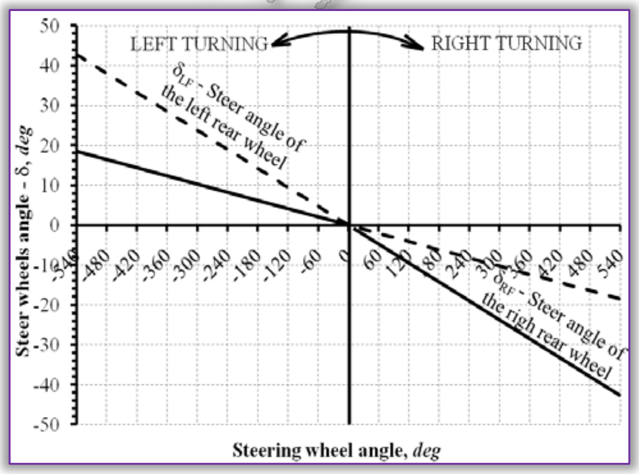

Figure 13: Steer angle of rear wheels of 4WS

To improve the stability of the terrain vehicle when it moves with high speed is necessary that the wheels in rear axis to lock and the vehicle will operate as conventional vehicles.

Expression (12) and (13) for determine left and right steer wheel angles on the front axis can given by matrix form through expression:

$$\begin{bmatrix}\delta_L \\ \delta_R\end{bmatrix} = \begin{bmatrix}1 & 0 \\ 0 & 1\end{bmatrix}^{-1} * \begin{bmatrix} a\tan\left(\dfrac{2\cdot 1}{2\cdot R_{2ws} - w}\right) \\ a\tan\left(\dfrac{2\cdot 1}{2\cdot R_{2ws} + w}\right)\end{bmatrix} \quad (19)$$

After replacing values in expression (19) that are given in Table 1 by check list, steer wheels angles are:

$$\begin{bmatrix}\delta_L \\ \delta_R\end{bmatrix} = \begin{bmatrix}55 \\ 34.59\end{bmatrix}, deg \quad (20)$$

When vehicle turns on the left, driver turn on the left steering wheel for 540° and left front wheel will turn for 55° around kingpin axis. Transmission ratio will be 540°/55° = 9.82, while the right wheel will turn in same direction for 34.59° and also creates a transmission ratio of 540°/34.59° = 15.61, Figure 14. Transmission also will work as reduction and multiplication. The diapason of regulation of the transmission is different from 4WS:

$$D = \frac{i_{max}}{i_{min}} = \frac{15.61}{9.82} = 1.59 \quad (21)$$

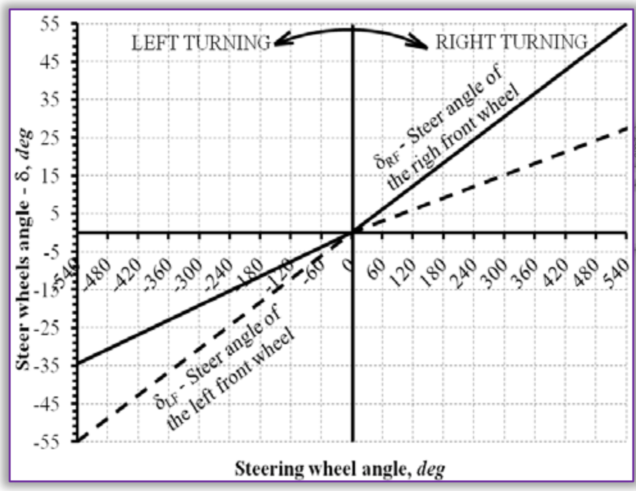

Figure 14: Steer angle of front wheels of 2WS

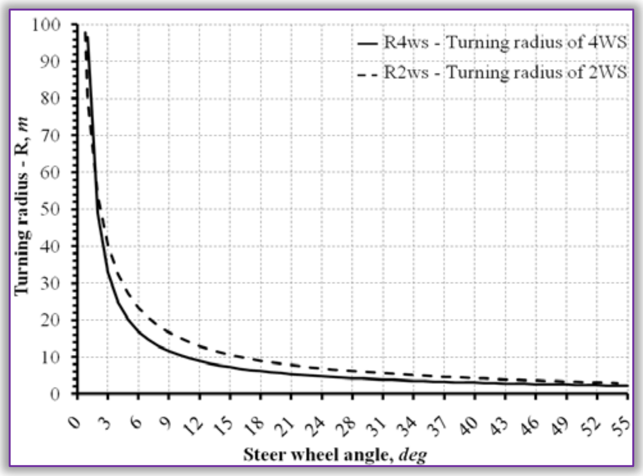

Figure 15: Turning radius versus steer wheel angle

In Figure 15 is presented diagram of changing the turning radius of the terrain vehicle versus steer wheel angle around kingpin axis when four wheel are steered (4WS) and the when only the front wheels is steered (2WS).

The diagram presented in Figure 15 shows that the turning radius is the smaller values when all the wheels are steer, thus ensure the best maneuvering the vehicle and also when the vehicle moves at high speed steer by lock rear axis, vehicle provides the better stability due to the increasing radius of the return.

CONCLUSIONS

In this paper the development of four wheels steered and four wheels driven terrain vehicle is presented. The special attention is focused on suspension and steering system. The following conclusions are presented:

≡ Presented suspension system developed for the terrain vehicle allows vertical displacement of the wheel up to 500 mm from lowest point to the maximum.
≡ Suspension system mechanism enables camber angle to be zero (γ=0) during the vertical movement of the wheel and directly increase stability of the vehicle.
≡ Terrain vehicle with four wheels steer has maneuvering advantage than front wheel steer only if its rear wheels can turn in the opposite direction to its front wheel, because only in that way have a relative reduction of the turning radius, and
≡ Stability of vehicle will increase by lock the steering of the rear wheels. That enables to the vehicle riding on the regular roads to behave as all other vehicles.

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